Guide to WDM Technology and Testing

A UNIQUE REFERENCE FOR THE FIBER-OPTIC INDUSTRY

EXFO

EXPERTISE REACHING OUT

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TABLE OF CONTENTS

PREFACE

When a new technology comes along, the process of moving from theory and lab experience to real-world deployment and practice takes time and hard work. The people and companies that use new technology often need to go through a period of learning and assessment to overcome both anticipated and unforeseen challenges.

WDM technology is no exception. Right now, the fiber-optic and telecommunications industries are in the middle of that period of changing processes and reassessing needs. And as WDM grows and becomes more widely implemented, more people and companies than ever need access to practical, yet thorough, information about testing WDM technology.

This is where EXFO's Guide to WDM Technology and Testing comes in. This book is aimed at the engineers, technicians, and scientists throughout the telecommunications industry who want to learn more about the practical aspects of WDM and DWDM technology. In addition, system and component manufacturers, installers, service providers, and private network operators will find useful information to inform corporate decision-makers. Also, newcomers to the field, and people who know about one aspect of WDM testing and would like to broaden their knowledge, are likely to find what they need in this guide.

Chapter 1 begins with a basic overview of WDM technology: what it is, what it does, and the challenges for the present and future. Chapters 2 through 5 cover the requirements and the fundamentals of WDM testing, as follows:

- Chapter 2 introduces definitions and concepts to people who are new to the field.
- Chapter 3 outlines critical WDM parameters according to component.
- Chapter 4 addresses the specific testing and qualification needs of component and fiber manufacturers.
- Chapter 5 covers the installation, maintenance, and monitoring of WDM systems.

Chapter 6 talks about standards. It should be noted that standards for WDM technology are still under development and, thus, subject to change. However, advanced readers will be interested in the details about standards that this chapter provides.

With WDM technology moving beyond long-haul links, it is important to outline the next stage: metropolitan area networks (Chapter 7). The testing needs for this arena can sometimes differ significantly from those of long-haul networks, so it was felt that this topic deserved a chapter of its own.

With WDM technology continuing to evolve, Chapter 8 will interest readers who need to keep an eye on the future: not just advances in technology, but also how testing needs will change. And finally, Chapter 9 solidifies previous concepts for readers. Using a case study of a telecommunications service provider deploying WDM on an existing link, readers can see a real-life example of how testing works.

André Girard, Ph.D

Senior Member of Technical Staff

CHAPTER 1

HISTORY OF OPTICAL COMMUNICATIONS

HISTORY OF OPTICAL COMMUNICATIONS

1.1 A GROWING NEED

The past decade has witnessed a tremendous growth in the need for communications capacity, both in terms of data rates and in geographic coverage. Rapid and reliable video, voice, and data transmission is critical to the continued growth of many aspects of modern life, in government, industry, and society at large. This need is widespread in North America, Europe, and Asia, and to an ever-increasing extent in other parts of the world.

In the late 1990s, a new phenomenon, the Internet, began to add significant traffic to international networks. Although the Internet had been sitting in the wings for some time, providing a then-novel communications service to the military and research communities, its potential to absorb almost any available communications bandwidth became evident when the World Wide Web offered a bottomless pit of information to the general public. Even the most enthusiastic forecasters of bandwidth expansion were caught off guard.

To an increasing extent, optical fiber has been the medium of choice to handle this vast volume of traffic, and time-division multiplexing (TDM) has been the most common way to divide the impressive capacity of a single optical fiber into useable communications channels. Even this technology, however, has been limited by the increasing complexity of modulation and multiplexing equipment as data rates soar. A new complementary approach has demonstrated its capabilities: wavelength-division multiplexing (WDM).

1.2 WAVELENGTH-DIVISION MULTIPLEXING (WDM)

WDM systems are based on the ability of an optical fiber to carry many different wavelengths of light—colors, essentially—simultaneously without mutual interference. Each wavelength represents an optical channel within the fiber. Several optical methods are available to combine individual channels within a fiber and to extract them at appropriate points along a network. WDM technology has evolved to the point that channel wavelength separations can be very small—a fraction of a nanometer or 10^{-9} m—giving rise to dense wavelength-division multiplexing (DWDM) systems. Networks in which individual fibers carry more than 100 independent optical channels are commercially available, as well as those in which bidirectional use is made of the fiber. And this is just the beginning.

The success of DWDM is largely due to the development of the erbium-doped fiber amplifier (EDFA), an optical device that uses energy from a laser pump to amplify all the signal wavelengths presented to its input (within its narrow bandpass centered at 1550 nm). By amplifying optical signals directly—that is, without requiring that they be converted into electrical signals and back again into optical signals—this device allows the construction of long-haul transmission networks, with few if any electronic components needed.

The TDM approach to increasing network capacity adds channels by subdividing those that already exist, but at some cost in equipment and signal-protocol complexity. The time slots of each channel must be carefully protected and identified, so that individual channels can be recovered. The WDM approach, on the other hand, simply transmits more signals along the fiber, with no timing or protocol implications. Of course, TDM techniques are applied to individual WDM channels to provide greater flexibility in the assignment of network bandwidth to particular users.

HISTORY OF OPTICAL COMMUNICATIONS

From early components able to handle from 4 to 16 channels, each accommodating a 2.5 Gb/s synchronous data hierarchy/synchronous optical network (SHD/SONET) signal, DWDM suppliers soon developed units to support dozens of channels. Systems with hundreds of channels are available now, providing a combined data rate of multi-Gb/s and approaching rates of Tb/s all on a single fiber! Even in applications not requiring such rates today, the installation of a system that can easily be expanded to reach such a performance level is extremely attractive.

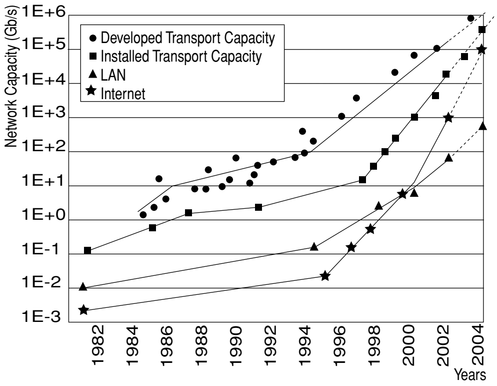


Figure 1.01 The evolution of transport capacity shows that the gap between development and installation is smaller every year.

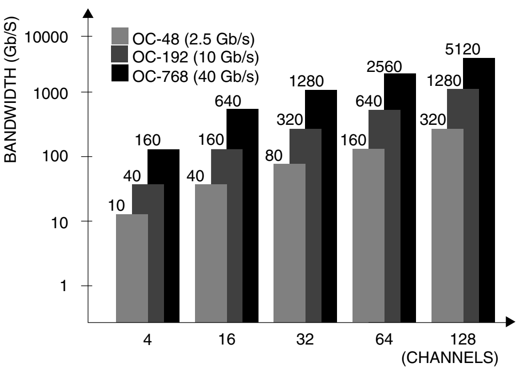


Figure 1.02 Bandwidth capacity increases rapidly with the multiplication of channels.

The increases in network transport capacity that have been supported by advances in WDM technology are summarized in Figure 1.02.

1.3 APPLICATIONS

DWDM systems have been used since 1996, primarily in long-haul sectors where the need for increased bandwidth is usually first experienced. Adding channel capacity this way, without any need to replace existing fiber, is a natural upgrade in the lifespan of a network. As service providers are called upon to supply more bandwidth to individual subscribers and to respond quickly to traffic patterns that are constantly changing, the DWDM approach will see greater use at other network levels. Competitive local-exchange carriers (CLECs) and several local carriers have already started deploying DWDM systems to relieve congestion along high-traffic portions of their networks, in particular to provide extra bandwidth in links joining central offices.

DWDM has not yet made a great impact on the incumbent local-exchange carrier (ILEC) market, where laying new fiber is often the most economical way of increasing bandwidth, although some use in point-to-point applications has been reported. Products are now entering the market that specifically address the problems of metropolitan area networks (MANs), products that provide ring and mesh architecture protection at the optical layer. Products intended to serve the pure-data market—primarily Internet traffic—are especially interesting because the reduced level of protection that is needed for this form of data, compared to voice traffic, could eliminate much of the equipment performing SONET functions. Direct optical connections to end-users are also feasible, along with lease-a-wavelength marketing strategies.

The use of DWDM for data transmission over fiber links, using Internet Protocol (IP), is another proven application of this technology. Potential reductions of data transmission costs are estimated at 100% for end users (Internet gratuity).

DWDM technology developments give credence to the feasibility and practicality of all-optical networks with no electronic signal regeneration at any point. Although much work remains to be done to ensure that such networks can provide SONET-like reliability, components are already available to split, combine, and multiplex optical signals carried by optical fiber. Fixed-wavelength, optical add/drop multiplexers (OADMs) have reached the market, and dynamically reconfigurable units are expected in the near future. Optical cross connect (OXC) units that serve as network hubs are also in development. A similar technology should eventually yield units to switch and convert individual wavelength channels in a fiber.

1.4 THE FUTURE

There is little doubt that demand for network bandwidth, which is now growing roughly 100% per year, will continue to be strong for at least the next decade. This demand will also spread over increasingly wide geographic areas. Price-cutting by suppliers, government deregulation, and—perhaps, above all—the unabated popularity of Internet use and of other high bandwidth-intensive applications in the entertainment area will bolster this growth. DWDM now provides the quickest proven way of increasing bandwidth in a cost-effective manner. In many cases, it allows increases in existing fiber capacity by a factor approaching 100.

Although at some point DWDM techniques will reach their limit, such a day still seems very distant. The transmission of several hundred channels along a single fiber has been demonstrated. Further increases can be expected by reducing channel spacing, by using wider spectral-range EDFAs such as in the L-band (up to 1610 nm), or by using the full available spectrum of the improved fibers down to 1200 nm without amplification.

Even more dramatic increases are on the horizon through the use of data rates greater than the 2.5 Gb/s and 10 Gb/s per channel that are found in today's advanced systems. Prototype systems at 40 Gb/s have already been demonstrated, and the combination of 160 channels, each at 40 Gb/s—which corresponds to an aggregate rate of over five terabits per second or nearly 1000 full CD-ROMs per second along a single fiber—is a foreseen reality. The demand for the transmission of motion pictures in real-time on the Internet could certainly stimulate such an increase in bandwidth.

DWDM, once considered merely a way to squeeze a little more capacity from existing point-to-point cable, now promises to offer the flexibility in routing and the overall bit-rate capacity to answer the challenge of future networks. Technology is even providing the means to generate, combine, route, convert, and separate individual information channels easily through purely optical means without conversion. As a result, high-speed, low-cost optical communication services will soon be widely available.

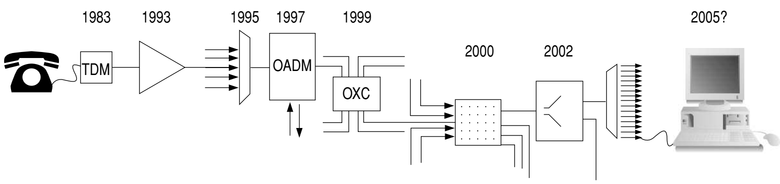


Figure 1.03 Communication evolution will allow fiber-to-the-desk in a near future.

1.5 NEW TECHNOLOGY, NEW TESTING PROCEDURES

Network service providers and their clients can be comforted by the apparent ability of equipment suppliers to meet any increase in communications needs. However, there is a significant cost in adopting the new technology. Verifying system performance and maintaining it will necessarily be far more complex than the corresponding operations were on first-generation fiber-optic networks or, indeed, than they are with present-day networks. In the past, a fiber carrying a single channel could be verified by observing signals with an oscilloscope at the protocol level and the parameter with an optical test instrument such as an optical time domain reflectometer (OTDR) at the physical level. Checking TDM networks requires an enhanced level of test equipment and expertise. DWDM systems, however, present a whole new dimension: all the parameters relevant to transmission efficiency and accuracy must be measured at each channel wavelength. This is not a trivial task, especially when wavelengths are very closely spaced.

Verification and multi-level testing is needed at all levels in a DWDM network: components, sub-systems, optical media, and for the entire system. Test instrumentation must match the complexity of the equipment to be verified, the nature of the communications system, the specific task undertaken and—most important—the experience, skill, and expectations of its operator.

1.6 THE HUMAN RESOURCES CHALLENGE

Above and beyond the outbreak of bandwidth capacity, technological progress, new applications, and new avenues for optical data transmission, remains a more complex problem: lack of human resources. The telecommunication industry is growing so fast that universities and technical institutions cannot deliver sufficient specialized personnel. Furthermore, experience is rare and an advanced technical education is watered down to enable the flow of more students. You just have to visit various company Web sites to discover that there is abundance of job openings in the field of fiber optics.

Optical systems are growing in size, not only physically but also geographically. This expansion has created a major demand for specialized personnel to deploy these systems along cities, countries, and oceans. All the components required to build optical systems have to be developed and manufactured by a team of engineers and technicians. Research departments are also looking for high-level scientists, while distributors and vendors are searching for qualified sales people. We have witnessed numerous startups begin operations in the last few years and it is most likely to continue in subsequent years. Wherever you are positioned in the telecommunications industry, human resources are definitely a major concern for years to come and should be seriously taken into account.

WDM GUIDE

CHAPTER 2

THE BASICS

THE BASICS

2.1 OPTICAL TRANSMISSION TECHNOLOGIES

WDM is not a game that you learn to play over night. Fiber-optic data transmission in general, and WDM techniques in particular, involve a complex mix of many diverse and sometimes rather esoteric phenomena, practical limitations, and economic constraints. Throughout this section, which covers optical transmission technologies, you will discover or rediscover the basis of traditional TDM systems and their evolution. New WDM systems and their components will be discussed in greater detail to clearly demonstrate their utility within a system. The differences between TDM and WDM will complete the section and lead to more complex definitions of the critical parameters in WDM technology.

2.2 TIME-DIVISION MULTIPLEXING

The need to narrow the gap between the inherent information-carrying capacity of an optical channel and the use that can be made of that capacity in everyday applications has spawned extensive research. Solutions are needed for both existing fiber lines and for the provision of new services. The first approach taken is analogous to the one used in conventional electronic communications systems. It combines a number of channels onto a single carrier with time-division multiplexing (TDM).

In TDM, the optical signal in a fiber is shared among a number of information channels by time slicing. For a brief period, or time slot, the signal is modulated with the first information channel; for the next time slot, the signal is modulated with the second information channel, and so on.
See Figure 2.01.

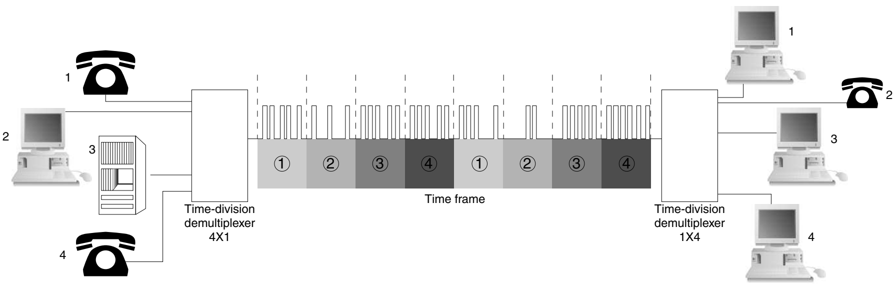


Figure 2.01 In TDM systems, channels are divided into time-slots propagating at the same wavelength on the same fiber.

The duration of a time slot depends upon a number of different engineering design factors and, in particular, upon the transmission speed needed for each link. Each communication path is assigned a specific time slot, a TDM channel, during which it is allowed to send data from the source to the user. No other source is permitted to transmit at the same time. The multiplexer at the source end takes in data from the sources connected to it, and inserts packets of data from each into the fiber during the appropriate TDM time slot. The demultiplexer at the other end must recognize the time slots, unload the data from each, and send it as a continuous stream to the corresponding user.

The use of TDM techniques has increased the useful capacity of a single optical fiber channel to more than 10 Gb/s, using technology and design methods that are familiar to telecommunications system designers; systems at this rate are gradually replacing early 2.5 Gb/s TDM implementations. The 10 Gb/s rate represents a turning point of sorts. Below this speed, the governing characteristics of optical fiber have a reasonably small impact on transmission quality; above it, their effects must be carefully taken into account. Although TDM systems operating at up to 40 Gb/s may soon be widely available, and research is underway into 100 Gb/s transmitters, further increases will

Optical carrier (OC-x)	Synchronous transport module (STM-x)	Line rate (Gb/s)
OC-3	STM-1	0.15552 (0.156)
OC-12	STM-4	0.62208 (0.625)
OC-48	STM-16	2.48832 (2.5)
OC-192	STM-64	9.9533 (10)
OC-768	STM-256	39.813 (40)

Table 2.01 Transmission data rates standardized

not be easy; existing electronic techniques become prohibitively complex and expensive at high rates. New laser-modulation methodswill be needed and effects that can be neglected at low bit rates will begin to degrade signal transmission at high rates.

Physical phenomena that can safely be ignored at lower data rates in short-distance systems become limiting factors as data rates and transmission distances increase. Chromatic dispersion—arising from the variation of the effective index of refraction of the optical fiber with wavelength—is one such parameter. Its effect on signal quality—it spreads optical pulses—is 16 times greater at the current 10 Gb/s (OC-192) data rate than it is at the 2.5 Gb/s OC-48 rate. Even though measures are available to control chromatic dispersion, these measures lead to increased system loss, cost, and complexity. For standard, step-index singlemode fiber (i.e., non-dispersion-shifted fiber often referred to as G.652 fiber), 10 Gb/s transmission is limited to distances of 50 to 75 km without any compensation or correction.

An early compensation measure consisted of using narrowband, source-laser pulses centered near the wavelength at which the fiber dispersion is zero. Operation at exactly the zero-dispersion wavelength should be avoided due to four-wave mixing, which will be discussed in Chapter 3. Unfortunately, directly modulated lasers exhibit a slewing of their carrier wavelength as they are modulated, a phenomenon known as "chirp" that leads to an effective spectral spreading of the generated pulses. Chirp can be subtantially reduced by using externally modulated transmitting lasers, an approach that is used in almost all high-speed systems.

As TDM transmission rates are pushed higher and higher, the design and implementation of their electronic elements becomes dramatically more difficult and expensive, especially since the rates needed exceed those used in other areas such as the computer industry. As a result, the full cost of developing new components must be borne by the optical telecommunications industry. Timing requirements are extremely tight and highly advanced electronic components are needed to modulate lasers and to multiplex and demultiplex electronic signals at these very high frequencies.

A powerful technology known as forward error correction (FEC) can add up to several dBs of system margin. Long used in satellite and wireless communications, FEC adds extra check bits to the data payload, enabling occasional errors in the digital signal (1s and 0s) to be corrected without retransmission. FEC is a process of detection and correction of bit error carried out at the software or hardware level, hardware correction being necessary in the case of very high-speed data transmission. Obviously, this error correction technique cannot resolve every major error, and other optical phenomena can cause transmission problems that it will not be able to rectify.

Another optical phenomenon, polarization mode dispersion (PMD), also affects signal quality at these rates by spreading the signal over time. PMD, which describes how various polarization states of the signal propagate at different velocities along the fiber, is especially difficult to handle because it is a stochastic phenomenon: there are no known practical ways of eliminating its effects entirely. PMD compensation has been demonstrated in the laboratory for small PMD values, but scientists still have a sizeable challenge on their hands before they can transfer this design to the field.

Despite these difficulties, higher data rates are coming on the scene. The new 40 Gb/s (OC-768/STM-256) rate was recently achieved and, even though commercial implementations are unlikely before late 2001, major players in the industry have announced successful transmission along links of more than 100 km, with hopes to raise the limit to much farther distances. So far, trials have not included full SONET support and these trials lack some of the features that will be needed for reliable network operation. Results, however, are encouraging, and suggest that upgrading 10 Gb/s links will be possible much sooner than was originally thought possible.

Making appropriate and economic use of the full bandwidth that OC-768/STM-256 offers will be a challenge to network designers and operators, but help is on the way in the form of an array of products to inject lower-rate tributaries (OC-48/STM-16 and OC-192/STM-64) into high-capacity networks. The distance limitations expected of early implementations will probably restrict their use to metropolitan areas, but wider applications can be expected as distance limitations are eliminated and other limiting optical phenomena are handled. Regeneration can also be an issue where the financial budget allows it.

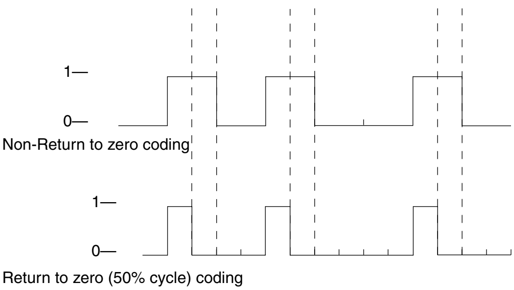


Figure 2.02 Return-to-zero transmission code

Recent papers describe transmission at high bit rates (10 Gb/s and higher) along very long distances. This technology takes advantage of dispersion-managed solitons, which use counter-balancing, non-linear, and dispersion effects, and return-to-zero (RZ) transmission code to avoid degradation of the pulses at the receiver.

A soliton is a special kind of light pulse that maintains its shape (typically Gaussian) as it travels over arbitrarily long distances, provided that the pulse is amplified at regular spacing. The shape or waveform of a soliton allows for compensation of the dispersion affecting traditional pulse waveforms; this compensation is based on the fact that the fiber index of refraction has a non-linear term that is dependent upon the pulse peak power. The soliton uses non-linear and chromatic dispersion effects to conserve its shape. Another important property of solitons is that they have stable propagation characteristics and are very robust to perturbations in the transmission path. Even if this new propagation technique is limited by fiber attenuation, it may be of great help for amplified, long-haul applications.

Whether TDM technology turns to a universal and independent protocol like IP or adopts a largely used protocol like SONET or STM, it will remain exploited and deployed by a significant number of operators for years to come. Advances in soliton research have provided a second wind to a technology that we considered at its limits. Therefore, whatever problems occur and whatever the solutions employed in TDM, no other technology will ever replace it. In a best-case scenario, another technology will be used side-by-side to increase efficiency: WDM.

2.3 WAVELENGTH-DIVISION MULTIPLEXING

WDM avoids many of the constraints and implementation difficulties that limit the performance of TDM systems. Rather than increasing the data rate to handle more information like a TDM system, a WDM system simply carries several optical signals, each at its own wavelength and each respecting the data-rate limitations applicable to the transmission system.

This technique can increase the capacity of existing networks without the need for expensive re-cabling and, thus, can significantly reduce the cost of upgrading a network. It also opens up a new era of marketing flexibility: the transport infrastructure can provide not only cable and fiber for rent, but also individual wavelengths. One wavelength could be used for cable TV, another for telephony, another for Internet traffic, another for video-on-demand, four others reserved to a specific customer, eight others rented to five different customer, and so on.

WDM technology will not directly affect fiber and cable installation. In fact, more fiber than ever is being deployed in North America, Europe, Asia, and the rest of the world. Even though fiber is being deployed throughout the world, we still have to remember that material costs for non-zero dispersion-shifted fiber (NZDSF) at about $150 per kilometer, a 100-fiber cable—with installation costs that often exceed the material costs—can easily run to $100,000 per km. Even if new materials and manufacturing techniques reduce this figure in the future, significant sums will remain tied in fixed transmission facilities. The key to their profitable use is, and will always be, flexibility, that is, the ability to increase bandwidth and reconfigure network services over a long life cycle without recabling or redesigning the existing plant. This is where WDM will come to the rescue of bandwidth needs by allowing a better management of installed and soon-to-be-installed fiber.

WDM technologies are particularly valuable in long-haul applications where greater bandwidth is needed, but wide area networks (WANs), such as cable television systems, potentially represent a large market by offering an economical way of making better use of the expensive base of installed cable. These and other applications have led to dramatic increases in the number of wavelengths carried on a single cable and the resulting narrow channel spacing that characterizes a new class within the WDM domain: DWDM. Although the term wavelength division may imply transmission using any one of a limitless set of possible wavelengths, very practical limitations on available communications equipment presently limit DWDM use to a relatively narrow spectral band centered around 1550 nm. Even within these limitations, the possibilities are enormous.

The many advantages of DWDM systems come at a price. First, optical component properties and cable characteristics, which could safely be neglected in systems using simpler transmission techniques, must be addressed. Furthermore, the new spectral dimension that is inherent to these systems implies new criteria for network design and for the selection of components, thus leading to different, often much tighter, specifications than those applicable to current OC–48/STM-16 TDM systems.

TDM practices and specifications cannot be forgotten. A proper mix of TDM and WDM technologies is still appropriate for new and improved services through cost-effective, non-intrusive additions and upgrades to installed equipment.

WDM offers many advantages at all network levels—from network planning through operation to eventual upgrading—and expanded business opportunities. Its technology is leading-edge, since it places new demands on the understanding needed to plan networks and services and on the skills and equipment needed to monitor and maintain them.

2.4 DEFINITION OF A DWDM SYSTEM

A DWDM system is much like a traditional TDM system. It has transmitters at one end, receivers at the other end, and fiber and repeaters in between, as shown in Figure 2.03.

The difference lies in the number of simultaneous optical signal channels carried by the fiber. In a basic TDM system, there is only one; in a DWDM system, there are several channels. We can think of a DWDM system as a number of parallel TDM systems, sharing fiber and equipment.

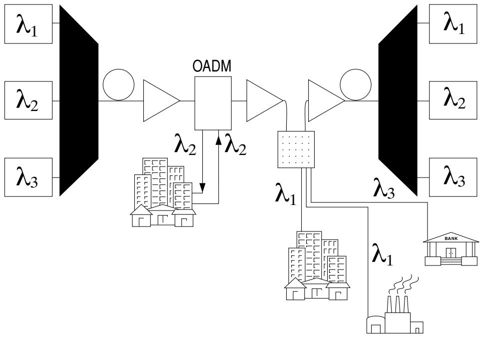


Figure 2.03 Typical WDM system with add/drop and cross connect capabilities

Basically, the optical part of a DWDM telecommunications system consists of one or more laser transmitters, a multiplexer, one or more EDFAs, add/drop units (OADMs), the needed optical fiber (generally a cable), a demultiplexer, and the same number of receivers as transmitters, as shown in Figure 2.02. Every component is essential for the proper functioning of the system as an entity. Each has to be carefully defined, manufactured, and characterized to complete the complex DWDM puzzle. Not shown are the communication protocol electronics and the network management system, although they form a crucial part of any telecommunications network.

2.5 MAIN COMPONENTS DEFINED

The criteria for the selection of components for DWDM systems are demanding; in particular, the channels must be treated equally throughout the optical path. This requirement means that optical sources, multiplexers, demultiplexers, optical amplifiers, and the fiber itself must be selected with care to obtain the expected performance from the complete network.

Therefore, the optical characteristics of both passive and active network components—their insertion and return losses, dispersion, and polarization effects, etc.—must all be measured as functions of wavelength over the spectral band used in DWDM systems. DWDM systems often include much more sophisticated devices than those found in single-wavelength systems, and they may be more difficult to characterize appropriately. Such devices include multiplexers and demultiplexers, narrowband filtering devices using technologies such as thin-film, fused biconic tapered (BFT) couplers, array-waveguide gratings (AWG), and bulk-optic and Bragg grating filters. In addition, the impact of active components on signal quality and integrity must be determined—for optical amplifiers, in particular—and, finally, channel interaction effects must be considered to minimize the potential for adverse interaction among the many components.

Although suppliers can be relied upon to provide material that has been tested at the manufacturing plant to meet all specifications, the mere installation of many components in the field can significantly degrade their performance. Furthermore, the characteristics of individual components may interact in unexpected ways when they are assembled in a system. As a result, reliable network services that satisfy given requirements can be guaranteed only when the system as a whole is shown to meet specifications, not merely when its components do so in isolation.

Testing components in isolation, however, can present many challenges. Wavelength spacing in WDM and, especially, in DWDM systems is very small, so tolerances in many components (multiplexers, for example) must be correspondingly tight. Yet, the whole point of DWDM systems is to support many optical channels, that is, many wavelengths, so the characteristics of several devices are critical over broad spectral bands as well.

2.5.1 Transmitters

Hybrid modules containing integrated circuits and laser diodes, modulated by separate integrated circuitry, have now largely replaced early fiber-optic transmitters made up of discrete electrical and electro-optical devices. Very large scale integrated (VLSI) circuit implementations have come along to meet the need for ever-higher modulation rates and to improve reliability. Present-day transmitters, although usually hybrid in construction, can safely be treated as "black box" modules at the system design level. They are electro-optical transducers: sources of signal light whose intensity can be modulated by digital electrical input signals, either internally (laser current) for low bit-rate transmissions or externally (laser optical beam) for fast rates.

A transmitter for a single channel (wavelength) is typically made up of a distributed feedback (DFB) laser (at least 0 dBm or 1mW) followed by a modulator, which is usually external to the laser especially when modulation rates are high. Recent developments in integrated optics have led to attractive and cost-effective transmitter designs in which the laser chip, modulator, and a subsequent solid-state optical amplifier, are combined in a package. Transmitter packages are now available that incorporate multi-lasers, multiplexers, and a booster amplifier, which is usually a semiconductor optical amplifier.

A variable attenuator covering the band of the modulator is sometimes mounted next to a laser to tailor its power to a specific value. This value is chosen to suit the characteristics of the first repeater down the transmission line, or when used with other wavelength transmitters to make sure that all transmitters combine to produce an equally flat spectral power distribution.

The aforementioned DFB laser is presently the source of choice for DWDM systems. In this device, the usual two-mirror Fabry-Perot laser cavity is reduced and controlled, and selecting the exact lasing wavelength through optical feedback is accomplished by a longitudinal grating manufactured as part of the laser chip (see Figure 2.04). The effect of the grating is to force the emission of a single, longitudinal lasing mode or line with a very narrow line width—typically less than 100 MHz full width half maximum—(FWHM)—with sidebands or sidemodes suppressed by at least 40 dB (see Figure 2.05). A sidemode suppression ratio is used to describe the relative intensity of the highest sidemode from the main peak. As with the Fabry-Perot laser, the waveguide geometry ensures a stable-oriented, highly polarized output.

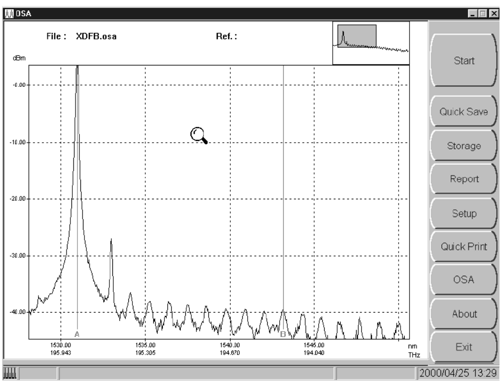


Figure 2.04 The optical spectrum of a DFB laser

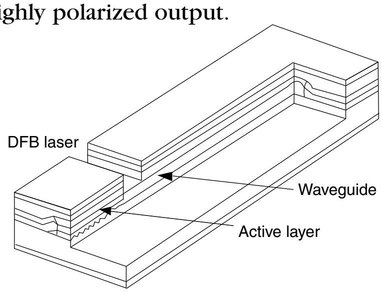


Figure 2.05 Simplified view of a DFB laser chip

In addition to the high-speedelectrical connections, a DFB package can include a thermoelectric cooler, temperature sensor, optical isolator, and monitoring photo diode. Output efficiency is quite acceptable: an output power of 0 dBm is produced with a drive current of about 40 mA.

Laser modulation is a matter of some concern because the method used in low bit-rate systems—modulating the laser drive current—introduces too much chirp for long-haul transmission at the high rates typical of advanced WDM systems. The option is to modulate the laser light externally (within or outside the source module), but this adds cost, circuit complexity, and optical loss, and can lead to state of polarization (SOP) management issues.

External modulators are generally based on switching technologies such as Mach-Zehnder interferometers or electro-absorption devices. Modulators based on integrated optics often use lithium niobate (LiNbO3) or indium phosphide (InP) to achieve fast switching due to their high refractive index. Although the high cost of integrated optics has limited their initial market penetration, improvements in manufacturing processes and economies of scale now appear to have changed this situation. Modulation up to 10 Gb/s (OC-192 or STM-64 rates) has been the highest commercially-available rate to date, but 40 Gb/s transmission is now also available and research is being performed on 80 Gb/s and >100 Gb/s.

With the use of an EDFA or a semiconductor optical amplifier (SOA) after the modulator, WDM laser transmitters have demonstrated transmit powers of more than +16 dBm, just under the +17 dBm limit to meet the IEC 60825 Class IIIb laser safety designation. Laser safety requirements, appropriate for even higher power transmitters, have been proposed, in particular a new Class 1M for +20 dBm and higher.

As mentioned DFB lasers have recently become available. These lasers incorporate external modulators on the chip, offering an integrated package for low-chirp, high bit rate modulation, with all the other parameters—excluding, perhaps, cost—well under control.

DFB lasers exhibit several shortcomings. For example, their very narrow spectral line width (or high coherence length) makes them susceptible to coherent interference from backreflection in the link they feed. Any accidental etalon-like section of the link—any pair of parallel, partially reflecting surfaces—whose spacing falls within this coherence length can produce strong reflections that can affect the stability of the output signal. Since the exact length of such parasitic etalons will vary with temperature, and because the critical length range to be avoided will vary with specific laser operating conditions within its stability range, the potential for this undesirable feedback in a particular configuration may be difficult to determine.

Transmitter Wavelengths

The provision of interchangeable components for WDM use and the need for interconnections among networks both lead to a requirement for the definition of a set of standard frequencies to be used in such systems. Study Group 15 on Transport Networks, Systems and Equipment in the ITU Telecommunication Standardization Sector is the international standards body responsible for defining this set (the set is defined in the G.692 Recommendation on Optical Interfaces for Multichannel Systems with Optical Amplifiers).

The ITU grid is a set of standardized frequencies based on a reference frequency at 193100 GHz. Available standard frequencies are defined both up and down from this reference, evenly spaced by 100 GHz and, more recently, at 50 GHz. A frequency list from the ITU grid is shown in Table 2.02, each frequency with its corresponding wavelength (based on c, the velocity of light in vacuum, of 2.997925 x 10^8 m/s).

A telecommunications service provider can select optical frequencies from the ITU grid at will for individual transmitters in a network. Adjoining providers must, of course, address compatibility issues when they select frequencies for portions of their networks that are expected to intercommunicate.

υ (GHz)	λ (nm)	υ (GHz)	λ (nm)	υ (GHz)	λ (nm)	υ (GHz)	λ (nm)	υ (GHz)	λ (nm)
197 100	1521.020	195 000	1537.400	192 900	1554.137	190 800	1571.242	188 700	1588.726
197 000	1521.792	194 900	1538.189	192 800	1554.943	190 700	1572.066	188 600	1589.568
196 900	1522.565	194 800	1538.978	192 700	1555.750	190 600	1572.891	188 500	1590.411
196 800	1523.338	194 700	1539.769	192 600	1556.558	190 500	1573.717	188 400	1591.255
196 700	1524.113	194 600	1540.560	192 500	1557.366	190 400	1574.543	188 300	1592.100
196 600	1524.888	194 500	1541.352	192 400	1558.176	190 300	1575.370	188 200	1592.945
196 500	1525.664	194 400	1542.145	192 300	1558.986	190 200	1576.199	188 100	1593.792
196 400	1526.441	194 300	1542.939	192 200	1559.797	190 100	1577.028	188 000	1594.639
196 300	1527.219	194 200	1543.733	192 100	1560.609	190 000	1577.858	187 900	1595.487
196 200	1527.997	194 100	1544.529	192 000	1561.422	189 900	1578.689	187 800	1596.337
196 100	1528.776	194 000	1545.325	191 900	1562.236	189 800	1579.521	187 700	1597.187
196 000	1529.556	193 900	1546.122	191 800	1563.050	189 700	1580.353	187 600	1598.038
195 900	1530.337	193 800	1546.920	191 700	1563.865	189 600	1581.187	187 500	1598.889
195 800	1531.118	193 700	1547.718	191 600	1564.682	189 500	1582.021	187 400	1599.742
195 700	1531.901	193 600	1548.518	191 500	1565.499	189 400	1582.856	187 300	1600.596
195 600	1532.684	193 500	1549.318	191 400	1566.317	189 300	1583.693	187 200	1601.451
195 500	1533.468	193 400	1550.119	191 300	1567.135	189 200	1584.530	187 100	1602.306
195 400	1534.253	193 300	1550.921	191 200	1567.955	189 100	1585.368	187 000	1603.163
195 300	1535.038	193 200	1551.724	191 100	1568.776	189 000	1586.206	186 900	1604.020
195 200	1535.825	193 100	1552.527	191 000	1569.597	188 900	1585.045	186 800	1604.878
195 100	1536.612	193 000	1553.332	191 900	1570.419	188 800	1587.885	186 700	1605.737

Table 2.02 ITU wavelength grid

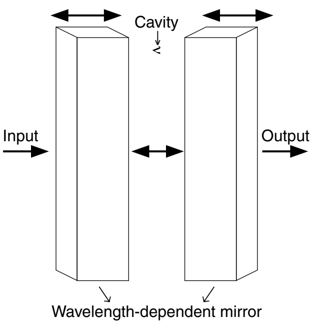


Figure 2.06 Simplified locker operating principle

WAVELENGTH LOCKER

The successful operation of WDM and DWDM networks depends on the stability of the signal source. Receivers, filters, attenuators, and wavelength-dependent couplers can perform their functions only if the signal they treat is within a very tight tolerance of the design optical frequency. Wavelength lockers provide this stability.

The exact wavelength of the laser is set by controlling its temperature or electrical current; a wavelength locker provides the control signal needed. The usual wavelength locker consists of a pair of dielectric-layer optical filters, cascaded so both work with exactly the same source power. One filter is tuned to a frequency just above the desired one, while the other is adjusted to a frequency that is the same interval below. The optical signals within the bandpass of these two filters are detected and compared to provide an electrical control signal that indicates how far the source wavelength has drifted from its design value.

Dielectric-layer filters can be made to pass very narrow, accurately positioned bandwidths and they are inherently extremely stable. As a result, wavelength lockers using these filters can provide the long-term wavelength stability required of WDM sources.

2.5.2 Receivers

The receiver converts optical signals to an electronic form by detecting whatever modulation has been applied to the light signal and demodulating it. Of course, the receiver must be completely compatible with the transmitter—both its primary wavelength and its modulation characteristics—and it must be designed to cope with whatever signal degradations other network components may have introduced.

Traditional optical techniques are used to couple light energy from a fiber to a detector, generally a photodiode. The resulting signal must be amplified electronically—adding as little noise as possible—within an electrical bandpass appropriate to the expected signal. Electronic filtering may also be needed to flatten the effective frequency response of the unit. All these operations are usually carried out within a single hybrid module, including a receiver module whose input is light from a fiber and whose output is a clean electrical signal that must be demodulated appropriately. The complexity of the demodulation process depends on the modulation used. For example, timing information must be extracted if the channel uses TDM, and various error detection and recovery schemes may be required at this level.

Two types of photodiodes are commonly used: positive-intrinsic-negative (PIN) diodes and avalanche photodiodes (APD). The PIN device operates with standard low-voltage, logic power supplies (5 V), but it is less sensitive and covers a narrower bandwidth than the avalanche model. High-speed PINs were used in 10 Gb/s and 40 Gb/s applications before the arrival of APDs. The latter is found mainly in long-haul applications, where its higher cost and greater circuit complexity is justified. In many cases, the use of an APD alone allows the user to forego the need for an optical preamplifier with a PIN photodetector. It is, therefore, economically very justifiable.

Critical selection parameters for receivers include spectral response (A/W as a function of wavelength, especially in relation to the detector used), sensitivity (a measure of the level at which intrinsic detector noise masks the incoming signal), both spectral and electronic bandwidth, dynamic range, and noise. Appropriate criteria for each depend on the individual application. For example, noise characteristics are more important than high output power in an optical preamplifier used just before a channel receiver. Furthermore, the need for optical filtering—such as within a demultiplexer—to reduce amplified spontaneous emission should receive attention.

2.5.3 Attenuators

Attenuators are often used after laser transmitters to tailor their output power to the capabilities of subsequent multiplexers and EDFAs (see Figure 2.07).

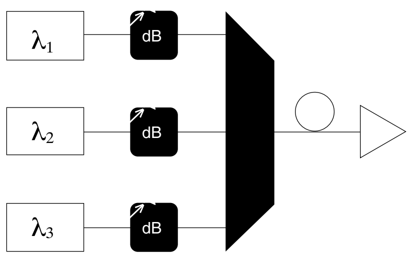


Figure 2.07 Attenuators are located between transmitters and the multiplexer.

High-power lasers can be used in network transmitters to reduce the need for in-line amplification. Attenuation may be needed in specific portions of the network to keep optical components from being exposed to radiation strong enough that their behavior becomes non-linear. Power tailoring is also often necessary to trim the gain of EDFAs to provide an overall network response that is spectrally flat. This is especially critical when a channel is added or dropped in EDFAs.

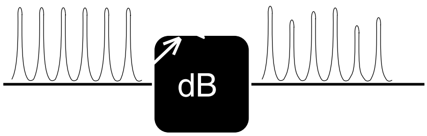


Figure 2.08-a Attenuators can be wavelength-dependent.

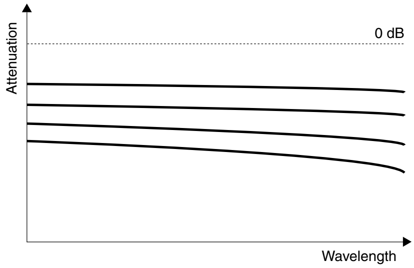


Figure 2.08-b Attenuation is also dependent on optical input power.

2.5.4 Switches

Early switching in fiber-optic networks involved converting the optical signal to an electronic one, performing the necessary switching operation, and reconverting the signal to optical—a cumbersome and expensive process that involves switching speed limitations and reduces WDM operability.

Switches are used in WDM networks to divert signals to alternate routes in response to network difficulties, or to reroute signals to other networks. As both network complexity and reliability expectations have grown, the need for just a few switches to offer simple rerouting possibilities has rapidly increased to a requirement for complex N-by-N cross-connect units that permit extensive, all-optical reconfiguration. The ability to switch signals easily is critical for the survival of the modern all-optical network. As a result, optical cross-connect (OXC) routers are now essential to this survival.

Standard optical switches used until now have tented to be 1xN switches, where an electrically-controlled mechanism moves a flexible input fiber from-one output fiber to another. In network applications, these switches have normally omly been used for restoration purpose and not for dynamic bandwidth allotment or redistribution.

2.5.5 Optical Cross Connects (OXC) Units

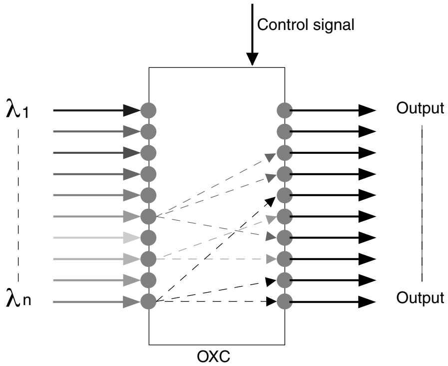
Individual switches or small switch arrays suffice to route several channels, but more complex network architectures require rapid, controllable, and flexible channel routing. This would be the case, for example, in a ring network structure or a metropolitan network where there are many nodes and access points. Recent research efforts have resulted in several approaches to all-optical switching, based on optical cross connect technologies. This NxN switching fabric can be constructed from, electromechanical switches that perform switching by positioning tiny mirrors in the optical path. This optical-mechanical approach has also been extented by micro-manufacturing or MEMS technology, which involves depositing many switching lenses and mirrors, and their actuators, on a silicon chip. Many hundreds of ports can be accommodated, insertion losses are low, interchannel isolation is very high (80 dB), and, by its nature, the device can be used over a wide wavelength range.

Pure optical solutions under study include waveguides, liquid crystals, or even bubble technology, whose characteristics can be quickly modified by heat, an electrical signal, or optical gates (individual optical amplifiers that can be turned on and off rapidly).

The ever-increasing need for fast, reliable, and inexpensive optical switching equipment will drive research and development efforts for the foreseeable future.

Addressable Add/Drop Units

The addressable add/drop device provides selective routing of DWDM channels, using optical switches combined with other components that can be based on fiber-switching or wavelength-switching technologies. The purpose of using an addressable add/drop unit is to keep all routing within the optical transmission layer and, thus, to avoid having to opto-electronically convert transmission signals and then regenerate them.



Arrayed waveguide grating (AWG) represents a good example of this technology. A generic exampleof an OXC is shown in Figure 2.09.

Figure 2.09 Signal λ_i coming to the input port of the OXC is rerouted to other ports.

In such a device, the wavelengths at each output depend on the wavelengths at the input. A control port can be added to allow selective wavelength routing.

2.5.6 Wavelength-Dependent Couplers

In WDM applications, it is often necessary to extract wavelengths individually representing information channels. Purely passive optical devices are now available to handle this task.

Frequency-dependent parameters of optical devices that must be overcome to produce components, such as broadband couplers, can also be used to produce components whose outputs are strongly wavelength-dependent. For instance, take a wavelength-dependent coupler. Units are available to separate the 1310 nm and 1550 nm wavelengths commonly used in early WDM systems, or to combine the 980 nm or 1480 nm pump with the 1550 nm input signal into the erbium-doped fiber in an EDFA.

2.5.7 Dispersion Compensation Devices

Various components of fiber-optic networks—and particularly the fiber itself—exhibit chromatic dispersion. Their index of refraction varies with wavelength, as does the propagation speed through them. The most easily noticeable result is the broadening of transmitted optical pulses, which makes their error-free recovery more difficult as neighboring bits overlap. A dispersion compensation device (DCD) is used to apply an equal but opposite dispersion to correct this pulse broadening. The two most commonly used DCD types are dispersion compensating fibers (DCFS) and dispersion compensating gratings (DCGS).

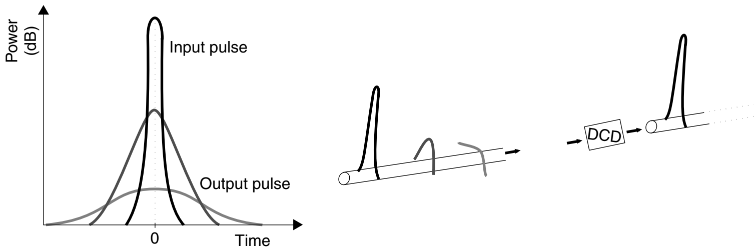


Figure 2.10 The broadening effect due to dispersion and its compensation

2.5.8 Multiplexers and Demultiplexers

The output of each laser transmitter in a WDM system is set to one of the allowed channel frequencies. These beams must then be multiplexed—superimposed or combined—and inserted into the first fiber cable span. The device used is called a multiplexer (also called a mux, optical mux, or OM). A similar device is used to extract the multiplexed channels at the receiver end of each link. It is called a demultiplexer (or demux, optical demux, or OD). Unlike the situation in TDM systems, where both these operations occur in the time domain and much attention must be paid to maintaining accurate clocks and to retrieving timing clues from incoming signals, multiplexing and demultiplexing in WDM systems are strictly a matter of dealing individually with a signal's spectral components. The characteristics of these spectral components are always known beforehand.

Multiplexing and demultiplexing functions both employ narrowband filters, cascaded and combined in other ways to achieve the desired result. Particular techniques that have been used to perform such filtering include thin-film filters, fiber Bragg or bulk optic gratings, tapered fibers, liquid crystal filters, and integrated optics (phased array waveguides, AWG, or phasar).

Many mux/demux devices are available today to handle the 100 GHz (0.78 nm) channel spacing that is common in WDM networks, and to accommodate the more demanding 50 GHz spacing—or even higher channel densities—that are appearing. Most recent models have been based on thin-film filters, with arrayed waveguides and fiber Bragg grating models close behind, but this technology distribution will shift as more stringent requirements of narrowly spaced DWDM systems come to bear.

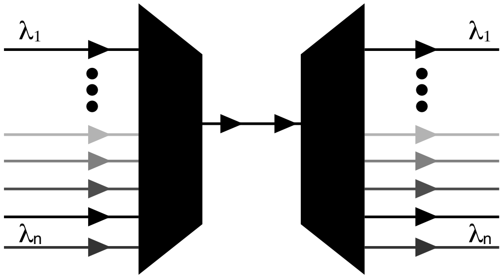


Figure 2.11 Typical representation of a multiplexer and demultiplexer

Multiplexing Technologies

Although a thorough discussion of the mechanisms underlying mux/demux operations is beyond our scope, we will outline the wavelength-dividing mechanisms used in the more common types.

Thin-Film Filters

Thin-film filters consist of a number of layers of transparent dielectric materials of differing refractive indices deposited sequentially on an optical substrate. Since the index of refraction changes at each interface in the stack of layers, a portion of the incident light is reflected at each interface. This reflected light interferes constructively or destructively with incoming light, depending on wavelength. Through judicious selection of the indices of refraction and the thickness of each layer, one can use this internal interference to produce a filter that will pass any desired range of wavelengths and reflect the others (Figure 2.12).

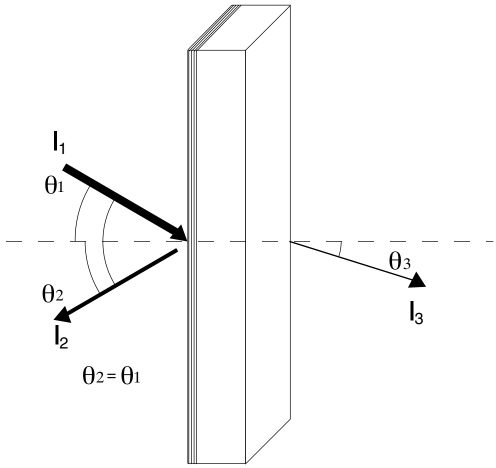


Figure 2.12 Incident wavelength I_1 *is reflected* I_2 *at the same angle, and* I_3 *is transmitted at a lower angle.*

The techniques for choosing design parameters and applying the coating have been known in the optical industry for decades. The selection of coating materials is limited. Many substances, whose optical properties are desirable, have physical properties that are less than ideal. Generally, the more stringent the requirements, the greater the number of optical layers needed. Despite these difficulties, filters with many highly specialized spectral response functions can be produced inexpensively without much variation during production.

Single-stage filters used in mux/demux applications must generally be mounted slightly askew to the optical axis, so that the light they reject by reflection is not reinserted backwards into the network. This angular displacement changes the effective thickness of the layers used and, thus, alters, the bandpass of the filter, so the tilt must be factored into the design of the unit. In multi-stage units for multichannel use, the beam reflected from each filter is the input for the next stage; thus, alignment is extremely critical.

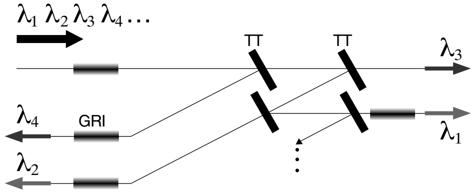


Figure 2.13 Example of a cascaded thin-film filter for multiwavelength demultiplexing

Thin-film filters provide bandpasses narrow enough for use in mux/demux applications in WDM systems of 16 or 32 channels. More densely spaced networks are now turning to other technologies.

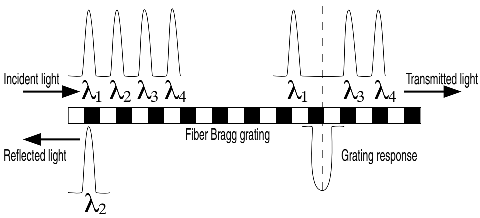


Figure 2.14 The fiber Bragg grating drop on a specific channel from the transmitted signal

Fiber Bragg Gratings

A fiber Bragg grating is essentially an optical interferometer built right inside a fiber. If a glass fiber is doped with a suitable substance—germanium is commonly used—its refractive index can later be modified by exposure to ultraviolet light. If this exposure occurs in an appropriate periodic pattern, the fiber becomes a grating. In other words, it will reflect light wavelengths almost completely within a predetermined band and transmit other wavelengths. If the pattern is not periodic and varies monotonically (i.e., is "chirped"), the fiber grating can be used to compensate for chromatic dispersion in a fiber link, or to correct the frequency-broadening chirp of laser sources used under certain conditions.

The central wavelength of a regularly spaced Bragg grating filter is determined by its periodicity; its bandwidth is inversely proportional to its length. Both of these parameters are temperature-sensitive, so such filters require constant-temperature enclosures or some other mechanism for temperature control.

A Bragg grating can be used as an optical filter in a mux/demux, as a compensator for chromatic dispersion, or in combination with circulators to manufacture add/drop multiplexers or demultiplexers.

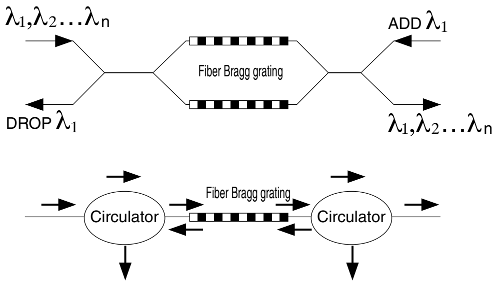


Figure 2.15 Two examples of fiber Bragg gratings used in an OADM device

Bragg gratings are seldom used alone as passive DWDM components. One common application involves an add/drop multiplexer with one or two optical circulators, as shown in Figure 2.14. On the drop side, the circulator recovers the reflected wavelength and sends it to the drop port. On the add side, the circulator recombines a new transmission signal at the same wavelength as that at which it was dropped. Therefore, a specific wavelength channel is either added to or dropped from the original transmitted signal. This technique is often used at the interface between a long-haul and a metropolitan network, where the former typically uses as many wavelengths as possible and the latter uses far fewer wavelengths.

Fiber Bragg grating devices are also beginning to appear in mux and demux devices in Mach-Zehnder configurations and in hybrid combinations with other types of filters.

Aside from mux/demux applications, this narrowband filtering technology is also used to perform EDFA gain flattening, wavelength stabilization, and wavelength locking.

Diffraction Gratings

A bulk-optic diffraction grating reflects light at an angle proportional to wavelength and, once again, the underlying physical principle is the same: constructive and destructive interference.

For each wavelength of incident light, there is an angle for which light waves reflecting from individual grating lines will differ in phase by exactly one wavelength. At this angle, the contribution from each line will add constructively, so this will be the angle of maximum transmission for that specific incident wavelength.

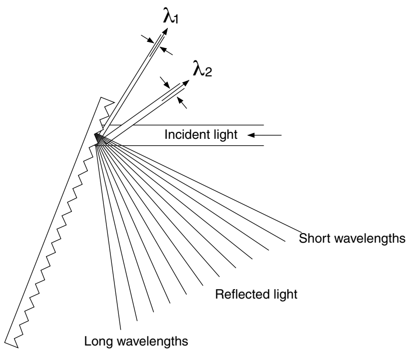


Figure 2.16 The incident light is divided into all primary wavelengths $\lambda_1, \lambda_2, \ldots \lambda_n$

Designing a mux or a demux using a diffraction grating, is a matter of positioning the input and output optics to select the desired wavelengths. Although they are difficult to manufacture and expensive, devices based on diffraction gratings have an insertion loss that is essentially independent of the number of channels, rendering this technology one of the more promising for high channel count systems. However, polarization control requires critical attention.

Integrated Optical Devices

Integrated optical wavelength multiplexing/demultiplexing devices are the optical equivalent of integrated electronic circuits. Typically, they consist of optical waveguides—core material surrounded by cladding material—layered onto silicon or lithium niobate-substrates using many of the techniques adopted by the large-scale integration manufacturers. The end result is a small package containing many optical components—usually interacting—that can be manufactured in significant quantities using totally automatic techniques. Integrated optics is a relatively new technology and significant research and development is still required before its full potential can be exploited. Some of the devices that are currently being produced include couplers, switches, modulators, erbium—and other rare-earth-doped waveguide amplifiers, Bragg gratings, and other DWDM components.

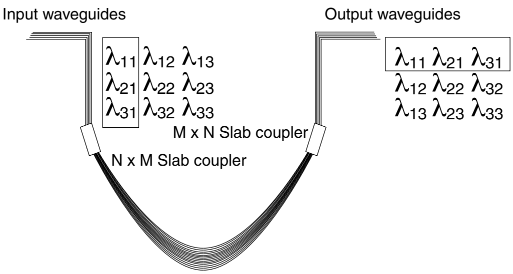


Figure 2.17 AWG : illustration and principle of operation

Integrated optics lends itself particularly well to arrayed waveguide gratings (AWG), whose principle of operation is outlined in Figure 2.16.

Input light, comprised of many different wavelengths is coupled into the input slab coupler where it is split among N optical paths making up the waveguide array. Since each of the N legs of the array is a different length, each introduces a different wavelength-dependent phase shift. The resulting interference in the converging beam in the output coupler directs different wavelengths into separate output waveguides.

An AWG can be used either to reassign wavelengths on one set of fibers to a different distribution on another set, or to demultiplex individual frequencies on a single fiber (Figure 2.16). This is becoming a key technology for manufacturers of wavelength multiplexers/demultiplexers. Since its architecture is easily scalable, it holds the potential for applications in systems with hundreds of channels.

An AWG is also called a Dragone router, a phase array, or a phasar.

Fused Biconic Tapered (FBT) Devices

In its simplest form, the biconic tapered coupler consists of a pair of singlemode optical fibers that have been fused together lengthwise. Signal light transmitted in a fiber-core mode that arrives at the fused region from one of the fibers on the left-hand side is redistributed into a variety of cladding modes as it crosses the joint. As the fibers once again separate, cladding modes reconvert to core modes in each of the output (right-hand side) fibers. The result is an almost loss-less coupler or splitter. The redistribution of energy does not need to be homogeneous; interference along the length of the fused region—a dimension that is fixed during manufacturing—determines how the input energy at a given wavelength will be redistributed at the output.

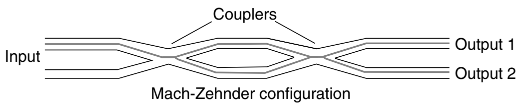


Figure 2.18 The fused fiber redistributes the input signal to the output of the device.

If two such devices are connected in series (Figure 2.18), the optical path difference between the two central connecting sections causes the combination to act like a Mach-Zehnder interferometer. The input energy is split between the two outputs, depending on wavelength, with a periodicity that is set when the device is manufactured. Thus, two frequencies that are present together on an input fiber can leave the device on separate fibers (the second input fiber is not used). In multi-frequency applications, evenly spaced frequencies on the input fiber will appear as two sets of frequencies on the output, each spaced at twice the original channel spacing. Further stages may be used to reduce the channel count to one per output fiber.

Arrays of these devices, sometimes in conjunction with Bragg gratings written in the tapered section, can be used to extract individual frequencies from multichannel WDM or DWDM systems, or to add new channels in the middle of networks. Since they are completely passive and exhibit low losses, the use of large arrays is economically feasible.

2.5.9 Optical Add/Drop Multiplexers (OADMs)

Add/drop multiplexers are assembled using various spectral separation techniques to combine multiple optical signals onto a single transmission medium or to extract these signals after transmission. In many parts of a network, one may not want to combine or disassemble the entire channel structure, but merely add a single channel to it or extract a single channel from it with an add/drop multiplexer. An optical add/drop multiplexer performs this operation without the need to convert the signals in all the channels to electrical form and back again.

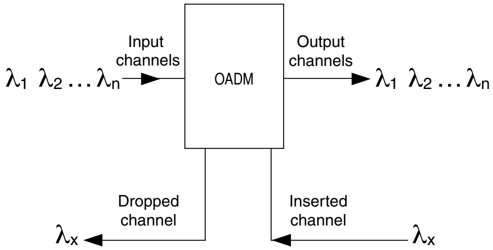


Figure 2.19 Typical representation of on OADM device.

The technologies mentioned are all applicable to the construction of OADMs. Today, devices are on the market to handle many commonly needed tasks including adding, dropping, or replacing OC-48 channels at a point in the network without disturbing the other channels carried in the same fiber. These devices provide major benefits for both network reliability and security. Future developments will certainly concentrate on making OADMs reconfigurable in the field, perhaps eventually remotely.

2.5.10 Optical Amplifiers

The erbium-doped fiber amplifier (EDFA) has sparked a revolution in the telecommunications industry during the last few years because it can directly amplify optical signals. Its ability to provide low-noise amplification over a range of wavelengths, fortuitously corresponding to the low-loss window of silica fiber, has made DWDM links and networks economically attractive.

An EDFA consists of a length of fiber that has been specially doped with the element erbium, so that it can convert energy from separately provided pump radiation to the wavelengths applied as signals, thus effectively amplifying them. In the simplest EDFA designs, the necessary amplification occurs over a relatively narrow wavelength band—from about 1525 nm to 1565 nm—but this 40 nm range offers enough space for many distinct DWDM channels.

A traditional electronic repeater restores the level of signals over a long link by extracting signal information from the fiber, converting it to electrical pulses, amplifying them, and reinserting them into the following fiber section. In contrast, an EDFA is transparent; that is, it is oblivious to signal protocol, format, bit rate, and (within its limitations) to the wavelength of the optical signal.

Since the EDFA is insensitive to—or unaware of—network protocols, it can be directly connected to varied equipment such as asynchronous transfer mode (ATM) switches and Internet Protocol (IP) components without danger of interfering with their functions. This flexibility is one of the major advantages of DWDM usage. The use of EDFAs in a network, however, involves several new concerns, especially the appropriate treatment of their non-uniform spectral gain and of the amplified spontaneous emission (ASE) noise that they add.

EDFA-equipped networks offer great advantages, such as the ability to make low-cost incremental upgrades, thus increasing capacity one channel at a time to meet demand. All-optical networks are feasible, since electronic signal-processing components are needed only at the points where the information is first inserted into the network and finally retrieved. Start-up costs for DWDM systems can be quite low, since most existing OC-48 network facilities can readily be incorporated into DWDM systems by treating each OC-48 path as an individual wavelength channel.

Another example of the contribution of optical amplification is in CATV applications where the user wishes to deliver ("broadcast") a common signal to as many subscribers as possible. Since direct fiber to the home (FTTH) is still rarely employed today, the CATV signal is generally delivered to a local distribution point close to a group of houses, from where the final connections are made via coaxial cable. Most CATV signals are analog and they require higher signal-to-noise ratios at the receiver end than digital signals; optical amplification can accomplish that task and is essential if onethe user is trying to maximize the number of subscribers sharing the signal. FTTH will become economically feasible only if subscribers can be equipped with low-cost, limited-sensitivity receivers, so the highest power possible must be delivered to network end points. With hundreds or thousands of subscribers competing for this signal power, the need for transparent, easily distributed optical amplification is obvious.

New research into high-power EDFA pumping schemes has led to an extended range—L-band or extended-band—unit operating from 1570 nm to 1605 nm. It is often referred to as a long-wavelength EDFA (LWEDFA).

Pump Lasers

A critical component of an EDFA is the pump laser, the source of energy that the amplifier adds to the signal. Pump energy is distributed among all optical channels in the EDFA. Therefore, as channel counts increase, so does the need for higher pumping power. EDFAs that can handle many channels frequently are designed to use more than one pump laser.

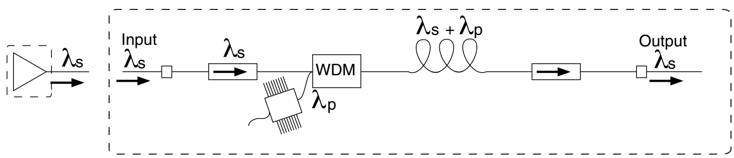


Figure 2.20 Simplified view of an EDFA device with isolators, pump laser (λ_p), and WDM coupler

Both 980 nm and 1480 nm lasers are suitable for EDFA pumping because both wavelengths correspond to the energy levels of excited ions and, therefore, are well absorbed by the erbium-doped fiber. Naturally, trade-offs must be considered. High channel count systems and pre-amplifiers can benefit from pumping at 980 nm because these lasers provide the EDFA with lower noise figures than the 1480 nm models. However, higher power at a lower cost is available at 1480 nm. The choice is complicated by the fact that the pump laser must be selected at the beginning of a network's life cycle, before the ultimate channel count can be known, so an appropriate power-noise trade-off can be difficult to weigh. Some EDFAs are pumped at both wavelengths to take advantage of both pump wavelengths.

If a laser transmitter transmits a signal of +16 dBm along a fiber having a typical 0.2 dB/km attenuation in the 1550 nm region, after 80 km the signal will have been attenuated to 0 dBm (or 1 mW), ignoring any other causes of loss such as splices. On the other hand, if the same laser emits 0 dBm, the signal will be down to –16 dBm after 80 km along the same fiber. In the early stage of fiber-optic telecommunications, lasers were able to emit relatively low power, and the signal had to be electronically regenerated after distances much shorter than the 80 km range. These repeaters received the optical signal, converted it to an electronic one, amplified it, and reconverted it into an optical form. Although this technique was not spectrally limited—it could easily regenerate signals at both 1310 nm and 1550 nm—it was quite complex and did not allow for future upgrades of the system bit rate without replacing the repeaters.

In the late 1980s, Payne and Laming of the University of Southampton in the UK proposed the use of erbium-doped fiber to amplify signals optically. The age of all-optical repeaters had arrived. However, the technology came with one small restriction: it worked only in the 1550 nm spectral region. Hence, erbium only provides gain over a narrow wavelength band centered around this region.

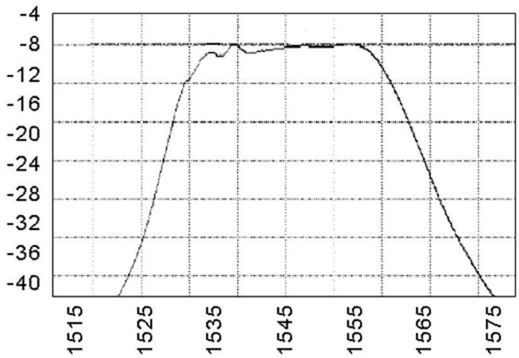
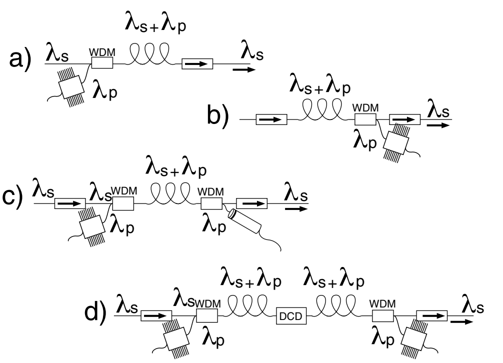


Figure 2.21 EDFA optical spectrum



Figures 2.22-a-b-c Typical EDFA designs with various pumping schemes, and Figure 2.22-d using a dispersion compensation device

EDFAs must be pumped to amplify the incoming signal. They can be pumped efficiently with a 1480 nm or a 980 nm laser signal. Several pumping schemes, shown in Figure 2.22, are possible at either wavelength.

The forward pumping direction provides the lowest noise. In fact, the noise is sensitive to the gain and the gain is the highest when the input power is the lowest, as is the case close to the input of the EDFA. Backward pumping provides the highest saturated output power, as shown in Figure 2.23.

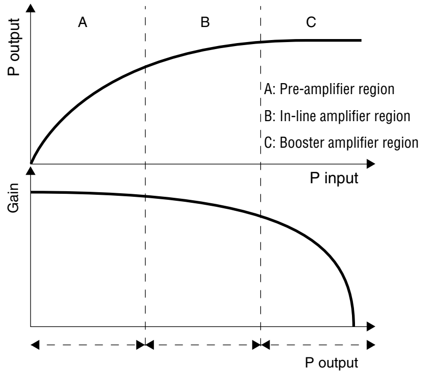


Figure 2.23 Gain performance regions of an EDFA

Due to these limitations, a specific procedure is recommended where two pump lasers of different wavelengths are used. Pumping at 1480 nm is usually used in the reverse direction and 980 nm pumping in the forward direction to make the best use of the strengths of each. The 1480 nm pump has a higher quantum efficiency but a somewhat higher noise figure, whereas the 980 nm pump can provide a near quantum limited noise figure. Typically, a single-stage pumped EDFA can provide a maximum of about +16 dBm output power in the saturation region or a noise figure of 5 to 6 dB in the small-signal region. Both pumps can be used simultaneously to provide higher output power; a double-pump EDFA can typically supply up to +26 dBm in the highest available pump-power region. Lower, near quantum limited noise figures needed for many pre-amplification applications can be attained from a multistage design. In such a design, an optical isolator is placed immediately after the critical noise figure of the first amplifying stage to prevent degradation of the first-stage performance due to backward-propagating amplified spontaneous emission (ASE) from the second stage.

Depending on the gain region (see Figure 2.23), an EDFA can be used as

- a booster (also called power amplifier or post-amplifier), when used in the saturation region immediately after the transmitter laser to boost its power, to allow the first repeater to be positioned as far as possible down the link
- an in-line repeater, with intermediate gain and noise performance, to amplify the signal as much as possible without introducing too much noise
- a pre-amplifier in front of the receiver, with the lowest noise possible, to boost the low signal at the end of the link. This pre-amplifier is almost always accompanied by in-line, narrowbandpass filter.

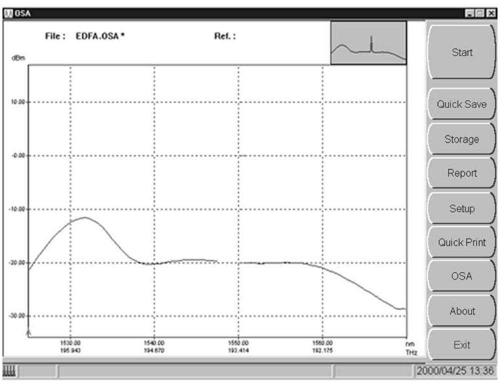


Figure 2.24 Typical gain spectral distribution of an EDFA

A typical EDFA has a small-signal gain that is not uniform across the spectrum, as shown in Figure 2.24.

There is a broad peak in gain at 1535 nm and a relatively flat zone from 1540 nm to 1560 nm. This leaves a relatively narrow spectral window of about 20 nm for DWDM transmission.

Various techniques have been proposed to flatten the gain and expand the DWDM amplification window to 40 nm or more. Gain flattening is also necessary to eliminate the distorted amplification of signals through cascaded, in-line EDFAs. Devices, such as the LWEDFA described earlier, stretch the gain window to about 1610 nm, providing the capability for bidirectional DWDM transmission in different non-interfering windows, and also potentially relaxing the requirements for more densely packed DWDM transmissions in a narrower window.

Today's EDFAs use internal components to promote reliable operation. Such components include isolators suppress the build-up of back-propagating ASE, to prevent sensitivity to any reflections from a downstream in-line EDFA, or to prevent any residual pump energy emanating from this downstream EDFA. Other components may include dispersion compensation elements, especially between the two stages of a double-stage EDFA, to equalize the propagation delay between the various wavelengths in a DWDM multichannel signal.

Two fiber-host materials, silica and fluoride, predominate in present-day EDFAs; other materials are being examined. The same general internal structure is used with both materials, but they differ in the fiber used to host the erbium dopant. Both technologies provide adequate amplification across the entire 1525 nm to 1560 nm erbium bandpass, but the gain curve of the silica-based EDFA is not quite as flat. See Figure 2.25.

Silica-based EDFAs have been available for several years. They gained early market acceptance due to their low-noise characteristics and wide bandwidth. Fluoride-based EDFAs produce even wider and much flatter gain across the entire erbium bandpass, but they have suffered from perceived reliability problems.

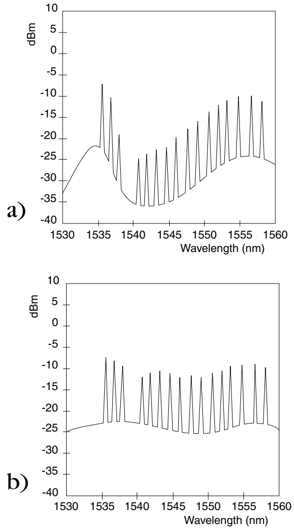


Figure 2.25-a Basic EDFA is not flat enough for WDM applications.
Figure 2.25-b Internal filtering yields improved gain flattening.

Other Optical Amplification Techniques

Other optical amplifiers have also been proposed, both to relax the restrictions of transmitting only in the narrow 1550 band and to eliminate the relative complexity and consequent cost of EDFA designs.

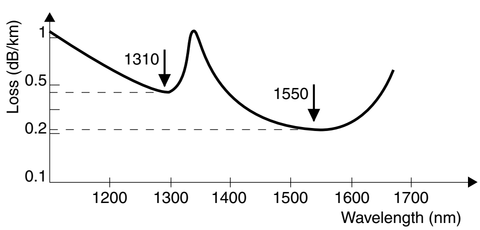


Figure 2.26 Spectral attenuation of a typical singlemode fiber

In one approach, praseodymium replaces erbium as a dopant to provide amplification in the 1310 nm region; the resulting amplifier is usually called a PDFFA (praseodymium-doped fluoride-based fiber amplifier). These units provide low-distortion and low-noise figures, although they are not as energy-efficient as conventional EDFAs. Saturation output power is high and, like EDFAs, gain is independent of polarization. Although optical fiber shows a little more attenuation at 1310 nm than in the 1550 nm region (see Figure 2.26), dispersion is lower at 1310 nm and high laser power is more easily achieved.

Unfortunately, reasonable pumping efficiencies can be obtained only by using praseodymium-doped fiber that is much smaller than standard optical fiber. The losses resulting from the mismatches at the two needed splices, and the difficulty to achieve reliable mechanical splices are costly enough to rule out widespread commercial use for now.

Other host-dopant combinations under study include the fluoride-based thulium-doped fiber amplifier (TDFFA) with two spectral operating regions: 1460 nm and 1650 nm. Its advantages include high saturation output power, polarization-independent gain, and a low-noise figure. Ytterbium is also used in EDFAs with very high output power.

A rather different approach achieves gain through the stimulated Raman scattering effect. In principle, this method, which uses the silica fiber itself as the gain medium, offers great flexibility in choosing the wavelength of the amplification region, and the mechanism is inherently low-noise. This Raman amplifier is especially useful for upgrading existing links to higher channel counts without having to replace already-installed EDFAs. It is also very useful for medium-haul undersea links that do not use repeaters (e.g., 300 km long), where the installation of an in-line EDFA can be very expensive. However, Raman amplifiers exhibit significant cross gain modulation, limiting their use to either a single-signal channel or to high channel count DWDM signals, where the effects of such modulation can be averaged out. Additionally, Raman amplifiers have some linearity and polarization-dependence problems, which, when combined with the extreme weakness of the effect in silica fiber, has limited the use of Raman amplifier technology to specialized applications, at least for now.

Semiconductor (solid-state) optical amplifiers (SOAs), in which photon emission is stimulated by electron-hole recombination in a semiconductor through direct injection of current, rather than by pumping an erbium-doped fiber, are also being developed. They have attracted considerable interest due to their promise of high performance and flexibility in operating wavelength, albeit with a high noise figure (typically more than 5 to 6 dB above that of EDFAs, largely due to inevitable losses as a result of pigtailing). Like Raman amplifiers, SOAs exhibit a significant cross gain modulation, precluding their use in low channel count DWDM applications, but this can be used to advantage in switching and wavelength-conversion applications. Like the praseodymium-doped, fluoride-based fiber amplifier, SOAs also present fiber-coupling problems because waveguide dimensions best suited to semiconductor optical amplification differ from those of optical fibers.

Integrated optical modulators for high bit rates are also becoming available, as are modulators integrated into packages with laser chips. Modules that integrate laser chips, modulators, SOAs, and a multiplexer have also been demonstrated.

2.5.11 Optical Fiber

Fiber—especially cabled fiber—is one of the most critical components of an optical network. After all, it is the physical transport medium. The first fibers to see widespread use were for long-haul communications: step-index, singlemode fibers exhibiting zero dispersion at 1310 nm, which were designated G.652 fibers by the ITU. More than 80 million kilometers of cable made up of these fibers was installed in the 1980s. Despite the tendency towards higher data rates and the ability of DWDM techniques to multiply the capacity of installed optical fiber, cable installation will continue unabated throughout the world for the foreseeable future.

Although this standard fiber (G.652) exhibits zero chromatic dispersion at 1310 nm, it shows high dispersion at 1550 nm (18 ps/nm.km). Despite this apparent incompatibility with the EDFA window at 1550 nm, recent tests indicate that this fiber can carry moderate-rate DWDM transmissions without loss of signal quality over significant distances. This is largely due to the fact that, although dispersion is high at 1550 nm, it can be compensated with dispersion compensating fiber or other compensation devices.

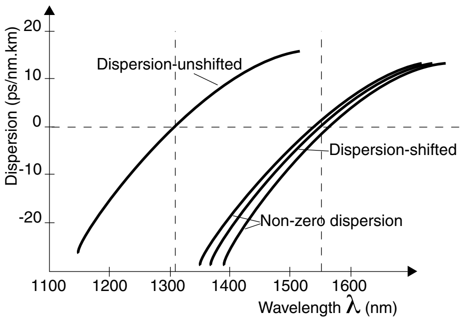


Figure 2.27 Typical dispersion figure for different types of fiber

Fiber manufacturers have developed dispersion-shifted fiber (G.653) that has zero dispersion at approximately 1550 nm. Fiber attenuation is lower at 1550 nm than at 1310 nm, so operation in the former region is preferred, especially for long-haul transmission. However, dispersion-shifted fiber is not necessarily the preferred fiber for DWDM transmission; its spectral dispersion profile slopes steeply around the dispersion zero wavelength, and dispersion compensation must be individually applied to channels.

Non-linear effects were witnessed as soon as EDFAs were introduced for DWDM transmission over dispersion-shifted fiber. Although dispersion-shifted fiber exhibits zero chromatic dispersion at 1550 nm, the effects of four-wave mixing limit the wavelengths at or very near the dispersion zero. To reduce the influence of non-linear effects, such as four-wave mixing in DWDM systems, the effective area of the fiber core must be increased, but not to the extent that singlemode propagation is lost. Non-linear effects—primarily changes in the refractive index with power—depend on the intensity of the propagating energy,that is, the power per effective cross-sectional area of the fiber, not the total power. Using uneven or wider channel spacing between the DWDM channels can also minimize four-wave mixing.

New fibers have been developed to address this issue such as the non-zero dispersion-shifted fiber (ITU G.655). Some of these fibers have refractive index profiles in the shape of rings (see Figure 2.28). A small, controlled amount of chromatic dispersion can be introduced over the 1530 nm to 1565 nm band (from more than 3 ps/nm.km at 1530 nm to less than 0.7 ps/nm.km at 1560 nm). This is just enough to suppress four-wave mixing and, yet, still allow individual channel rates of at least 2.5 Gb/s over 1000 km. Such fibers are preferred for DWDM systems.

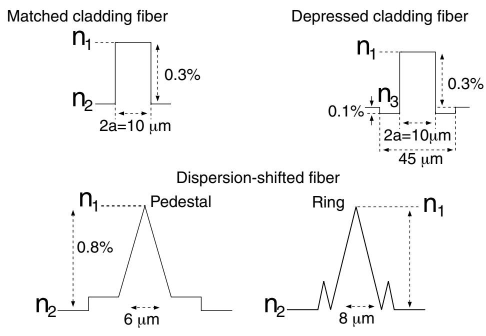


Figure 2.28 Typical refractive index profiles for singlemode fibers

2.6 WDM AND TDM: A COMPARISON

Both WDM and TDM techniques can be used to increase the information-carrying capacity of a network. Although the two are more complementary than competitive, their features can be compared one-on-one on the basis of link design flexibility, speed, and impact on the bit error rate.

2.6.1 Link Design Flexibility

TDM can be engineered to handle different types of links to accommodate different user applications. A TDM scheme can divide a given fiber-optic cable into a multitude of links carrying different types of traffic at different transmission rates. A variety of strategies can be applied to time-slot assignment. They can be assigned permanently or on-demand, which is also known as demand assignment multiple access (DAMA). Their duration can also vary and slots can even be eliminated altogether. If slots are eliminated, data can be encapsulated into packets, each carrying a source and a recipient address (statistical multiplexing). Generally speaking, however, TDM works best when it is applied to a number of logical links, all carrying the same type of traffic, with equal and permanently assigned time slots. This simple version of TDM is easy to design and to manage. It also has less maintenance costs.

Since WDM provides totally independent channels, it is inherently more flexible than TDM. For example, a link can easily be carved into a multitude of channels. However, the characteristics of the traffic and of the data rates on each channel can be quite different, without posing any design or implementation difficulties. A mix of 10Base-T Ethernet LAN traffic, 100Base-T Ethernet LAN traffic, digital video, and out-of-band test signals is easily managed. It is easy to add new channels to an existing WDM architecture, without facing the need that would exist in a TDM system to reallocate all the existing channel time slots.

2.6.2 Speed

The capacity increase that TDM offers results from pumping more information bits along a link. How fast this can be done depends—within some fundamental fiber-cable limits—on the electronic components used. Digital circuitry is required to accept data from each source, to store it, to load it into appropriate time slots, to unload it, and to deliver it to the correct user. All these digital components must operate at, or close to, the speed of the composite link of the multiplexer; that is, each channel, regardless of its net bandwidth, must be equipped with at least electronic equipment capable of handling the overall bandwidth of the link. A fiber-optic cable transmission medium can handle rates of several Gb/s, while the logic speeds of commercially available digital electronics are of the order of 1 billion operations per second. Although electronic speeds are bound to rise, TDM will forever be limited by the economics of needing leading-edge electronics in each signal path, so the technique will unlikely provide a composite link speed commensurate with the tremendous bandwidth presented by fiber-optic cable. This limitation applies to the WAN as well as the premise environment.

Although individual WDM channels are subject to the same end-of-link requirements for supporting electronics as TDM channels, other equipment in the channel only need to deal with its own low data rate, not the rate of the composite signal. The overall channel capacity is not constrained by the speed of the supporting electronics. Capacity can be increased at any time simply by adding more channels on demand. The fastest TDM link design, using the most advanced electronics, can always be transmitted over a single WDM link as one of many channels. WDM can provide composite link speeds that are in line with the enormous bandwidth offered by fiber-optic cable.

In this chapter, we have presented the main building blocks of a DWDM system and we have pointed out how TDM and DWDM technologies are being combined to provide dramatic bandwidth upgrades. All these technological advances in a DWDM system generate new testing methods to ensure that each component and set of components work together to deliver expected performance. In the next chapter, we will describe these critical testing parameters, which will be followed by a detailed discussion of testing methods in Chapter 4.

WDM GUIDE

CHAPTER 3

CRITICAL PARAMETERS IN WDM TECHNOLOGY

CRITICAL PARAMETERS IN WDM TECHNOLOGY

3.1 THE MAIN CONCERNS

The arrival of DWDM, as that of any other technology, introduces new difficulties as well as powerful advantages. The main concern for users of the new DWDM system is its reliability and stability over time. Testing optical quality parameters and system behavior from component manufacturing up to the system integrator is an important means of ensuring that a DWDM system will be commissioned with the right specifications and will deliver robust performance for many years.

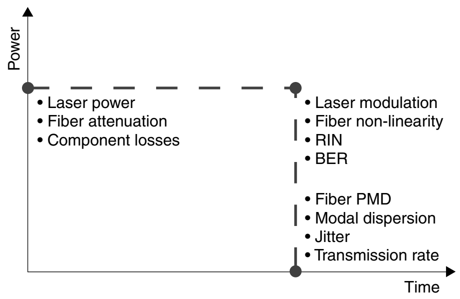


Figure 5.01-a Critical factors limiting TDM performance

We can examine the critical factors limiting the performance of a time-domain multiplexing (TDM) system by placing them on a two-dimensional power-versus-time representation, as shown in Figure 5.01-a.

On the power axis, the critical issues are laser power, fiber attenuation, and component loss. On the time axis, the critical factors are fiber PMD, chromatic and (for multimode fibers) modal dispersion, as well as signal jitter and transmission rate. At the junction of the power and time axes, new factors come into play: laser modulation depth, fiber non-linearity, relative intensity noise (RIN), and bit error rate (BER).

WDM adds wavelength as a new dimension and complicates considerably the representation of the critical factors (Figure 5.01-b).

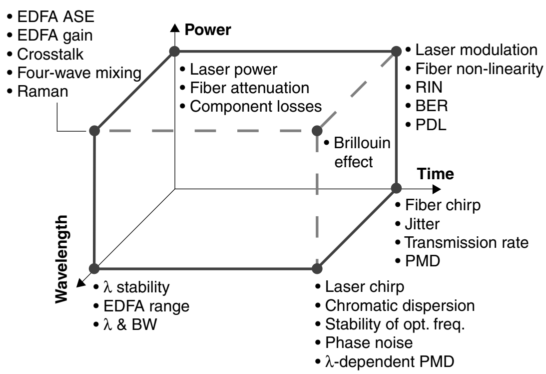


Figure 5.01-b Addition of the wavelength dimension in WDM systems

On the wavelength axis, we are now faced with such critical elements as spectral stability, EDFA spectral range, central wavelength, and bandwidth. At the corner of wavelength and time, we encounter laser chirp, chromatic dispersion, stability of the optical frequency, and phase noise (self-phase modulation and cross-phase modulation). At the corner of wavelength and power, we find EDFA amplified spontaneous emission (ASE), EDFA gain, crosstalk, four-wave mixing, and stimulated Raman forward scattering. Where all three axes meet, we encounter stimulated Brillouin backscattering. Although WDM technology makes networks more efficient by adding bandwidth and channels, its effective application requires care. In the planning, designing, manufacturing, and implementation stages, these factors must be considered and appropriately countered.

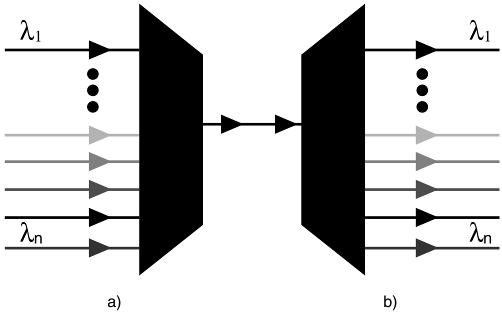


Figure 3.03 Multiplexed wavelengths together have to be precise and linear.

We will describe, here, the most important parameters and phenomena to be tested. These parameters are related to the fiber, optical components, effects of non-linearities, effects of fiber dispersion and active components on the system.

3.2 MULTIPLEXERS AND DEMULTIPLEXERS

A multiplexer (mux) is used to combine signals of different wavelengths onto a single optical fiber (Figure 3.03). A standard broadband coupler might be considered for use as a mux. However, the insertion loss would be too high, about 4 dB for two-channel systems, 7 dB for four-channel systems, 13 dB for 16-channel systems, and so on. Therefore, other techniques such as filtering technology are generally used to multiplex input signals. A practical DWDM narrowband mux is a device that combines multiple wavelengths onto a single fiber with as little signal loss as possible.

A demultiplexer (demux) separates a multiwavelength signal into its individual components. Conceptually, it functions as a multiplexer used backwards. Thus, the technologies applicable to multiplexing are also relevant to demultiplexing. However, ademux requires more complex technology. While it is desirable that the insertion loss of a demux be as low as possible, strong rejection of wavelengths outside each of the signal channels is much more important. This is to supply the final receiver with channels having a high signal-to-noise ratio. As channel spacing becomes increasingly small, wavelength selectivity becomes more important.

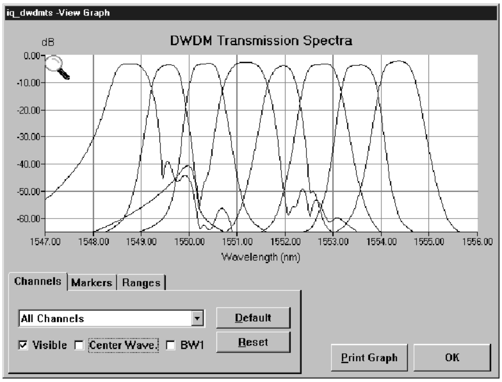


Figure 3.04 Performance criteria for a typical mux/demux

3.2.1 Channel Band

The performance of a mux/demux depends on its ability to isolate incoming or outgoing channels. Each channel band is characterized by the following parameters, illustrated in Figure 3.04:

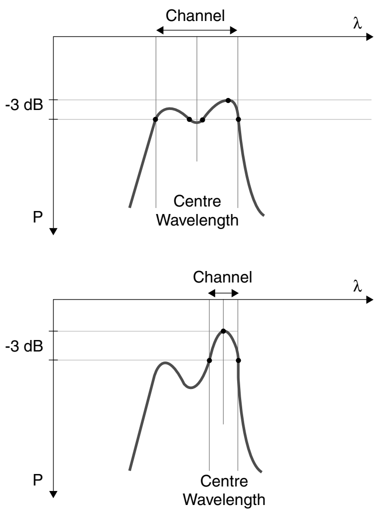


Figure 3.05 A comparison between two traces shows how an apparently minor change can affect the central wavelength.

1. Channel central wavelength

The measured central wavelength is often used to characterize a filter or multiplexer/demultiplexer channel. Central wavelength is the mean wavelength, halfway between the upper and lower cutoff wavelengths $[(\lambda_{upper} + \lambda_{lower})/2]$. It is not necessarily the wavelength of maximum transmission.

The central wavelength parameter is most meaningful for filters whose spectral shapes are symmetric or nearly so. Generally, the central wavelength is defined as the midpoint between the 3 dB downward-sloping wavelengths on either side of the wavelength of peak transmission. For a perfectly symmetrical distribution, the central wavelength would be the same as the peak transmission wavelength, but this is seldom the case. In fact, relatively minor differences in the shape of the transmission curve can lead to marked changes in central wavelength—compare the two traces in Figure 3.05

CRITICAL PARAMETERS IN WDM TECHNOLOGY

The channel transmitter will be operating near nominal wavelength, the wavelength at which the device is designed to operate, usually one of the standard ITU wavelengths. So the central wavelength will have to be as close as possible to this frequency such as that of the channel ITU wavelength.Cutoff wavelengths, upper or lower, are the wavelengths at which the insertion loss reaches a specified value, usually 3 dB.

2. Channel spacing (which is intended to match the network standard channel grid)

In existing network systems, both evenly spaced and unevenly spaced channels are used. Evenly spaced channels are most commonly in accordance with the ITU grid, spaced at 100 GHz intervals.

Uneven channel spacing is used to minimize and predict non-linear effects such as four-wave mixing. Four-wave mixing arises when two or more wavelengths interact to generate new wavelengths. With even channel spacing, these new wavelengths fall on top of existing channels and create crosstalk. With uneven spacing, four-wave mixing causes noise between channels.

3. Bandwidth at -3 dB and at some other appropriate value (typically -0.5 dB, –20 dB or lower)

Bandwidth is the spectral width over which the transmission (or, in the case of reflective devices such as Bragg gratings, the reflectance) exceeds some stated value (-3 dB from maximum or full width half maximum—FWHM—for example). It is meaningless to cite bandwidth without specifying a threshold level. Bandwidth defines the spectral range over which the device can be used effectively.

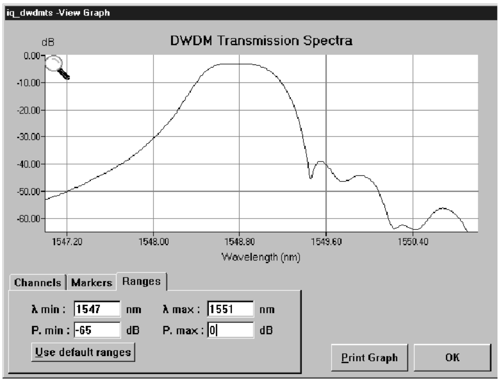


Figure 3.06 Bandwidth measurement of a wide signal

Knowing the bandwidth at two or more levels indicates the shape of the band edges (which is generally related to the order of the filter design); see Figure 3.06. The values at very high attenuations (-20 dB or -30 dB) are useful to predict possible crosstalk in adjacent DWDM channels. The particular threshold value to be used depends on the adjacent channel isolation required by a particular network application.

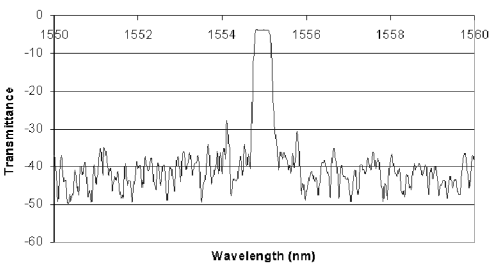


Figure 3.07 Bandwidth measurement of a narrow signal

The bandwidth of all components (and sub-components, in the case of multiplexers) is critical in determining the allowable channel spacing and laser source characteristics.

Some manufacturers use a figure –of merit (FOM) to describe the shape of a filter. It is defined as the ratio of the bandpass bandwidth to the rejection-band bandwidth. For an ideal square-spectral-response filter, the ratio would be one. In general, a high-order filter will have sharper transitions and thus a higher FOM.

4. Isolation and crosstalk (the amount of energy from one channel that appears in an adjacent channel)

Broadly speaking, channel isolation and crosstalk describe the rejection of signals from an adjacent or other channel in a multichannel device. The measurement takes the bandpass characteristics of each channel into account and is normally specified under worst-case conditions. Isolation and crosstalk have slightly different interpretations. Whereas channel isolation describes the rejection of signal power from or to another channel, crosstalk describes the power leaking through a channel band from other channels. Isolation is the minimum value in dBm at which the DUT eliminates an outside signal, while crosstalk is the difference in dB between the maximum input power value and the minimum leaking power (isolation).

Figure 3.08 shows the loss spectra for three channels: A, B, and C. The operating wavelength limits for channel B are also shown; the channel-B transmitter may operate at any wavelength in the range indicated. Measuring isolation determines how much channel-B power will leak into channel A. Placing the loss spectra of the two channels over each other, we can identify this value and express it in dB. Normally, we will do so for the worst possible case, in this case at the band edge (a typical situation for thin-film devices). With the type of device shown above, the isolation between any two non-adjacent channels is very high, and non-adjacent-channel crosstalk can be neglected. This may not be so for some technologies such as arrayed waveguide gratings (AWGs).

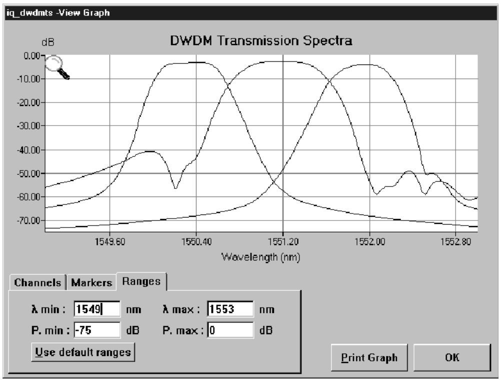


Figure 3.08 Loss spectra of a 3-λ device

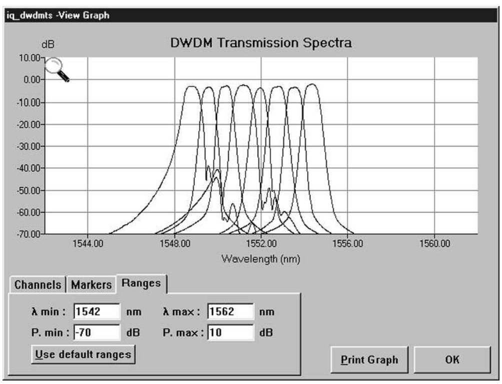


Figure 3.09 8-λ AWG device characterization for isolation and crosstalk

Figure 3.09 presents the loss spectrum for a four-channel AWG device. Both the bandpass and stopband shapes are quite different from those of the thin-film devices treated so far. Worst-case isolation does not necessarily occur at the band edges, and non-adjacent channels may display lower isolation than adjacent ones. In such systems, isolation measurements must be considered in a matrix form—comparing performance in each channel with that in all other channels—and an estimate must be made of the total crosstalk.

CRITICAL PARAMETERS IN WDM TECHNOLOGY

Besides measuring or estimating the worst-case crosstalk between, or among, channels in a WDM system, the user must also determine the levels of crosstalk that can be tolerated. Traditionally, adjacent-channel isolation of 25 dB or greater were sufficient. However, as network complexity grows, and receivers are required to reliably deal with lower signal levels, higher isolation becomes necessary. For the same reason, non-adjacent channel isolation, once a negligible parameter, must now be taken into careful consideration in network designs.

5. Ripple on the peak of the channel power versus wavelength (the power variation at the top of the band in Figure 3.10)

Examined closely, the spectral response of a DWDM device is never perfectly flat. Single-valued insertion loss specifications reveal the loss at a single wavelength, but do not describe the variation in loss over the bandpass or ITU channel. The variation—the difference between the minimum and maximum losses over the defined or measured bandpass—is called ripple (an inverse quantity, flatness, is also often used to describe the same property).

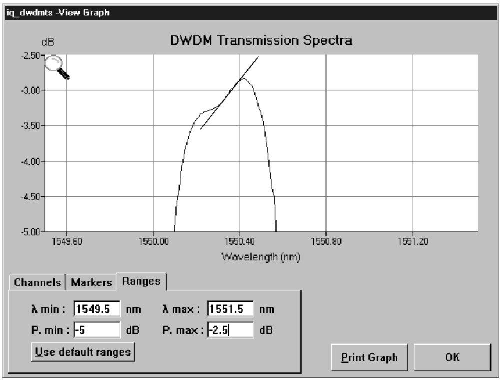


Figure 3.10 Close-up of a mux channel spectrum that shows the ripple on the peak wavelength

The ripple in a channel gives the system designer information about the possible variations in transmitted power as transmission wavelength varies within the nominal bandpass (Figure 3.10). Excessive ripple is unacceptable in many practical applications.

Another important parameter is the maximum ripple slope, which is the change in loss over change in wavelength (δloss/δλ). Using this parameter, the designer determines how much the channel power may change for a very small change in transmitter wavelength. In some instances, both the overall insertion loss and the overall variation in insertion loss for a device may be acceptable, but a small short-period ripple may disqualify it for a particular DWDM application.

6. Channel uniformity

Channel uniformity refers to the amount of variation in the transmittance or the insertion loss from channel to channel in a mux/demux.

3.2.2 Polarization Dependent Effects

At any point in a fiber-optic network, the state of polarization of the optical energy is essentially unknown. It depends on the geometric path of the fiber, on birefringence due to asymmetries in the transmission medium—either intrinsic or brought about by thermal, tensile, and compressive stresses—as well as a variety of optical effects in the network components .

Since the characteristics of many of the components commonly used in fiber-optic networks vary as a function of the state of polarization, overall channel characteristics such as insertion loss, central wavelength, and bandwidth will also vary with polarization. Therefore, to guarantee reliable performance, a network designer must accommodate the worst-case polarization dependence of all the passive components used in the system.

Loss, bandwidth, and central frequency are particularly sensitive to the state of polarization. Each must be measured at different states of polarization, using a polarization controller. The variation in results is the polarization dependence of the parameter in question. Ideally, measurements should be performed for all polarization states, but a random selection usually suffices. The following sections describe the three principal measurements.

Polarization Dependent Loss (PDL)

Polarization dependent loss (PDL) is the variation in loss over the range of possible polarization states. It is obtained from the ratio between the transmittances in the best and worst polarization states (Figure 3.11) and is normally expressed in dB. When half of its value is added to the insertion loss, where the insertion loss is measured with unpolarized light, it gives the worst-case loss for the component at the specified wavelength (usually the nominal operating wavelength).

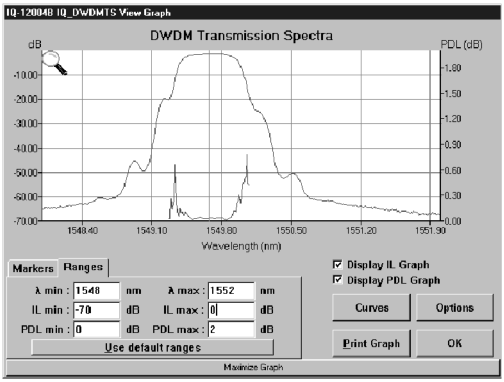


Figure 3.11 Polarization dependence of the insertion loss of a typical mux/demux

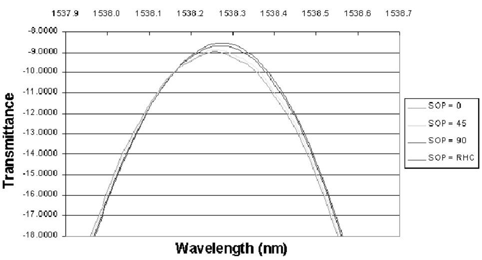


Figure 3.12 Polarization dependence of the central wavelength of a typical mux/demux

In general, PDL is lowest in the bandpass, higher in the transition region, and highest in the filter stopband. Most component manufacturers and users find that it is sufficient to perform the PDL measurement at the channel center and at the bandpass edges. For most applications, a PDL less than 0.1 dB in these regions is required.

Other mux parameters that vary with polarization include the central wavelength (Figure 3.12) and bandwidth. They are estimated in the same way as PDL.

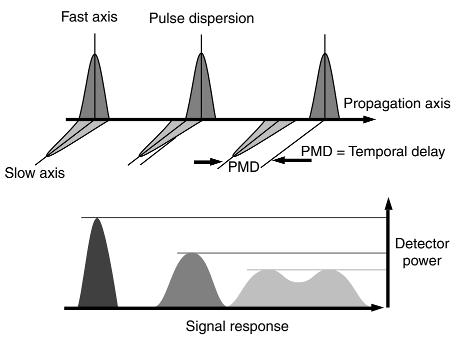


Figure 3.13 The effect of PMD on the pulse

Polarization Mode Dispersion

Another important effect, polarization mode dispersion (PMD), results when the two polarization components of a signal travel at different velocities and, therefore, fall out of phase along a fiber link. This effect, which is aggravated in the presence of PDL and transmitter chirp, distorts signal pulses, broadens and affects error rates in digital systems, and can introduce serious harmonic distortion in analog systems such as CATV networks. Under the conditions that usually prevail in fiber networks, PMD accumulates statistically as the square root of distance, rather than linearly along the length of a fiber link. Thus, although total PMD is generally quoted in time units (e.g., ps), its coefficient, that is, its value per unit length of fiber, must be expressed as a delay per square root of the unit distance (e.g., ps/km). However, for components such as mux/demux, the PMD process is deterministic and we are normally only interested in the total PMD of the device (or per channel of the device). Thus, component PMD is normally simply specified in time units (e.g., ps).

3.2.3 Insertion Loss

The insertion loss (IL) of a component is the difference between the power entering and leaving it, i.e., IL (dB) = $10\log_{10}((P_{in} - P_{out})/P_{in})$. It quantifies the power loss in the device at a particular wavelength or over a given spectral region. For a DWDM component, IL is normally quoted for the transmission band of the device. Obviously, insertion loss should be as low as possible.

To quantify the IL of a DWDM device completely, a curve of loss versus wavelength is required (Figure 3.14).

This figure shows a loss curve for a typical DWDM channel at and near the ITU channel it is intended to serve. The exact ITU wavelength is marked, as are the ITU channel tolerances (crosses on the curve), that is, points marking the extreme wavelength values permitted from the transmitter.

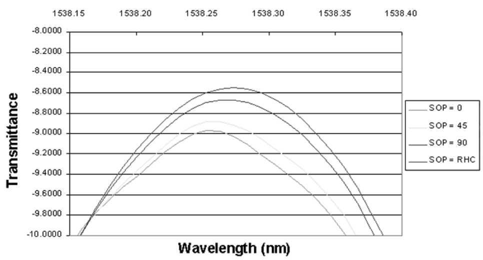


Figure 3.14 Insertion loss of a typical mux/demux

The most useful single measure of IL is the value at the wavelength where the loss is greatest. Using this value, the designer can safely calculate a loss budget that will apply at any transmission wavelength. In fact, this is the way most component manufacturers specify channel insertion loss. Note once again, however, that the ITU center is not necessarily the center of the bandpass.

This method is applicable when the channel width is known, but some components are intended for general applications where the exact operating conditions cannot be determined in advance. In such situations, the best way to describe the IL of the device is to calculate the central wavelength of the bandpass and to determine the IL at that wavelength. This method is often used to characterize single-channel devices or those with symmetrical bandpass.

There is not yet an accepted standard as to how insertion loss should be defined in the presence of PDL. One very reasonable definition has been proposed by standards committees. First, it is necessary to measure insertion loss with a depolarized source according to the formula above; the PDL will be the (max-to-min) variation about this value. Alternatively, the insertion loss may be defined as the best-case loss as the input state of polarization into the device under test (DUT) of a fully polarized source (e.g., laser) is adjusted. The worst-case loss would then be the sum of the IL and PDL.

Important factors to consider when comparing the IL values for different devices include the effect of connectors and the uniformity of the IL across channels in a multichannel unit.

3.2.4 Directivity

Directivity, which is sometimes referred to as near-end crosstalk, is a measure of the isolation between the inputs ports of a multi-input device (Figure 3.15). It is particularly important in a multiplexer, where power returned to the system transmitters must be kept to a minimum.

The users must provide a non-reflective termination on the output side of the device when measuring directivity. If not, reflections at the fiber end-face may degrade the measurement.

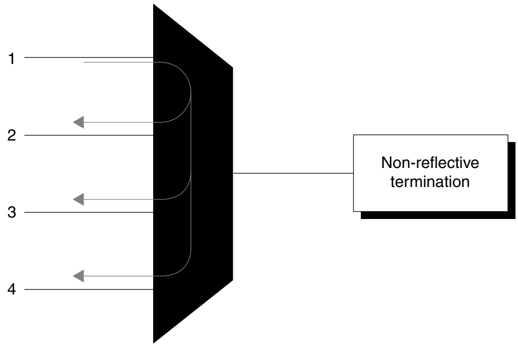


Figure 3.15 Illustration of undesired signal leakage from input 1 to other inputs

Often, it is sufficient to perform directivity measurements only at nominal channel wavelengths. In Figure 3.15, for example, we could insert a signal into channel 1 at its design wavelength and measure the power that is returned to the other inputs. The difference between the power inserted and that returned to other inputs is the directivity for that particular channel combination. Measurements should be taken for all channel combinations. This makes it difficult to automate directivity measurements, especially for high channel count devices.

3.2.5 Optical Return Loss

When light is injected into a fiber-optic component, such as a connector, a multiplexer or fiber itself, some of the energy is transmitted, some is absorbed, and some is reflected. In fiber-optic systems, light is reflected because of Rayleigh scattering and Fresnel reflections. Rayleigh scattering occurs within the fiber itself as an inevitable result of interaction between the light energy transmitted and the molecules that make up the fiber. Therefore, Rayleigh scattering depends on the composition of the glass. It is also wavelength-dependent. The amplitude of Rayleigh scattering is about –75 dB per meter of typical fiber at 1550 nm, and its effects can be considerable over long fiber links. Fresnel reflections occur at discrete interfaces (connectors, adapters, etc.) as a result of air gaps, misalignment, and mismatched refractive indices.

Reflected optical power is undesirable for a number of reasons:

- It contributes to overall power loss.
- High-performance laser transmitters like those used in dense WDM systems are very sensitive to reflected light, which can significantly degrade the stability of the laser and the signal-to-noise ratio of the system. In the extreme situation, strong reflected power can damage the laser transmitter.
- Reflected light can be re-reflected in the forward direction. Such forward-propagating reflections lag the original signal, causing problems at the demodulation stage. This phenomenon is termed multipath interference (MPI).
- Reflections occurring inside an EDFA optical amplifier—especially if the gain medium lies between them—can lead to additional multipath interference and can contribute significantly to amplifier noise .

All things being equal, a component with a –55 dB reflectance would be preferable to one with a reflectance of –50 dB.

3.3 OPTICAL FIBER

Four key parameters of optical fiber limit the performance of WDM systems: non-linearity, chromatic dispersion, and first- and second-order polarization mode dispersion.

3.3.1 Chromatic Dispersion

All glass, including that used to make fiber, exhibits a material dispersion because its index of refraction varies with wavelength. In addition, when a singlemode optical fiber is drawn from this glass, the geometric form and refractive index profile can contribute significantly to the wavelength-dependence of the speed of propagation of information-carrying pulses in the fiber, that is, the waveguide dispersion. Together, the material and waveguide dispersions yield what is termed the chromatic dispersion of the fiber.

Chromatic dispersion would not present a problem if an optical channel was represented by a single wavelength, but even the narrowest of channels has some finite bandwidth. Even an ideal monochromatic source has a non-zero linewidth when it is modulated, by virtue of the fact that it is carrying information. Moreover, additional real-life phenomena, such as chirp, can lead to even broader, effective source linewidths.

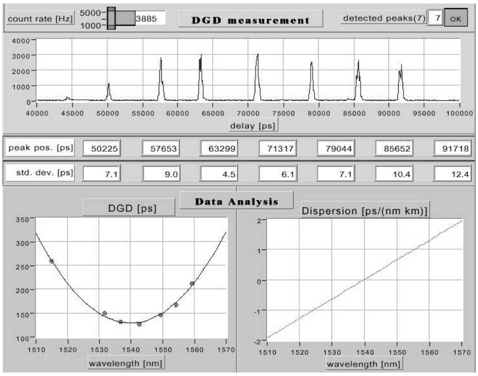


Figure 3.16 Chromatic dispersion as a function of wavelength

Thus, a given channel is represented by a range of closely spaced wavelengths rather than a single wavelength. Because different wavelengths travel at different speeds (or rather, at different group velocities), a pulse that is a sharp square at the input end of a communications link will become increasingly wide as it passes through a fiber link. In many cases, this pulse will eventually blend into adjacent pulses, making accurate signal-recovery difficult. As bit rates and link lengths increase, the effects of chromatic dispersion become greater.

Singlemode silica glass fiber with a step-index profile has dispersion zero, mainly determined by the material dispersion (i.e., the refractive index) of the silica glass. This fiber is often called dispersion-unshifted fiber. However, with an appropriate design of a more complex index profile of the fiber core and inner cladding, the waveguide dispersion can be made to play an increasingly important role. In this way, the dispersion zero can be shifted substantially, and the shape of the dispersion-versus-wavelength curve tailored for specific applications. In particular, dispersion-shifted fiber—in which the dispersion zero wavelength λ_0 has been shifted to 1550 nm— has been widely produced and deployed. Together with λ_0, designers use the S_0 parameter to describe the slope of the dispersion at λ_0. This instantaneous slope is constant and locally defines a linear dispersion at about λ_0. This slope is, in general, different at any wavelength other than at λ_0. The form of the dispersion curve as a function of wavelength is crucial for WDM transmission, especially in G.653 dispersion-shifted fibers.

The chromatic dispersion of a fiber link is cumulative with distance, and is stated as the change in group delay per unit wavelength, in ps/nm. The delay coefficient is the dispersion for a particular fiber type and is generally quoted in units of ps/(nm.km).

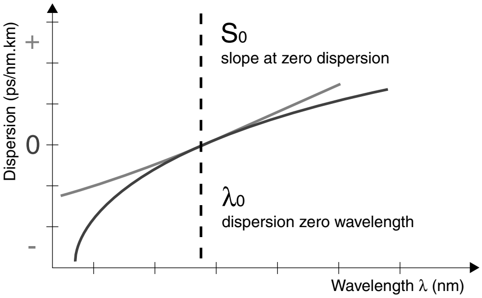


Figure 3.17 Key chromatic dispersion parameters are the dispersion zero, λ_0, and the slope at zero dispersion, S_0.

Chromatic dispersion in a system is sensitive to

- an increase in the number and length of spans
- an increase in the bit rate (since the effective source linewidth is increased)

It is not significantly influenced by

- a decrease in channel spacing
- an increase in the number of channels

The effects of chromatic dispersion decrease with

- a decrease in the absolute value of the fiber's chromatic dispersion
- dispersion compensation

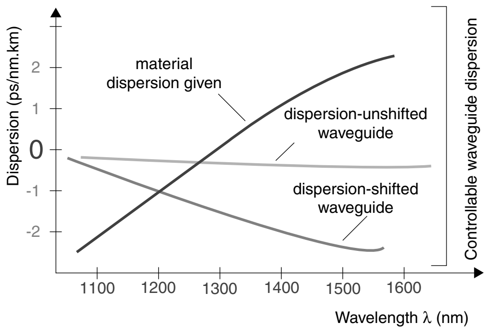


Figure 3.18 Dispersion varies as a function of wavelength for a given material.

Chromatic dispersion requires more attention in WDM systems using G.652 fibers, since the dispersion is large in the 1550 nm region.

3.3.2 Polarization Mode Dispersion

Describing the characteristics of an ideal optical fiber is relatively straightforward. It involves how energy propagates along the fiber, what polarization modes it supports at given wavelengths, and so on. However, when real fibers are combined in cable and the cable is installed in the field, it is more difficult to achieve an ideal fiber. During the fiber-manufacturing process, stresses in the fiber core and cladding are frozen into place, inducing an intrinsic, essentially unpredictable birefringence to the fiber. In addition, the mechanical action of winding fiber into a twined cable introduces asymmetrical strains, which are increased when the cable is wound onto a mandrel. And once out in the field, the cable is continuously subjected to further stress when it is being installed and when mounting brackets, pass-throughs, connector mounts, and so on. All of these mechanical actions result in quasi-random local deformations of the fiber, deformations that disturb its circular geometry or the concentricity of the core within the cladding, or that elongate it or bend it sharply.

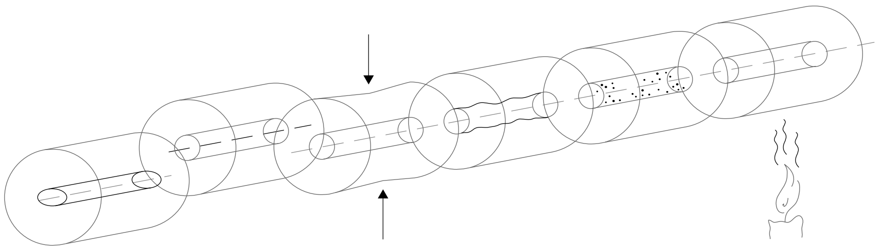


Figure 3.19 PMD is affected by physical stress, temperature, and fiber imperfections.

Polarization mode dispersion is the primary mechanism through which these flaws affect performance.

At any point along a fiber, a polarized light pulse can be decomposed into components aligned with two local, orthogonal axes of the fiber: a fast axis and a slow axis. It should be noted that these axes do not necessarily correspond to a linear state of polarization.In the real world of cabled fiber, the orientation of these axes, and the relative difference in propagation speed corresponding to each axis (directly related to the magnitude of the local birefringence) changes along the optical path. In a somewhat idealized scenario, different sections of the fiber will have different orientations of these local birefringence axes. (The change in orientation of the local principal axes is known as a mode-coupling event.) In each segment, a time delay will be introduced between that portion of the light aligned with the local fast versus the local slow birefringence axes. Since the relative orientation of these axes in adjoining segments is different, the pulse will experience a statistical spreading over time.

For a particular wavelength, the input state of polarization of a light pulse launched into the fiber can be adjusted so that the pulse undergoes no spreading (at least for a measurement time sufficiently short that environmental perturbations can be neglected). In fact, two such mutually orthogonal input states of polarization exist. These are known as the input principal states of polarization, one of which corresponds to the fastest and the other to the slowest pulse propagation time through the fiber.The difference in these two propagation times is known as the differential group delay (DGD) corresponding to that wavelength, and the PMD is defined as the wavelength-averaged value of the DGD.

Because the individual factors that cause PMD cannot be measured or even observed in isolation, the phenomenon must be viewed as a constantly changing, unstable stochastic process. This process results in a broadening of the pulses carrying information, which can impair the ability of a receiver to decode them correctly. PMD is thus a critical phenomenon that limits the transmission rate.

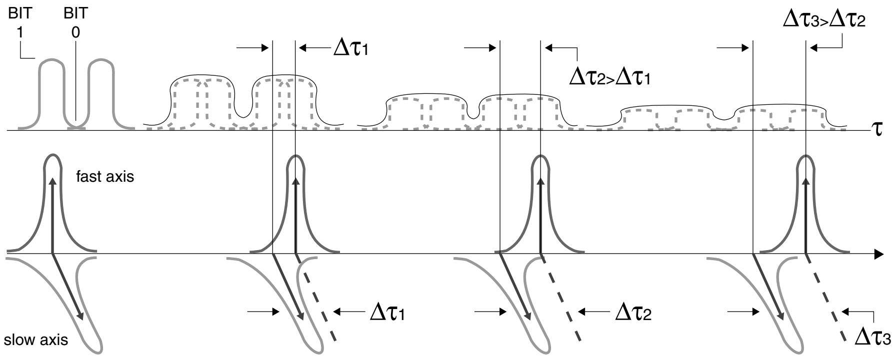


Figure 3.20 Transmission bits (0,1) get wider along the fiber so that 0 and 1 are undetectable.

PMD is measured in ps for a particular span of installed fiber. Because each new flaw along the fiber may partially counteract the effect of an earlier flaw, but the overall result is a gradual increase in PMD, the appropriate units for the coefficient that characterizes the fiber itself are ps/km$^{1/2}$.

An averaging procedure must be used to determine the PMD of a particular link made of a number of sections. The total PMD of a number of spans in a network is given by a root mean square summation:

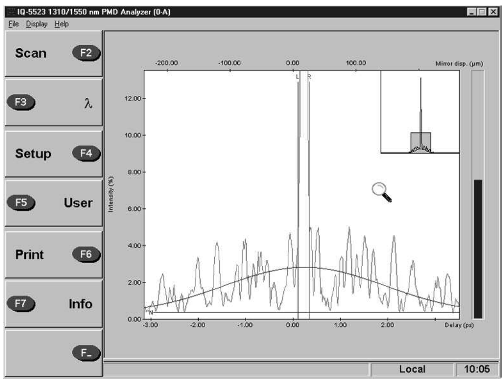


Figure 3.21 Example of PMD measured with the interferometric method

$$PMD_{TOT} = (\Sigma_N (PMD_N)^2)^{1/2}$$

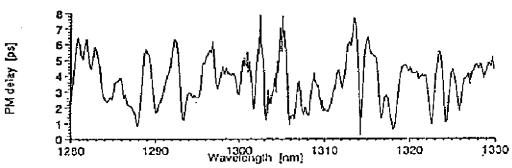


Figure 3.22 The average DGD value over the wavelength range gives the mean fiber PMD.

If, for example, nine out of ten spans in a network each have a PMD of 0.2 ps, but the tenth one has a PMD of 2 ps, the total PMD would be 2.088 ps. In other words, the single bad section dominates the overall figure. Thus, all spans in a network must be tested; it cannot be assumed that if a few spans show low PMD that, overall, they will be acceptable.

The impact of PMD in a system is particularly sensitive to

- an increase in the channel bit rate (one of the most important criteria)
- an increase in the number of spans (equivalent to an increase in the length of the fiber link)
- an increase in the number of channels (since the more channels there are, the higher the probability of one of them being affected by a larger instantaneous value of the differential group delay than its mean value)

PMD is not significantly influenced by a decrease in channel spacing (except if it is to provide more channels in a fixed bandwidth such as the 40 nm bandwidth of the EDFA). However, it will decrease with better control over fiber geometry, or by increasing mode coupling (the level of energy exchange between the principal states). The impact of the use of chromatic dispersion compensation techniques on PMD is unclear, but research into this issue is underway. Soliton-based transmission systems using return-to-zero (RZ) bit coding have been shown to be less susceptible to PMD impairment than non-return-to-zero (NRZ) coding (see Figure 3.23).

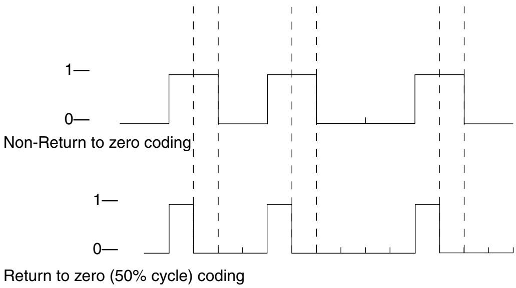


Figure 3.23 Return to zero reduces the 1 time slot to avoid overlapping distortion.

PMD is a more important issue for WDM installations using older G.652 fibers (80 million kilometers of which were installed in the late 1980s) than for those using newer G.652, G.653, and G.655 fibers.

ITU has proposed the criteria for PMD outlined in Figure 3.24 as guidelines to maintain acceptable receiver error rates.

Proposed PMD coefficient for a 99.994% probability that the power penalty will be less than 1 dB for 0.1 of the bit period		
Bit rate (Gb/s)	Maximum PMD (ps)	PMD coefficient 400 km fiber (ps/km$^{1/2}$)
2.5	40	2.0
10	10	0.5
20	5	0.25
40	2.5	0.125

Figure 3.24 Maximum PMD value for a given bit rate

Figure 3.25 presents PMD criteria in a different way. For each of three common bit rates, it shows the sensitivity penalty at the receiver that will be introduced by a given differential group delay (i.e., the difference between the group velocities of the two propagating principal states of polarization).

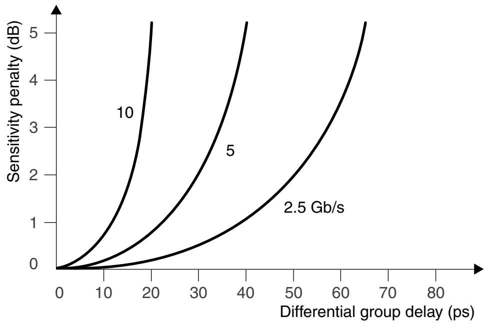


Figure 3.25 PMD-induced sensitivity penalty

As noted earlier, PMD affects individual components, not just fiber. However, in the case of component, PMD is generally constant, not quasi-random, and can be reduced through quality control during the manufacturing stage.

3.3.3 Second-Order Polarization Mode Dispersion

Until recently, second-order PMD, related to the variation of polarization mode dispersion with wavelength, has had a negligible effect on network performance. However, as transmission rates reach 10 Gbps and beyond, it can become an important factor in system degradation. Second-order PMD is always present in long singlemode fibers if first-order PMD is present. (In fact, there is a simple mathematical relationship between the two for the usual case of strongly coupled fibers.) However, second-order PMD will normally only lead to system degradation if the link has chromatic dispersion or if there is transmitter chirp. The magnitude of this degradation can be of the same order as that of chromatic dispersion, and is proportional to the link length, unlike that of first-order PMD. It is therefore of particular consideration for long-distance links. In contrast to chromatic dispersion, however, second-order PMD behaves stochastically.

Second-order PMD affects the statistics of the DGD probability distribution, increasing when very low bit error rates (BERs) are required. Second-order PMD depends to some extent on the rate of change of the DGD as a function of wavelength. However, it depends to a much greater extent on the change of direction of the output principal states of polarization (the polarization dispersion vector) as a function of optical frequency.

3.3.4 Non-Linearity

Non-linearity in fiber optics has similar effects as non-linearity in other physical systems, be they mechanical or electronic. It causes the generation of spurious harmonic and sum and difference frequencies. These added signals cause unexpected loss effects in optical communications networks.

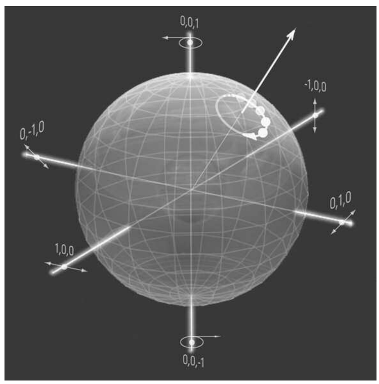


Figure 3.26 Second-order PMD is the variation of the polarization dispersion vector orientation and its magnitude (i.e., DGD) as a function of wavelength.

Fiber non-linearity is not a manufacturing or design defect; it is an inherent characteristic of any electromagnetic energy passing through a physical medium. It is of particular concern to designers and users of fiber-optic communications systems, due to the very high coherence of laser energy these systems use. The strength of the electric field needed for a given level of transmitted power increases with the level of coherence in the wave. Thus, even moderate power levels in highly coherent WDM systems lead to electric field levels sufficient to produce non-linear effects.

Fiber non-linearity becomes noticeable when the laser signal intensity (the power per unit area) reaches a threshold value. Also, non-linear effects generally become evident after signals have passed through a length of fiber, depending on the characteristics of its construction and the operating conditions under which it is placed.

In fact, the electric field (*E*) of the propagating signal is proportional to the signal power P times the fiber non-linear index n_2 divided by the fiber core effective area A_{eff} as expressed in:

$$E(z + dz) = E(z) \exp\left[(-\alpha/2 + i\beta + \gamma P(z,t)/2)\, dz\right]$$

where α is the fiber attenuation, β is the phase of the propagating wave, and γ is the non-linear coefficient equal to $(2\pi/\lambda)(n_2/A_{eff})$. If we assume that the light beam propagates in a Gaussian form, then:

$$A_{eff} = \pi(MFD)^2$$

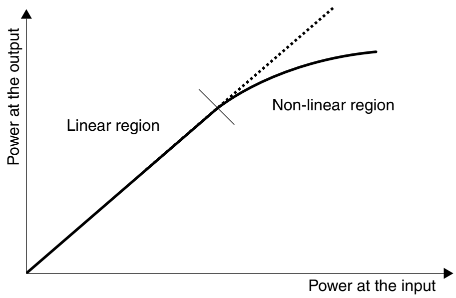


Figure 3.27 Non-linearity appears at high power level.

where *MFD* is the mode field diameter. For G.653 dispersion-shifted fibers and G.655 non-zero dispersion-shifted fibers, A_{eff} is approximately equal to 50 to 60 μm², while G.652 dispersion-unshifted fibers have A_{eff} approximately equal to 80 μm². The effective fiber length L_{eff} has the same effect as A_{eff}. For typical singlemode fibers, L_{eff} is typically equal to 20 km.

Non-linear effects fall into two categories, depending on the behavior of the non-linear coefficient γ. These are scattering phenomena (when g is a real number and gives rise to gain or loss) and refractive index phenomena (when g is an imaginary number and gives rise to phase modulation).

1. With scattering phenomena, the laser signal is scattered by sound waves (acoustic phonons) or fiber molecular vibrations (optical phonons) and is shifted to longer wavelengths. The following are two different types of scattering phenomena:
   a) stimulated Brillouin backscattering (acoustic phonon phenomenon)
   b) stimulated Raman scattering (optical phonon phenomenon)

2. With refractive index phenomena, the signal power is high enough that the refractive index may no longer be assumed to be a constant, but instead is approximated by:

$$n = n_0 + n_2 I$$

where n_0 is the fiber linear refractive index, I is the signal intensity, and n_2 the non-linear index (about 2 to 3 x 10^{-16} cm^2/W for silica fiber). The following are the different refractive index phenomena:

a) self-phase modulation, or the effect a signal has on its own phase

b) cross-phase modulation, or the effect a signal in one channel has on the phase of that in another channel

c) four-wave mixing, or the mix of a number of wavelengths to produce entirely new wavelengths

Stimulated Brillouin Backscattering

In stimulated Brillouin backscattering, the laser signal creates periodic regions of altered refractive index, that is, a periodic grating that travels as an acoustic wave away from the signal. The reflections caused by this virtual grating appear as backscattered light, which is amplified and Doppler-shifted to lower frequencies (longer wavelengths). The SBS effect can result in a very noisy and unstable forward- propagating signal, since much of the optical energy is backscattered.

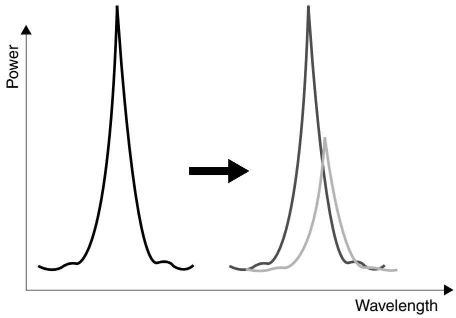


Figure 3.28 The Brillouin backscattering effect creates a side mode downshifted by about 116 Hz.

For G.653 fibers at 1525 nm, for instance, the backscattered signal is downshifted by about 10.7 GHz (+0.085 nm) with a bandwidth of about 60 MHz. For G.652 fibers in the same window, the backscattered signal is downshifted by about 11 GHz (+0.088 nm) with a bandwidth of about 30 MHz. As a rule of thumb, SBS should be considered as a potential problem if monochromatic light of more than about 6 dBm is launched into the fiber.

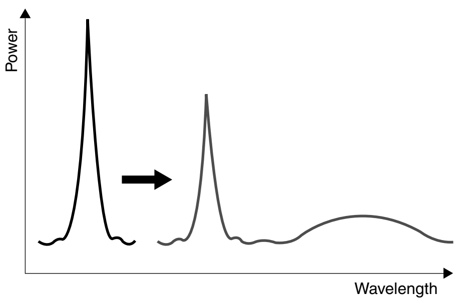


Figure 3.29 Raman scattering creates a wide peak wavelength.

A number of techniques have been developed to suppress SBS in real systems. The most popular involves a rapid (~50 kHz) dithering of the carrier wavelength over a range of about 1 GHz, much greater than the 30 to 60 MHz SBS bandwidth.

Stimulated Raman Forward Scattering

The coefficient for Raman scattering, 10^{-12} cm/W, is much smaller than that for Brillouin backscattering. But the signal frequency is shifted to much lower frequencies (between 10 to 15 THz in the 1550 nm window, or about +100 nm longer wavelength) with a much wider bandwidth (about 7 THz or 55 nm). In WDM systems, the effect is a transfer of power from shorter wavelength channels to longer ones.

Self-Phase Modulation

When the intensity of the laser signal becomes too high, the signal can modulate its own phase. This modulation broadens the signal spectrum and temporally broadens or compresses the signal, depending on the sign (positive or negative) of the chromatic dispersion it sees. A shift to short wavelengths occurs at the trailing edge of the signal and a shift to long wavelengths at the leading edge.

In WDM systems, the spectral broadening created by self-phase modulation in a signal channel can interfere with adjacent signals.

Self-phase modulation increases with

- an increase in injected channel power in a fixed fiber with fixed effective area
- an increase in the channel bit rate (higher bit rates have faster rise-and-fall bit slopes)
- negative chromatic dispersion

In WDM systems, self-phase modulation is more of an issue for G.652 fibers (zero dispersion at 1310 nm) than for G.653 dispersion-shifted fibers at 1550 nm and G.655 non-zero dispersion-shifted fibers. It is not significantly influenced by a decrease in channel spacing or by an increase in the number of channels.

Self-phase modulation decreases with

- a zero or small positive value of chromatic dispersion
- an increase in fiber effective area
- dispersion compensation

Cross-Phase Modulation

In this case, the signal in one channel modulates the phase of an adjacent channel.

Cross-phase modulation is sensitive to the same factors as is self-phase modulation, as well as to an increase in the number of channels. It is not significantly influenced by a decrease in channel spacing, as is the case for self-phase modulation, but will decrease with

- an increase of the fiber effective area
- dispersion compensation

Cross-phase modulation is less important in WDM systems using fibers with large effective areas.

Four-Wave Mixing

Four-wave mixing is one of the most disruptive non-linear effects in WDM systems. When the intensity of the laser signal reaches a critical level, ghost signals appear, some of which may fall within the true channels. The number of these ghost channels is given by:

$$N^2(N - 1) / 2$$

where N is the number of signal channels. Thus, 24 ghost channels appear in a four-channel system, 224 in an eight-channel system, and 1920 in a 16-channel system (see figure 3.30). Interference of this magnitude can be catastrophic at the receiver end.

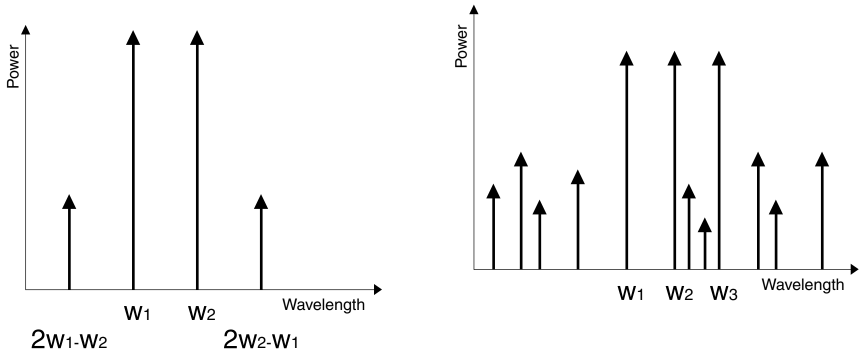


Figure 3.30 Four-wave mixing creates unwanted signals within the transmission spectral range.

Four-wave mixing is sensitive to

- an increase in the channel power
- a decrease in the channel spacing
- an increase in the number of channels (although a saturation value may be reached)

Four-wave mixing is a particularly serious issue in systems using G.653 dispersion-shifted fibers. It is less important with G.655 non-zero dispersion-shifted fibers, especially those with large effective areas. It is not significantly influenced by an increase in the channel bit rate.

Four-wave mixing decreases with

- an increase in the fiber effective area
- an increase in the absolute value of chromatic dispersion

Four-wave mixing is less serious for dispersion-unshifted (G.652) fibers in DWDM systems at 1550 nm because the dispersion is relatively flat compared to dispersion-shifted (G.653) fiber, where the dispersion slope is much steeper.

3.4 OPTICAL AMPLIFIERS

Optical amplifiers, generally erbium-doped fiber amplifiers or EDFAs, are crucial to the economic operation of dense WDM networks. This is because they provide transparent amplification of all channels, without regard for the modulation schemes or protocols used in each. Their use means that a modulated optical signal can be transmitted over very long distances without the need for the recovery and regeneration of the information carried. However, the wavelength-dependence of the gain of EDFAs must be determined and addressed during network design, especially when individual channels will traverse several amplifiers. Furthermore, as the noise figures of the individual EDFAs used will critically affect the integrity of the optical signal, these figures will determine the number of amplifiers that can be cascaded, and thus the maximum link distance.

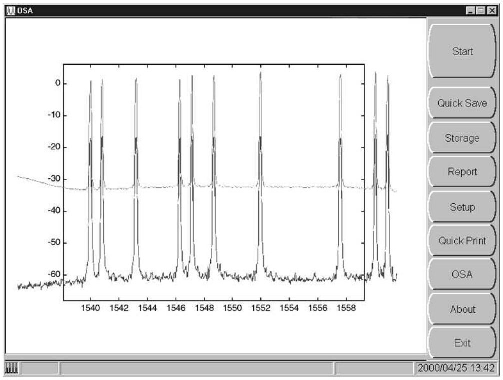


Figure 3.31 Gain can vary from one peak to another.

Since gain is the essential function of an amplifier, optical amplification is one of the most important parameters to measure. Gain depends on many parameters that, separately or together, can modify device performance. Gain varies with signal wavelength, input polarization state, and power. The gain curve (Figure 3.31), which characterizes the gain across the channel spectrum, will change depending on the relative input power of each channel. Thus, the effect of a temporary redistribution of the input power, such as when a channel is being added or dropped, must be characterized and controlled in multi-signal applications.

Gain is measured as the ratio between the average output and input powers, omitting the contribution of the amplified spontaneous emission (ASE) of the amplifier itself.

$$G \text{ (dB)} = 10 \log ((P_{\text{out}}(\lambda_c) - P_{ASE}(\lambda_c))/P_{\text{in}}(\lambda_c))$$

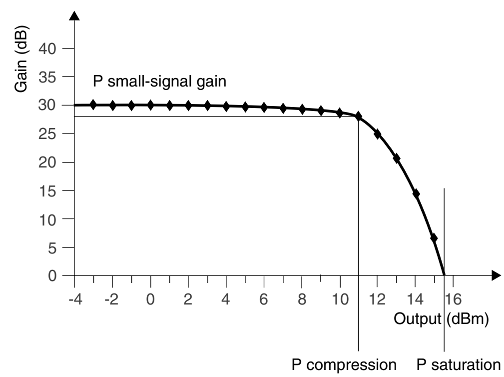


Figure 3.32 EDFA gain is linear and flat in its operating window.

where *G* is the gain in dB; *P*out(lc) is the average output power at the channel wavelength (in mW); *P*ase (lc) is the ASE power in mW; and *P*in(lc) is the average input power in mW.

The gain exhibited by an optical amplifier is very dependent on the input-signal level, as shown in Figure 3.32. The amplifier exhibits a typically large small-signal gain for weak input signals (e.g., >30 dB for an EDFA pre-amplifier with an input signal of <-20 dBm). For intermediate power input signals, the gain begins to deviate from its small-signal value, and this gain compression is an important parameter. For high-power input signals (typically >3 dBm in the case of an EDFA), the amplifier is in deep gain saturation, and the output power corresponding to an input power level where the gain ≅ 1 is termed the saturated output power.

In general, the values of these three key amplifier gain parameters, that is, the small-signal gain, 3 dB gain compression, and saturated output power, vary with input signal wavelength. Consequently, users wishing to fully characterize amplifier performance will require a test system that performs measurements at different optical input powers for a number of wavelengths of interest.

To measure saturated gain for DWDM applications, the amplifier is saturated at one particular channel wavelength and the gain measurements are taken at other channel wavelengths, using an input signal. Probing at all wavelengths over the operating spectrum reveals the spectral sensitivity of this parameter. The measurement can also be bidirectional, to provide so-called reverse saturated small-signal gain.

Gain Cross Saturation
Gain cross saturation is the change in the gain of one specific channel when the input power in another channel (or several channels) is changed by a specific amount.

Gain Flatness
Gain flatness is the maximum difference among individual channel gains when their input powers are equal.

Polarization Dependent Gain
Polarization dependent gain (PDG) characterizes the difference in gain for different input polarization states. It is usually determined by scanning or sampling all possible input polarizations and noting the lowest and highest gain values.

Signal Gain
The signal gain of an EDFA is the gain that applies to a large signal such as the traffic signal, which, for a power amplifier application, normally drives the amplifier into saturation. This is the main factor determining the operating point of the amplifier. In contrast, noise gain is the gain that applies to a small signal that has one with little or no impact on the amplifier's operating point, while another large signal is driving the amplifier into saturation (Figure 3.32).

Profile
The term profile is often used to refer to the wavelength-dependence of a particular property. For instance, the noise gain can be a simple value (expressed in dB) for one wavelength, while the noise gain profile describes how the parameter varies with wavelength.

Channel Gain
Channel gain is the gain of one particular signal in a DWDM system. In general, it is different for different wavelengths or channels. Spectral flatness (or gain flatness) describes the change in gain with wavelength, i.e., the slope of the gain profile, usually in dB/nm. Gain tilt describes how this property changes as individual channel wavelengths are added or removed.

3.4.1 Amplified Spontaneous Emission

The main source of noise in an optical amplifier is amplified spontaneous emission (ASE), which is not unlike the background hiss that can be heard from an audio amplifier. This ASE appears as a background level across the optical spectrum, as seen with an optical spectrum analyzer. It introduces noise in the rf baseband (i.e., in the electrical signal coming out of the receiver) via mechanisms that will be discussed in more detail below.

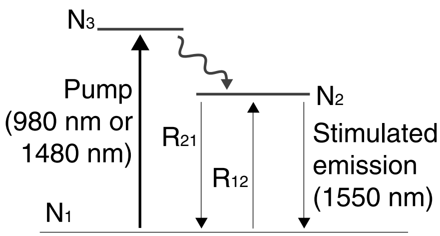


Figure 3.33 3-Level population level system of a typical EDFA

As an optically-pumped amplifying medium, erbium-doped silica has what is known as a three-level structure (Figure 3.33), where the upper level in the 1550 nm band transition is metastable and can give rise to spontaneous and stimulated emission.

A metastable level has a long decay time. Consequently, an erbium ion can remain in this state for a long time, resulting in a population inversion. In the presence of such an inversion, isolated atoms, or ions, produce spontaneous emission of radiation. In a gain-producing medium, such as that in an EDFA (Figure 3.34), this spontaneous emission has a given probability of being captured in each elemental slice of doped fiber and, thus, being amplified by successive elements, producing amplified spontaneous emission (ASE). ASE is generated in both forward and backward directions.

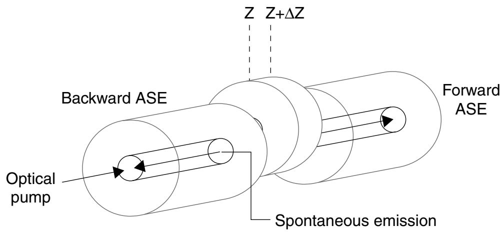


Figure 3.34 Every small piece (z, z+Δz) of fiber creates forward and backward ASE.

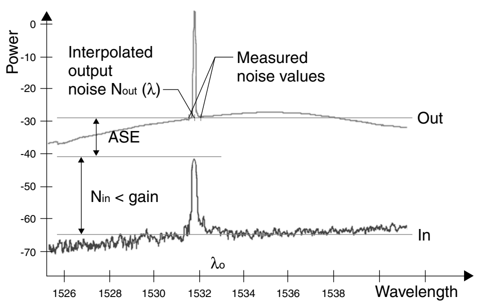


Figure 3.35 Different levels used to calculate ASE and gain for the linear region.

The ASE power in the signal can be deduced by measuring the noise level of the input signal ($N_{in}(\lambda)$) and the total noise level of the output signal ($N_{out}(\lambda)$) using the following equation:

$$N_{out}(\lambda) = (N_{in}(\lambda) \times G) + ASE$$

In saturation or gain compression , the ASE contribution is small. Gain is simply the output/input power ratio, without taking amplified spontaneous emission into account (see Figure 3.35).

3.4.2 Noise Figure

The noise figure (NF) is defined as the degradation of the signal-to-noise ratio (SNR) of the signal after it has passed through the optical amplifier. (There is frequently confusion on this point. This SNR is defined in terms of the Radio Frequency (RF) baseband signal that carries the information, and not directly the ratio of the optical carrier to the surrounding ASE power, as seen on an optical spectrum analyzer, for instance.)

This degradation of the SNR ratio arises from several processes:

- shot noise
- spontaneous-spontaneous beat noise
- signal-spontaneous beat noise
- interference noise
- excess noise (noise in the source)

The first noise source—shot noise—is an inescapable consequence of the discrete nature of light. It is caused by random fluctuations in the arrival times of the photons making up the signal, or more precisely, by random fluctuation in the resulting electrons from the photodetector. It is, by nature, "white"; i.e., its frequency spectrum is flat. In most practical applications, photon rates are high enough that the Poisson-predicted $N^{1/2}$ uncertainty in a stream of N photons can safely be ignored.

The second contribution comes from spontaneous-spontaneous beat noise between ASE signals within the frequency bandwidth of the amplitude-modulated signal, also termed ASE-ASE beat noise. Since ASE noise decreases with output power or when approaching saturation conditions, this noise is usually neglected for power amplifiers. However, spontaneous-spontaneous beat noise can be very important in pre-amplifiers unless narrowband filtering is used.

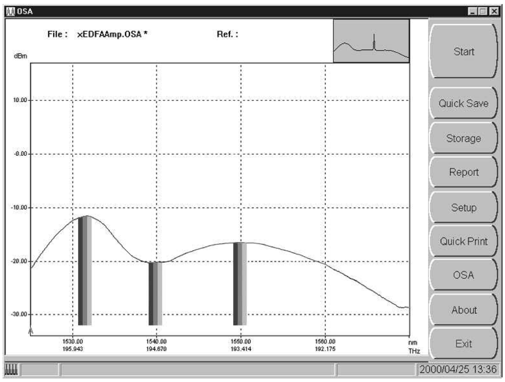


Figure 3.36 ASE-ASE beat noise generation; the gray bars represent the various ASE contributions to the noise of other adjacent ASE noise contributions.

Beat noise occurs when two uncorrelated, but closely spaced signals interfere with each other. In an EDFA, each spectral ASE slice can beat with neighboring slices, giving rise to interference with spectral characteristics like those shown in Figure 3.36.

This form of noise generation can be eliminated, for all practical purposes, by using narrowband optical filtering.

Signal-spontaneous beat noise, generally termed ASE beat noise, arises from signal heterodyne mixing with essentially white ASE noise. Since the beat frequency of the signal with the surrounding ASE noise is within the frequency bandwidth of the modulated information carrier, it cannot be removed by optically or electrically filtering the signal. Measuring it is therefore important. The noise figure (NF) specification of most EDFAs is a measurement of this effect.

The noise figure that reflects signal-spontaneous beat noise can be determined from the ASE power lying below the laser signal, P_{ASE}, at the signal wavelength λ_s (see Figure 3.37), the gain G, and the measurement bandwidth B (in frequency units) as follows:

$$NF\ (\mathrm{dB}) = P_{ASE}\ (\lambda_s)\ /\ G(\lambda_s)^{*}h\nu^{*}B(\lambda_s)$$

Since signal-spontaneous beat noise cannot be filtered away like spontaneous-spontaneous beat noise, the amplifier noise figure is normally defined in terms of this mechanism.

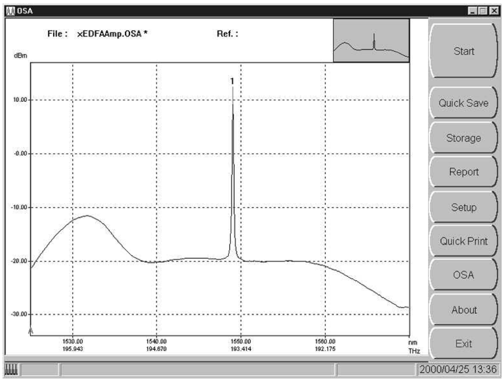


Figure 3.37 Noise figure is determined by measuring the ASE spectral density under the peak wavelength.

3.4.3 Multipath Interference Noise

Multipath interference (MPI) is due to small internal reflections inside an EDFA that can degrade the amplifier performance. These reflections can induce serious and unstable parasitic etalon effects that, because of the high amplifier gain, lead to multiple noise spikes in the relative-intensity-noise (RIN) spectrum. Since it is difficult and time-consuming to analyze backreflections that may be induced by splices, connectors, etc. during EDFA fabrication, amplifiers must be tested for MPI after production. Except for the RIN subtraction method, the methods for determining noise figure that have been discussed will not normally detect MPI noise. For most applications, nearly any degree of MPI is unacceptable in amplifiers. The MPI noise figure of an optical amplifier is defined as:

$$NF_{MPI}\ (\lambda) = SNR_{\mathrm{out}}\ (\lambda) - SNR_{\mathrm{in}}\ (\lambda)$$

all expressed in dB, where SNR_{in} is the signal-to-noise ratio at the amplifier input and SNR_{out} is the signal-to-noise ratio at its output. It is assumed that narrowband filtering is used at the receiver input.

With a 980 nm pump and a complete erbium-ion population inversion, the ideal NF—the smallest achievable noise figure for high-gain amplifier—is about 3 dB.

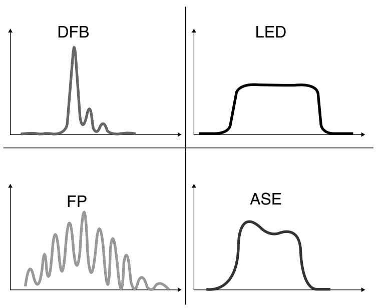


Figure 3.38 An LED, FP laser, and a DFB laser have very different bandwidths and spectral shapes.

3.5 TRANSMITTERS

Dense WDM systems owe their bandwidth advantage to the use of multiple channels at different wavelengths. All of these wavelengths must fit into the operating band of the EDFAs. If there are many channels, each must be very tightly controlled. The characteristics of the light source for each channel determine the success of this control. Even in low channel count WDM systems, compatibility with adjoining networks, potential for upgrading, and adherence to international standards all imply tight control of transmitter characteristics. The following paragraphs discuss the major requirements.

The linewidth of the laser should be narrow to allow close DWDM channel spacing. Narrow linewidth minimizes pulse distortion caused by fiber dispersion and allows narrowband filters to be used in front of the receiver to improve the signal-to-noise ratio. Also, very low residual sidebands are required to ensure that no source output interferes with any other channel.

Operation in a single longitudinal mode is necessary to minimize the generation of beat noise. The line broadening (chirp) tendency of lasers directly modulated by the drive current makes them unsuitable for dense WDM systems. External modulators that are physically integrated with the source are preferred.

Peak power, peak wavelength, spectral width, and susceptibility to chirp must stay within acceptable bounds both in the short- and long-term, as the device ages. Short-term drifts due to temperature and other ambient influences must also be sufficiently low. If not, means must be provided to detect and counteract them. Laser sources must be suitably protected if they are subject to backreflection, which can cause them to become unstable.

Laser modules themselves are expensive, and their replacement can involve very costly and complex mechanical disassembly and re-alignment of components that are critical to the effective operation of a link. A long, stable life is evidently a prime requirement.

Energy not converted to light results in heat that affects the characteristics (wavelength and power) of the laser and creates instability. Thermoelectric coolers are generally used to maintain the laser sources at the desired temperature.

The transmitter must remain within the system channel bandwidth and should not drift in wavelength over time. The typical spectral drift in DFB lasers is less than 0.1 nm/°C and 0.01 nm/mA; the sensitivity to case temperature is typically 0.002 nm/°C and the aging drift should typically be no greater than 0.001 nm/year. The output power should be stable over time and side modes should be suppressed to better than 40 dB below the peak output. The laser is optically isolated and should not be affected by spurious reflections from the transmission medium, especially those coming from the first in-line EDFA.

The modulator should provide minimal laser chirp, ideally less than its modulation bandwidth (in other words, the line broadening should only be due to the modulation of the signal itself). Its insertion loss should be as low as possible.

We will take an individual look at the main transmitter components: the optical source used and the modulator.

3.5.1 Optical Transmitters

The optical source must meet a number of requirements. Mechanically, of course, its physical dimensions must be compatible with the size of the fiber-optic cable being used, and appropriate means must be available to couple this power into the fiber-optic cable with high efficiency. To avoid assembly problems in DWDM systems, where a number of transmitter modules will necessarily be used in close proximity, the source should be physically small, lightweight, and extremely reliable.

The source must be able to generate enough optical power to meet the bit error rate (BER) requirement in the particular application, and its output must be easily modulated at the required rate. Linearity can be important if output power is to be varied or when analog modulation is performed.

Although both the light emitting diode (LED) and the laser diode (LD) meet these requirements to a useful extent, the power and bandwidth advantages of the LD make it the source of choice in demanding WDM systems.

Sources to be used in a 2.5 Gb/s system can, in general, be directly modulated by their current. Sources to be used at higher transmission rates require separate modulators to minimize chirp. In either case, appropriate means must be provided to efficiently couple the output energy to the next component, the modulator, and to the transmission line. Heat-dissipating measures, i.e., thermometers, are usually required.

3.5.2 Transmitter Modulators

Light from the optical source must be modulated with the bit content of the information the channel carries. This modulation should be sufficiently linear to avoid generation of excessive harmonics and intermodulation distortion. These could lead to deleterious effects elsewhere in the network, or interfere with the extraction of information (demodulation) at the receiver end of the link.

Although a number of modulation techniques are available, intensity modulation is most common. For rates of up to about 2.5 Gb/s, direct pulse modulation of the operating current is used. For higher rates, a rapidly opened and closed optical gate provides an on/off light signal.

3.5.3 Wavelength Lockers

Lockers are devices that provide an error signal proportional to the wavelength shift of a laser source from a desired ITU grid value. Most locking techniques are based on comparing the optical power transmitted by narrowband optical filters whose central wavelengths straddle the reference value.

3.6 RECEIVERS

The function of the receiver is to provide the demodulator with the cleanest electrical signal it can extract from the optical signal it receives. Receiver performance is measured by the bit error rate (BER) it delivers. The result, for a given received signal, depends, in turn, on the receiver's sensitivity, its bandwidth, and any noise it adds to the signal before demodulation.

The overall performance of a receiver is described by its sensitivity curve, which plots the BER as a function of optical power received for a given data rate.

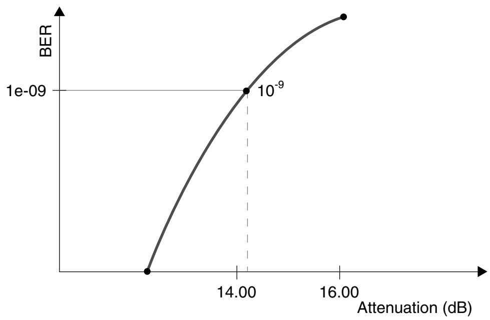


Figure 3.39 Typical BER screen result with the important 10^{-9} mark.

Such a curve applies to a particular set of operating conditions and, thus, incorporates the effects of bandwidth, detector noise, and demodulation techniques.

Mechanical and environmental factors must also be considered, including size, weight, power needs, and possible temperature sensitivity (especially for avalanche photodiodes), as well as ease of servicing and replacement.

3.7 DISPERSION COMPENSATORS

We have already discussed how chromatic dispersion broadens signal pulses over a fiber link and have mentioned dispersion compensation as a possible remedy.

A dispersion compensator is often a length of optical fiber made of a material that displays anomalous chromatic dispersion at the wavelength of operation. Therefore, its dispersion is negative, while that of the principal fiber medium is positive. The magnitude of the dispersion per unit length in the compensator is usually much greater than that in the fiber to be compensated, so a short length of dispersion-compensating fiber can compensate for the chromatic dispersion of a considerable span of ordinary fiber. Dispersion compensation can also be achieved using discrete components such as Bragg gratings.

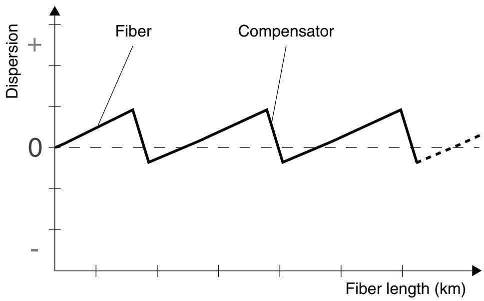


Figure 3.40 Compensation diagram

For dispersion compensation techniques to be effective, it is necessary to be able to measure the total dispersion in the fiber to be corrected as well as the dispersion coefficient of the correcting fiber. It must also be possible to check that inserting the calculated length of compensating fiber does indeed eliminate the dispersion.

3.8 SWITCHES

Switches are used in the network to rearrange the links. They allow signal re-routing and are used for configuring a path or restoring a link. They are also used in conjunction with optical add/drop muxs. The key parameters that determine the performance of switches and, thus, their suitability for particular network applications, are

- insertion and coupling loss
- return loss
- PDL
- crosstalk and isolation
- reliability
- switching time
- stability

3.9 ATTENUATORS

The main application of attenuators in WDM systems is to tailor the power in each channel so that the power delivered to the first in-line EDFA is spectrally flat. Consequently, flatness over a channel width is a key performance parameter. Other parameters, whose relative importance depends upon the specific system applications, include

- stability
- reliability
- ORL
- PDL
- PMD
- accuracy
- repeatability
- insertion loss

3.10 ISOLATORS

Isolators are used in situations where backscattered light or the light reflected from an interface can degrade the performance of a sensitive component such as a DFB laser. The following are the critical parameters that determine the performance of isolators:

- Wavelength-dependence, especially for so-called narrowband isolators that are designed to operate in a spectral range narrower than 20 nm. Isolators are described both by a peak reverse-direction attenuation figure and by the bandwidth for which the isolation is within 3 dB of the peak value.
- Small insertion loss <1 dB in the forward direction, but typically in excess of 35 dB (single stage) or 60 dB (double stage) in the reverse direction, and low polarization dependence
- Polarization mode dispersion (PMD). Isolators are constructed using highly-birefringent elements, and are very prone to PMD (typically 50 to 100 fs), especially for single-stage designs. Double-stage isolators can be designed so that the PMD induced by the first stage is largely canceled by the second stage.
- Polarization dependent loss (PDL), which also degrades the performance of optical isolators
- N/=on-PMD multipath interference dispersion (an additional dispersion effect caused by spurious reflections in the device or unbalanced optical paths)

People involved with DWDM technology have very direct questions regarding DWDM testing. They need to know what to test, how to test, and where to test. In this chapter, we have answered the first question. The second one will be addressed in the next chapter, where test methods for component characterization are described. The last question is dealt with later on as part of installation and commissioning.

WDM GUIDE

CHAPTER 4

COMPONENT TESTING AND QUALIFICATION

COMPONENT TESTING AND QUALIFICATION

4.1 OVERVIEW

A whole new family of sub-systems and components is needed to permit and facilitate the development, manufacture, and deployment of systems using dense WDM technology. As is the case for any evolving technology, new terminology, specifications, and measurement techniques have been developed to describe each of these elements. This section describes the key measurement and testing techniques used to characterize the major network elements of a dense WDM system.

The components of a DWDM network include transmitters (including lasers and modulators), receivers (including filters and detectors), transponders, optical amplifiers (including boosters, in-lines, and pre-amplifiers), multiplexers, demultiplexers, optical add/drop multiplexers, routers and switches, fibers, cables, and compensators. As dense WDM technology moves to closer and closer wavelength spacing, the requirements and performance specifications for wavelength-selective components become increasingly demanding and test procedures become correspondingly complex.

A device under test (DUT) must be fed with an optical signal that has known characteristics, and its output must be analyzed to determine in detail, how it differs from the input. Both the measurement source and the analyzing instrument should be selected to test and analyze the intrinsic value of the parameter being measured without introducing extraneous effects. (See Figure 4.01)

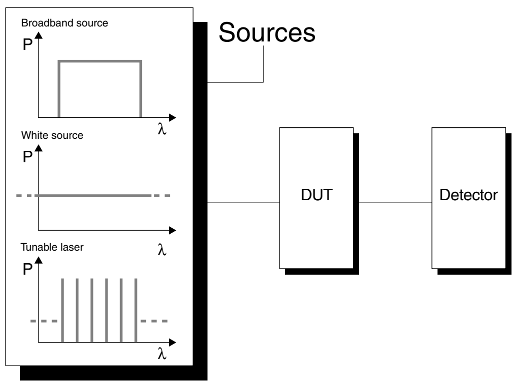


Figure 4.01 Test setup using perfect sources

In real life, such ideal sources—infinitely variable in wavelength, able to produce spectrally pure multiple wavelengths, perfectly stable—and measuring instruments—high resolution and accuracy, stable calibration, infinitely tunable—do not exist. The test engineer must select equipment carefully, to ensure that the desired parameter is actually being measured and that the measurement technique itself does not introduce undesirable side effects.

4.2 OPTICAL SOURCES FOR TESTING

Several characteristics are important in the choice of an optical source to be used to test passive components. Adequate power must be available so that reliable measurements can be made on high-loss components, or at the extreme transmission limits of wavelength-sensitive devices where two or more signals may have to be compared, each attenuated by at least 40 dB.

Broadband sources are required in a measurement, and these should be reasonably flat over their spectral range to minimize corrections. Non-coherent broadband sources, including near-black-body sources such as high-intensity incandescent lamps, LEDs, and amplified spontaneous emission (ASE) sources, are available covering all the spectral ranges of interest both for WDM and more traditional components. Because their output is non-polarized, or nearly so, measurements made will minimize any polarization dependencies.

ASE sources provide high-intensity light over wide wavelength bands, but they must be selected to display a spectral power distribution as flat and as uniform as possible over the wavelength range of interest.

Requirements for narrowband sources are usually met by external cavity lasers (ECLs), whose precise lasing wavelength can be adjusted by mechanical means with accuracies of a few picometers over a spectral range exceeding 120 nm. Such sources are strongly polarized and very nearly monochromatic, making them suitable for demanding wavelength-sensitive measurement situations. Spontaneous emission can be controlled with appropriate filtering, and their noise performance can be adequate for low insertion loss measurements. New tunable laser designs are now available, including the fiber laser, which combines the advantages of the EDFA and narrow tunable filtering technologies. It offers very low baseline noise compared to the ECL (lower than 65 dB).

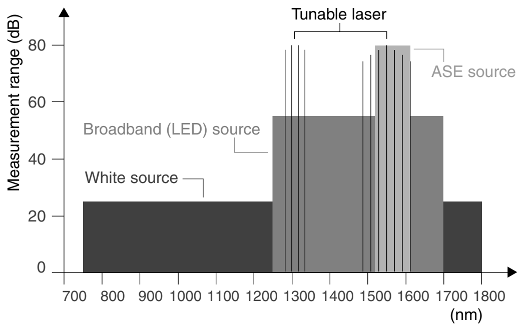


Figure 4.02 Spectral emitting region and dynamic range of different type of sources

Figure 4.02 indicates the spectral regions in which each of the source types discussed is particularly applicable.

4.3 RECEIVERS FOR TESTING

Testing WDM components almost invariably involves addressing the wavelength and loss sensitivity of the device, so measurement techniques usually include either a wavelength-selecting detection system with a broadband source or a broadband detection system with a tunable light source.

The desirable characteristics of receivers in test applications are analogous to those for sources. Broadband receivers (or power meters) should be spectrally flat. They should respond linearly over as wide a dynamic range as possible, and they should contribute as little noise as possible to the measurement. Their polarization sensitivity should be as low as possible.

4.3.1 Power Meters

Broadband optical power meters generally use photodiode detectors that are sensitive ove r spectral ranges appropriate to the wavelength bands in common use (they may use plug-in modules to switch bands). Their wavelength response is smooth and usually reasonably flat (especially so for InGaAs detectors), and they can be calibrated to ensure measurement accuracy at any wavelength. Power meters—especially thermoelectrically cooled models—are stable and they generally offer sufficient dynamic range for the most demanding attenuation measurements. They have small sensitivity to polarization.

4.3.2 Optical Spectrum Analyzers

Several of the techniques that may be used in an optical spectrum analyzer (OSA) to discriminate wavelengths are shown in Figures 4.03-a-b-c. In one technique, mutual interference in the two arms of a Michelson interferometer results in an output signal that varies as the length of one of the two optical paths is changed by moving a mirror. The resulting electrical output signal can be analyzed (digitally, using fast Fourier transform techniques) to obtain the spectrum of the input energy. Another approach (Figure 4.03-b) uses a moving dispersive grating to sweep all the wavelengths present across an output slit (in the arrangement shown, additional resolution is gained by passing the beam through the system twice). A third approach (Figure 4.03-c) is similar, but the grating is fixed: it spreads the spectral content of the input beam over a number of discrete detectors or a movable single detector.

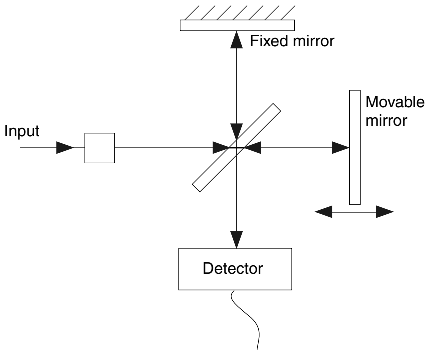


Figure 4.03-a The interferometric method uses a movable mirror to create interference between the two divided signal paths.

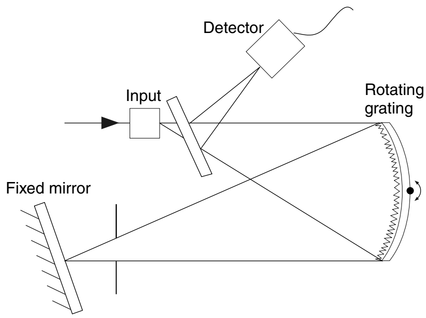


Figure 4.03-b The rotating grating sends the mirror different wavelengths during the rotation.

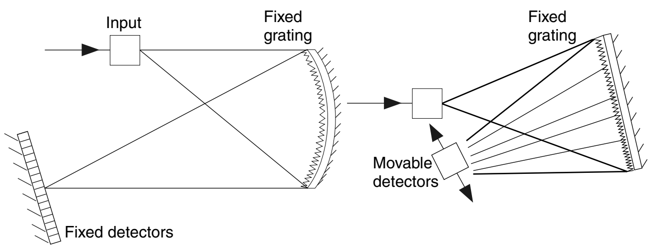


Figure 4.03-c The fixed grating divides the input into primary elements before reaching the detectors.

Important criteria for OSA's include

- Dynamic range: the ability to measure a wide range of signal strengths, needed, for example, in characterizing the band shape of an optical channel, in which sideband anomalies that are 50 dB down may be important.
- Sensitivity: the ability to measure optical signals of very low intensity.
- Resolution bandwidth (RBW): the ability to resolve closely spaced wavelengths, needed to investigate the detailed properties of DWDM channels—a parameter of increasing importance as higher channel densities come into service.
- Accuracy: the ability to indicate exactly and correctly the measurement wavelength and power.

The first two criteria depend mostly on the detector used, and, therefore, they can be tailored to a certain extent to meet particular measurement needs. Resolution is the strong point of a grating-style OSA: gratings can be produced to meet the demanding resolution needs of DWDM testing. Accuracy is the grating OSA's Achilles heel: absolute wavelength calibration depends upon the positioning of many mechanical components—the rotational position of the grating, in particular—so it is difficult to ensure its constancy. Some form of outboard calibration—the sharp absorption lines of an acetylene cell, for example—is usually used to provide the reference needed to convert the OSA's intrinsically high relative accuracy to an acceptable absolute value. Alternatively, the wavelength of a tunable laser (in particular a narrow linewidth ECL) can first be accurately determined with a wavelength meter and then the laser used to calibrate the OSA.

Although the design parameters governing the performance of an OSA can, to a degree, be tailored to specific measurement needs, the criteria we have discussed interact strongly. Increasing spectral resolution, for example, means using a grating of higher dispersion, or collecting the diffracted light through a narrower slit. Both steps decrease the amount of light collected in the case of a signal of equivalent or larger bandwidth. Modulated signals can also reduce sensitivity and, in many instances, the dynamic range.

4.3.3 Wavelength Meters

The second wavelength-selective receiver, the wavelength meter, is essentially a Michelson interferometer (Figure 4.03-a). As the moveable mirror in the reference arm of the interferometer is displaced, interference between the light in the two arms will cause the signal captured by the detector to vary: sinusoidally for monochromatic input light, in a more complex pattern for a mixture of input wavelengths. The output electrical signal is "deconvoluted"—usually using fast Fourier transform (FFT) algorithms—to reveal the input spectrum.

The wavelength meter may be judged by the same criteria as used for the OSA, but its strengths and weaknesses are quite different. First, because all the source energy is used all of the time, measurements across a spectral region or at several different wavelengths are carried out truly in parallel, unlike the OSA, whose detector only looks at a very small spectral region at any one time. It is thus well suited to broad, fast channel measurements. Highly accurate relative wavelength information is extracted from the signal by computational means—the FFT—and an absolute wavelength reference—a HeNe laser—is usually built into the instrument. Therefore, overall absolute accuracy is high, better than 0.005 nm; certainly adequate for detailed verification of channel positioning in 80-channel WDM systems, for example.

The wavelength meter is weakest in its ability to deal with large dynamic ranges (limited to slightly over 30 dB; inadequate to characterize dense WDM channels properly) and with low-level signals. Nevertheless, its intrinsic wavelength accuracy and its ability to scan entire wavelength bands simultaneously make it a very useful complement to the OSA. The wavelength meter, designed with its own internal reference, is more likely to maintain calibration with heavy use.

4.4 TYPICAL COMPONENT TESTING COMBINATIONS

There are many ways broadband and tunable sources and receivers can be combined in real-life measurement situations to achieve the wavelength-dependent measurements needed to characterize DWDM components. A discussion of some of the common situations follows, using the very demanding task of multiplexer (or demultiplexer) testing as an example.

First, a few general principles need introduction. If only one of the source/receiver pair is narrowband, then obviously that element will determine the resulting spectral resolution. If both are narrowband, however, then either can be the dominant, depending on the technique used.

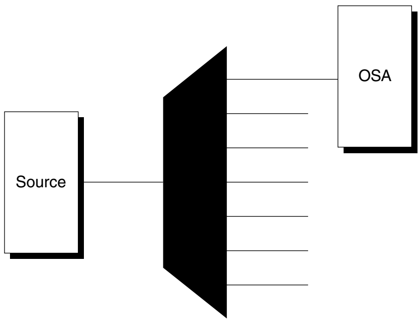


Figure 4.04 The OSA located after the mux characterizes the device.

4.4.1 Multiplexers/Demultiplexers

Multiplexers and demultiplexers are important components of DWDM systems, and their bandwidth, crosstalk, insertion loss, return loss, isolation, and polarization properties are critical to network performance. The desirable spectral attributes of several other DWDM components are very similar to those needed in multiplexers and demultiplexers (or, more particularly, in individual mux/demux channels), and test procedures for these devices are included in this section.

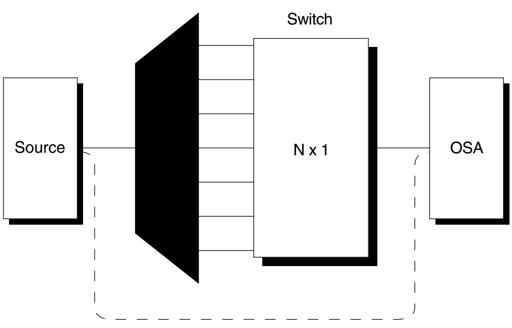


Figure 4.05 The ASE source shoots through the mux while the OSA gets the signal for each output port.

Insertion Loss

Figure 4.05 shows a typical setup to determine the insertion loss of a DWDM mux/demux. A flat, broadband ASE source is used, whose output covers the DWDM band. The OSA output will, therefore, directly indicate the shape of the insertion loss. A suitable reference measurement, made by connecting the source directly to the OSA, can be used to convert this relative loss curve to an absolute one. In this case, the spectral resolution of the measurement is limited by the OSA RBW and its shape.

The 1xN switch is included to ease or even automate the testing of multichannel devices. All measurement components must have low polarization state sensitivity.

Polarization Dependent Loss

Spectral polarization dependent loss (PDL) can be measured using a similar setup: a broadband source and an OSA. A number of OSA scans must be made at different, randomly chosen polarization states. The difference between the minimum and maximum loss measured is the PDL. Software is usually available for the calculation. The accuracy of the final measurement increases with the number of scans made.

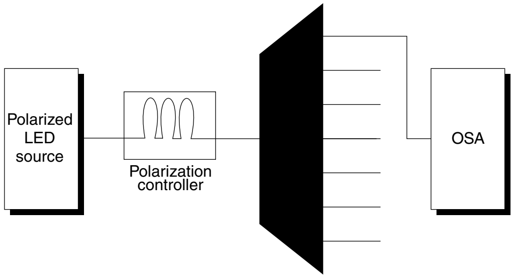


Figure 4.06 In this setup, a polarization controller is added to measure PDL.

PDL is also often measured using a single-wavelength source, a polarization controller, and an OSA or power meter, as shown in Figure 4.06. The polarization controller varies the signal state of polarization rapidly and quasi-randomly, while the OSA or power meter compares the optical signal level sent to the device under test to that transmitted through it. Both PDL and IL can be determined at a single wavelength in 2 to 5 seconds depending on the acceptable level of uncertainty.

For many dense WDM components—filters and Bragg gratings, in addition to multiplexers and demultiplexers—PDL must be measured as a function of wavelength. To accomplish this, a tunable laser source can be substituted for the fixed source in the configuration shown.

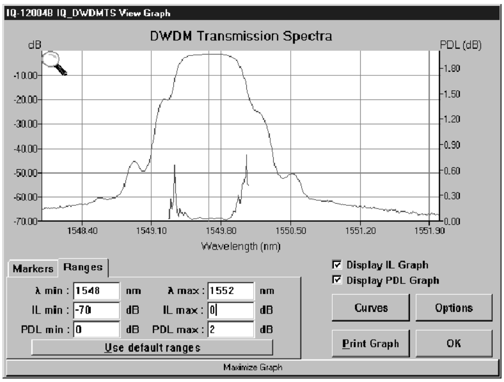


Figure 4.07 PDL can be measured across the bandpass of a multiplexer channel.

Values of PDL common to many dense WDM components are very low, so great care must be taken to compensate for any PDL introduced by the measurement technique itself. Available PDL-measurement modules usually include a reference channel to eliminate the need for any manual compensation.

Mueller-Stokes PDL Measurement Method

It is possible to represent an optical wave as mathematical vectors called Stokes vectors (S). The elements constituting the vectors are power measurements easily obtained with a source, polarizer, and detector. The input signal (input vector) will be changed by the DUT and will give a new Stokes vector. The complete DUT effect on the polarization of light will then be represented in the Mueller matrix. This 4x4 matrix represents the transmission characteristic of the DUT.

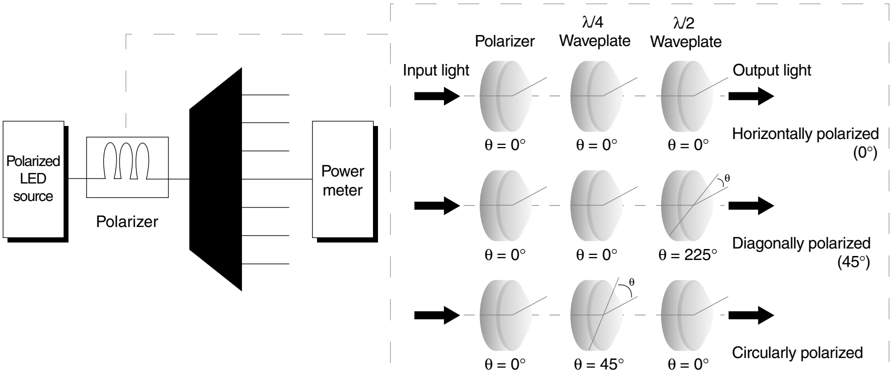


Figure 4.08 Three different waveplates are used to create different polarization states.

Four different input polarization states are needed to determine the four parameters of the Mueller matrix. The polarization controller (Figure 4.08) generates those four polarization states. After a reference measurement between the polarizer and the detector, the DUT is inserted after the polarizer. The power is measured by the detector with respect to every polarization state, and then the Mueller element is calculated with the transmission coefficient (*T*). Since the Mueller element is related to the DUT maximum and minimum transmission coefficient, the PDL is obtained with:

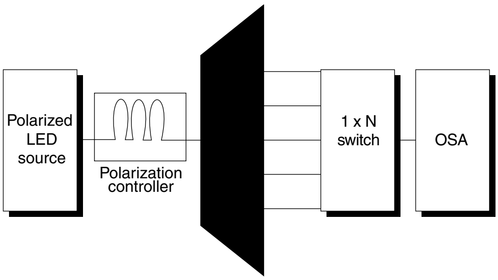


Figure 4.09 Polarization dependent bandwidth measurement

$$PDL\ (\mathrm{dB}) = -10 \log\left(\frac{T_{\min}}{T_{\max}}\right)$$

This method is fast and requires low-cost equipment. PDL could also be measured as a function of wavelength by using a tunable laser in sweep mode. However, the Mueller-Stoker method is sensitive to patchcord manipulation. This method is ideal for automated test systems such as described in section 4.5.

A related parameter, polarization dependent bandwidth (PDBW), can be similarly measured. This spectral characteristic of an optical filtering device is the difference between the minimum and maximum bandwidth when the channel is measured under all states of polarization: PDBW = $BW_{max} - BW_{min}$ (see Figure 4.10). Measurement accuracy increases with the number of polarization states examined, but there is obviously a practical limit to this number; several minutes of continuous measurement normally suffice.

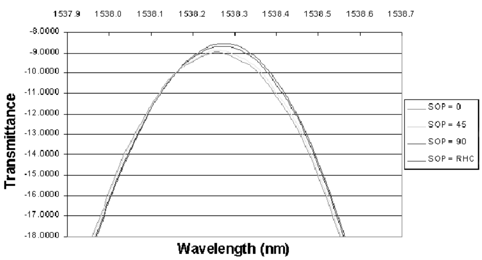


Figure 4.10 Bandwidth measurement dependent on polarization

polarization dependent central wavelength (PDCW)—the change in the central wavelength of a filter passband under different states of polarization (Figure 4.11)—can be measured similarly. Certain components exhibit high values of PDCW (1 nm or more), which can seriously impact the performance of a network.

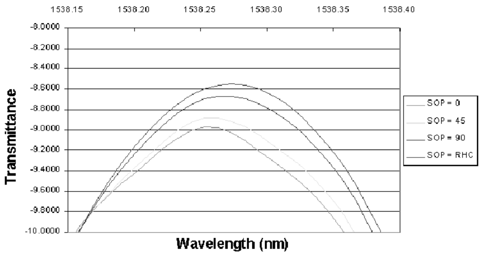


Figure 4.11 Result of polarization dependent central wavelength

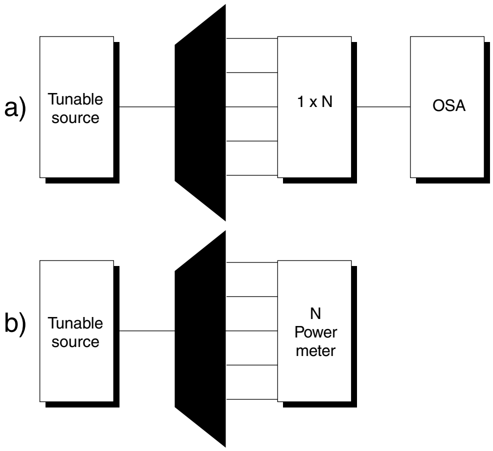


Figure 4.12 Crosstalk can be measured using a) a tunable laser with on OSA or b) a tunable laser with power meters.

Crosstalk

Crosstalk between DWDM channels is measured by replacing the ASE source used in the previous setups with a narrow-linewidth, tunable laser source. Repeated OSA scans are performed on all of the multiplexer or demultiplexer channels while stepping the tunable source through the wavelength region of interest at the desired resolution. The measurement resolution is determined by the tunable-laser steps, not by the OSA, but loss curves with a resolution as high as 0.001 nm can be obtained with excellent dynamic range. The procedure is time-consuming, however, especially for multichannel DUTs, unless a multichannel power meter is also available. A wavelength meter should be used for calibration.

Optical Return Loss

Optical return loss (ORL) is measured using the combination of a source, coupler, and photodetector, often referred to as an optical continuous wave reflectometer (OCWR). After a calibration step in which a component with a known reflectance is substituted for the DUT, the DUT is inserted. The detector then measures the power it reflects, a correction factor based on the calibrating step is applied, and the ORL is displayed. With a high-power, non-coherent optical source and a high-sensitivity, high-resolution detection system, return losses of 70 dB or lower can be detected and measured with this configuration.

ORL can be wavelength-dependent. If this dependence must be characterized, either a high-power, moderate-coherence tunable laser or a wide-band source (an ASE laser) can be used as the source in the configuration just described, with an OSA used as a detector (Figure 4.13). Because of the limited dynamic range of an OSA, however, it will be difficult to track ORLs lower than about –40 dB.

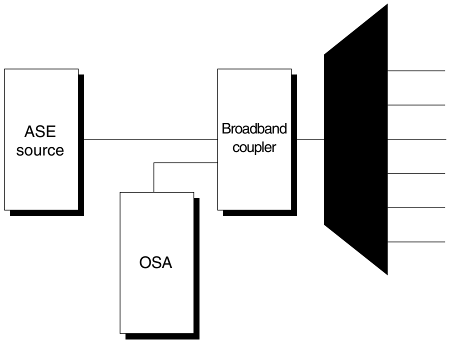


Figure 4.13 Wavelength-dependent ORL measurement

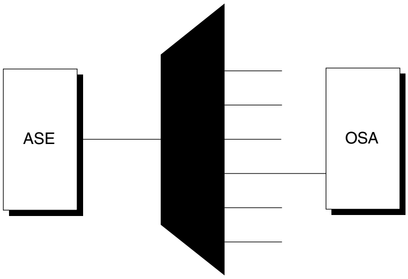


Figure 4.14 This very simple setup using an ASE source and an OSA provides bandwidth characteristics.

Bandwidth

Optical bandwidth is measured using a procedure very similar to that used to measure insertion loss. The spectral characteristics of the measurement system can be removed with a reference measurement. A typical setup is illustrated in Figure 4.14.

If the band edges must be characterized precisely—to a spectral resolution less than 0.1 nm, for instance—an alternative configuration should be used, with a tunable source and a power meter or OSA (Figure 4.15). Here, the spectral resolution is limited by the tuning resolution of the source (probably about 0.01 nm), and the dynamic range by the sideband rejection of the tunable source. The sensitivity is determined by that of the power meter (perhaps –100 dBm).

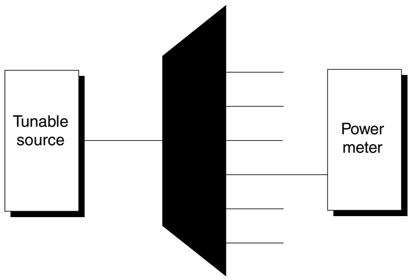


Figure 4.15 Alternative bandwidth measurement with a tunable source and a power meter

COMPONENT TESTING AND QUALIFICATION

Many of the measurements already discussed share test equipment in similar configurations, so they can readily be combined. This approach is particularly attractive when test methods are being automated.

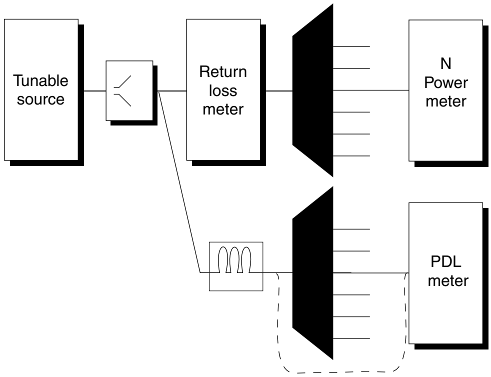


Figure 4.16 Automated test setup that measures PDL insertion loss and ORL

The configuration shown in Figure 4.16, for example, uses a low-noise tunable laser source (TLS) that scans across the wavelengths of interest, while at the same time multichannel power meters acquire transmission data for each channel of the DUT. With this type of instrument setup, the measurement time is independent of the number of device channels. This particularly suits automated testing of multichannel components. The upper portion of the figure indicates how incorporating an optical switch in the measurement setup can allow other devices to be prepared for testing while a particular test is going on, using much of the same equipment.

The resolution of the measurement is determined by the TLS, and the measurement dynamic range is determined by the spontaneous emission (or noise) of the source, and the dynamic range and the sensitivity of the power meter. By using a TLS, such as a fiber laser, a dynamic range of more than 65 dB is easily attained. The diagram also shows how ORL and PDL measurements are integrated into the process. With this arrangement, it is easy to add additional power meters to deal with devices having many channels.

Polarization Mode Dispersion (PMD)

A PMD test set is used to measure PMD, and four methods—the Jones Matrix Eigenanalysis (JME), the Poincaré Sphere Analysis (PSA) method, the Wavelength-Scanning/Fixed-Analyzer (WSFA) technique, and the Interferometric Method (IM)—can be used. JME and PSA are polarimetric methods that obtain the differential group delay (DGD) as a function of the optical frequency or wavelength, while IM and WSFA measure PMD in the time domain and are particularly suitable for characterizing broadband devices. Other methods have also been proposed: modulation phase shift, for example. The methods are discussed in more detail in a later section that covers PMD in optical fiber.

4.4.2 Switches

Optical switches are tested using a source and a multichannel power meter, along with a suitable switch controller (see the configuration shown in Figure 4.17).

Switching speed is often a characteristic of considerable interest, so a high sampling rate and rapid stabilization are essential qualities in the power meter. If tests are to be automated to any extent, the power meter must be able to recognize, and be triggered by, the electrical signals that drive the switch. Appropriate read-out facilities are also needed for both switching rates and interchannel crosstalk.

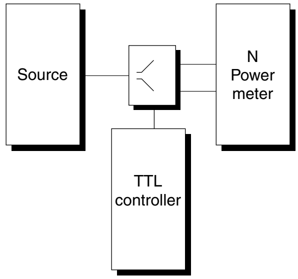


Figure 4.17 The high-speed power meter makes it possible to test today's switches.

The loss, crosstalk, and transient behaviors of switching elements can be critical in network applications, so the instrumentation used to characterize them must offer very high dynamic ranges at very high measurement rates.

4.4.3 Optical Sources

The output power and central wavelength of laser diodes are parameters that are critical in WDM applications, and manufacturers need automated or at least semi-automated methods to measure them. Wavelength meters and fast-sampling, fast-responding power meters, coupled with appropriate optical switches, expedite these measurements.

The test configuration in Figure 4.18 performs a fast scan of output power versus laser input current for four devices at a time using a four-channel power meter. A second wavelength measurement at one or more specific power levels can then be performed using a 1x4 optical switch.

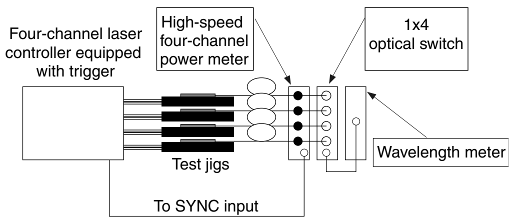


Figure 4.18 Laser source characterization

The measurement sequence is

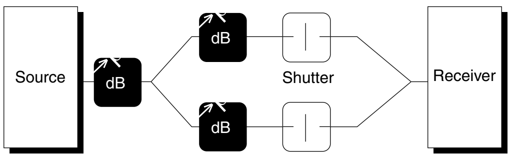
1. A controller trigger signals the start of a current ramp applied to all the lasers, starting just below the expected lasing threshold.
2. The same trigger starts sampling with the power meter at the input channels. If the rate of change of the drive current is constant, output power can be accurately correlated with input current throughout the scan. With high-speed power meters, many thousands of data points can be acquired in a second, enough to provide adequate resolution in the threshold region, even in a short overall acquisition period.
3. After the output-versus-drive-current characteristics (also called L-I curve) have been obtained, the controller can fix the current of each device at a specific value, slightly above the threshold, that represents a typical operating power level. The wavelength meter can then be used to accurately measure the wavelength.

Determining the PDL of a wavelength locker is particularly demanding. The configuration generally used combines a tunable laser source, whose wavelength can be tuned anywhere in the ITU-T wavelength grid, and a polarization controller to vary the source polarization over all possible states.

Because of the very high wavelength accuracy demanded of wavelength lockers, which are the primary wavelength standard in an operating WDM network, a wavelength meter is generally included in the measurement setup to ensure that tests are performed at exact ITU-T grid wavelengths. The maximum change in the error-voltage signal for all states of polarization yields the polarization dependency of the locker (in percent or dB).

4.4.4 Receivers

Linearity testing is needed for semiconductor photodetectors, which saturate as the input power increases. Biasing the p-i-n junction improves this behavior, but increases dark noise, which thus limits the measurement of very low power levels. Various measures taken to increase dynamic range (trans-impedance pre-amplifiers, automatic gain control circuits, or automatically selected fixed amplification steps), all tend to increase non-linear behavior, especially at very low signal levels or if discretely stepped amplification schemes are used and are inadequately calibrated.



The configuration beside shows the typical setup of a linearity test using the superposition method. This method is easily automated.

Figure 4.19 Automated setup used to characterize receiver sensitivity and detection time

4.4.5 Optical Fiber Amplifiers

Many characteristics of an erbium-doped fiber amplifier (EDFA) must be determined before the device can be integrated into an effective network design. Gain is the most evident, and it must be measured using the channel configuration for which the device will be used. Gain flatness must be determined, and appropriate equalization steps taken to ensure equal treatment of all channels throughout the network. Gain must also be suitably flat within individual channels. Small-signal gain must also be determined over the entire wavelength band.

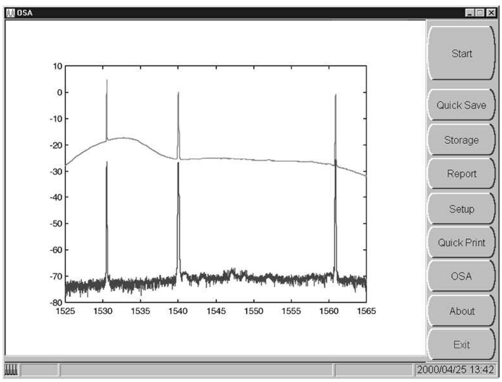


Figure 4.20 Example of an optical amplifier signal

Noise in an EDFA originates from amplified self-emission, which must be measured across the operating spectrum to determine signal-to-noise ratios for each operating channel. The sensitivity of the device to backreflections must be determined, and appropriate measures made of the common polarization phenomena (PMD, PDL, and polarization dependent gain, or PDG).

To determine the spectral dependence of an EDFA, a tunable laser source is connected to its input through a variable attenuator. A power meter is connected to the EDFA. An InGaAs or Ge detector able to measure power levels up to +25 dBm is generally used, but care must be exercised when a Ge detector is used in the 1550 nm window because its spectral response varies sharply in this region. Small-signal gain is measured, at each wavelength, by reducing the input power to less than –30 dBm, using the variable attenuator. Input power is then increased and the gain continually calculated, watching for the point at which the gain drops by 3 dB, i.e., the 3-dB compression point, which usually marks the ultimate operating point.

The measurement described offers only an approximation to the complete spectral-gain characteristics of the device: it does not take into account "gain sharing" when all the signal channels are present. It does, however, provide performance figures adequate for estimating of network loss budgets.

To obtain a more complete description of spectral gain, a number of sources must be provided, enough to duplicate the channel population expected in the ultimate application. The resulting EDFA output signal can be examined using a multichannel power meter, OSA, or wavelength meter. The procedure outlined for a single source is followed, but for each channel in turn. Channels other than the one being measured should be carrying power typical of eventual operating conditions.

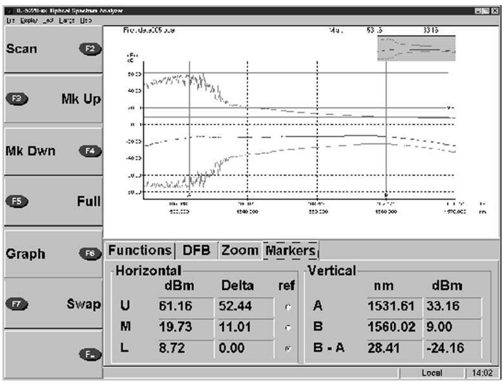


Figure 4.21 Insertion loss figure with input and output results

For some applications, it is important to know the insertion loss produced by a passive EDFA, one not being pumped optically. This parameter can be measured, as a function of wavelength, using a broadband source such as an LED or an ASE laser, together with an OSA detector. The physical arrangement and the test procedure are analogous to those just described for spectral gain measurements and the result indicates the loss to be expected should the amplifier fail. A typical result is shown in Figure 4.21.

The return loss of EDFAs is often wavelength-dependent, because of the filters, circulators, or other components that are included within the amplifier module. A tunable laser source can be used, along with a return loss meter, to characterize this spectral dependence. Both are connected to the EDFA input and the device is not pumped (Figure 4.22-a).

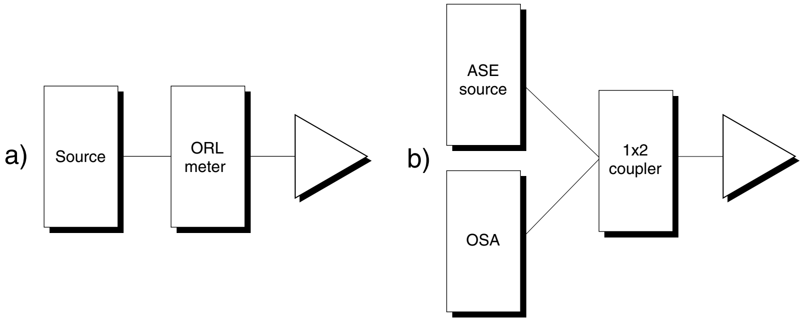


Figure 4.22 Two different setups used to measure ORL

Alternatively, a broadband source can be used—an ASE source, for example—and an OSA in a similar configuration, using a 1x2 coupler (Figure 4.22-b).

A complete description of the behavior of an EDFA that is amplifying a number of channels must take into account its gain-sharing property and, particularly, the differences in this property across the WDM spectral region. An active EDFA will divide its gain among the number of channels presented to its input. The EDFA output power is constant, so if one of these input channels is removed, the gain applied to the remaining signals must change in order to maintain the output power. This redistribution of gain will be slightly different, depending on the change of the input spectral content, i.e., on which input channel was removed.

Figure 4.23 shows a test setup to measure this effect—suitable sources representing each input channel multiplexed to the EDFA input, probably through a spectrally flat variable attenuator used to adjust the total power to a value typical of a network application. An OSA analyzes the EDFA output. The spectral gain redistribution characteristics of the EDFA and the stability of the spectral flatness it delivers are measured by extinguishing the source lasers in turn, one by one, and observing the distribution of output power to the remaining channels.

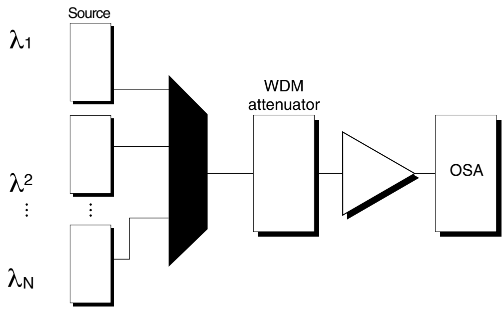


Figure 4.23 The OSA measures the spectral gain redistribution of the EDFA as a function of attenuated input signals.

This type of measurement lends itself well to automation, and test-set modules are available to perform the appropriate measurements and analyze their results.

Backreflections are yet another potential disturbing influence on EDFAs.

Every active device in a network is subject to backreflections: power reflected unintentionally from components farther along the link. This reflected energy may affect such parameters as continuous power stability, wavelength stability, spectral broadening, and multi-path interference. Although backreflection affects EDFAs in particular, tests similar to the following may occasionally be called for to characterize other devices.

The setup in Figure 4.24 tests the sensitivity of the power and wavelength characteristics of devices to backreflection.

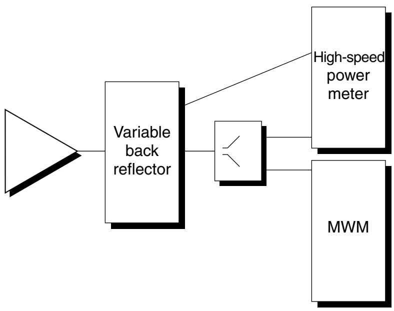


Figure 4.24 The high-speed power meter detects light reflected back to the EDFA.

By setting the variable back reflector to the maximum level likely in real life (the reflectance of a glass-air interface: 4% or –13.9 dB), one can check for fluctuations in the power and wavelength characteristics of the DUT, and thus set confidence limits on its isolation behavior in actual use. The optical signal-to-noise ratio of a typical wavelength meter is adequate to detect the presence of secondary peaks or wavelength shifts of 1 pm.

The noise figure of an EDFA determines such cost-critical network characteristics as the input power requirements and allowable repeater spacing. The accurate measurement of noise figure is complicated by the fact that the major contributor to noise, amplified spontaneous emission (ASE), varies with the signal level, so simple methods of measuring noise figure that are adequate in most electronic applications—measuring the output in the absence of an input signal—cannot be used. There are four common ways to overcome this difficulty: three optical and one electrical.

The optical methods are interpolation, polarization nulling, and time-domain extinction.

Interpolation involves measuring the amplifier output over a broad spectral range, with a signal present. The ASE within the signal bandwidth is estimated by interpolating output levels just outside it (Figure 4.25).

But if the source used in the measurement has appreciable ASE noise at the signal wavelength, it will be amplified and will be indistinguishable from the amplifier ASE, increasing the apparent noise figure. This effect is particularly troublesome for the relatively high input powers found in booster amplifier applications, especially if the amplifier is not operated in a deep gain-saturation region.

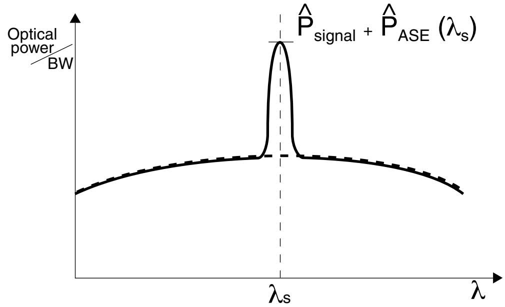


Figure 4.25 Interpolation method for EDFA noise figure determination

The source ASE, determined by other measurements, may be removed by computation:

$$P_{amp\ A\Sigma E}\ (\lambda_s) = P_{tot\ A\Sigma E} - G \times P_{\Sigma\Sigma E}$$

where $P_{amp\ A\Sigma E}$ is the true amplifier ASE at the signal wavelength λ_s, $P_{tot\ A\Sigma E}$ is the total (measured) ASE, G is the amplifier gain, and $P_{\Sigma\Sigma E}$ is the source ASE.

This simple and inexpensive method is fast and cost-effective, but it is sensitive to spontaneous emission in the source used.

A slightly more complex optical measurement method—polarization nulling—can be used to eliminate the effects of source spontaneous emission (SSE). It is based on the fact that the laser signal is polarized but the EDFA ASE is not; it is noise. It also presumes that the SSE is polarized in the same state as the source signal. A polarizer is used to remove the source signal; the signal remaining in the wavelength band measured is half the ASE (see Figure 4.26).

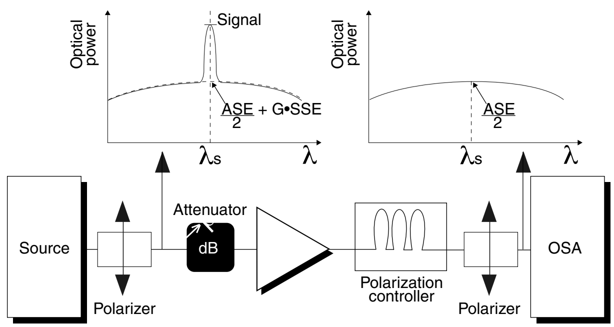


Figure 4.26 Polarization nulling method for EDFA noise figure determination

The polarization nulling method is generally not sensitive to SSE and is particularly useful in detailed ASE studies. However, it is difficult to automate and it may be affected by PMD.

The third optical method, time-domain extinction, is based on the fact that the mechanisms governing changes in carrier population in an EDFA are relatively slow, and there is a period of a millisecond or so after a signal disappears before the corresponding ASE generation ceases. Thus, the ASE in a channel bandwidth can be observed by looking at the power output in that channel immediately after the channel input signal is cut off (see Figure 4.27).

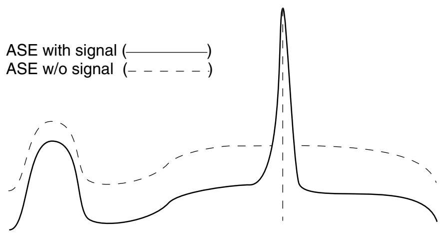


Figure 4.27 Time-domain extinction method for EDFA noise figure determination

The measurement must be made quickly—within about 10 ms—so the requirements for accurate synchronization are high. Despite its complications and cost, the method is very useful in detailed studies of other characteristics such as amplifier gain slope.

The time-domain extinction method of noise measurement is limited to EDFA amplifiers; the gain dynamics of semiconductor optical amplifiers are too rapid for the method to be useful.

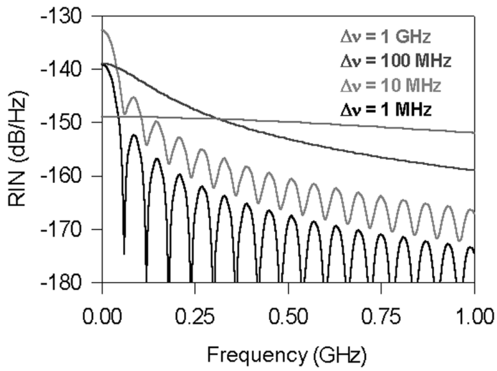


Figure 4.28 Relative intensity noise (RIN) measurement

The electrical noise-measurement method is known as relative intensity noise (RIN) subtraction, which is based on measurement of the intensity variation of the optical carrier as a function of frequency (see Figure 4.28).

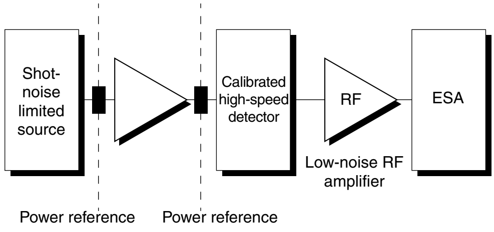


Figure 4.29 RIN subtraction method for EDFA noise figure determination

An RIN measurement looks at high-frequency variations in the intensity of a nominally constant optical carrier, evidenced as electrical signal variations. A shot-noise-limited source feeds the DUT, and a calibrated, fast, low-noise detector and RF amplifier feed its output, as a signal to an electrical spectrum analyzer (ESA), as shown in Figure 4.29.

The noise figure of the DUT, which may be an optical amplifier or a complete end-to-end system, can be determined from the "floor" of the RIN signal plotted against frequency (Figure 4.30).

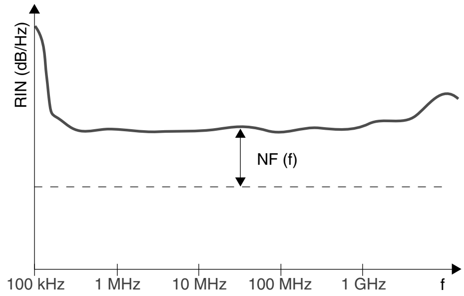


Figure 4.30 Typical RIN measurement of an EDFA

The RIN method is particularly suited to detect multipath interference (MPI) effects produced by reflections due to discontinuities or misalignment in the device; effects that are not detected by the optical methods discussed. But RIN subtraction is expensive to perform, as it requires very low noise instrumentation and extensive calibration.

Polarization Effects

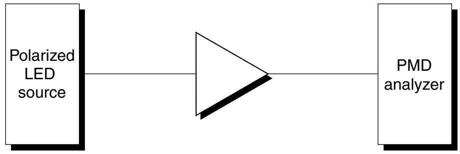


Figure 4.31 Setup used when measuring PMD with an interferometry-based PMD analyzer

A PMD analyzer based on an interferometric technique can measure the inherent PDM of a non-active EDFA module, as long as the device does not contain narrowband filters. A polarized LED source is used, at a wavelength well above the strong 1531 nm absorption band of the erbium (Figure 4.31). Such interferometric methods will also reveal multipath noise interference effects, including those caused by spurious Fabry-Perot etalons resulting from faulty components or fiber splices.

Strong MPI noise effects can be detected with a simple combination of a high-speed photodiode detector and an oscilloscope. MPI will appear as a sinusoidal signal (with harmonics) superimposed on the background noise.

Results can be improved by replacing the oscilloscope with an electrical spectrum analyzer, but even so, valid quantitative measurements require careful calibration of the entire measurement system across a wide RF frequency range.

Although an EDFA does not exhibit appreciable MPI noise in normal use, it may do so if it is exposed to high levels of reflected signal power at its output. A variable backreflector is used to test for this effect, and a well-isolated EDFA should remain stable at backreflection levels approaching 100% (0 dB).

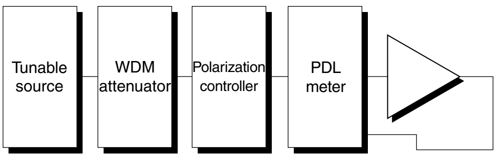


Figure 4.32 Measurement of the wavelength-dependent polarization dependent gain of the EDFA

Wavelength-dependent polarization dependent gain (PDG) is measured with a PDL test set, an appropriate source—a selection of fixed models or a tunable laser—and a polarization controller (Figure 4.32). An attenuator is often needed to maintain power levels typical of operational networks.

Bidirectional Testing

EDFAs are increasingly used bidirectionally: amplifying signals simultaneously in both directions on a link. All of the tests described can be performed in both directions, often in quick succession using a switching arrangement like that shown in Figure 4.33.

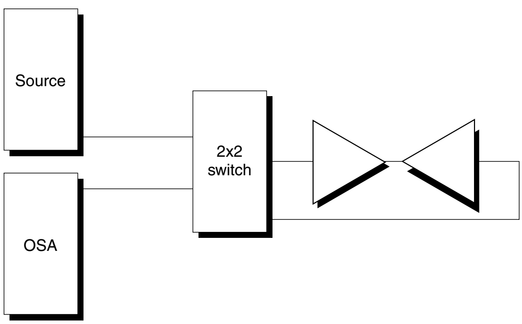


Figure 4.33 The 2x2 switch allows bidirectional testing.

4.4.6 Bragg Gratings

Devices that incorporate Bragg gratings (multiplexers, add/drop filters, etc.) employ selective spectral reflection to accomplish the necessary task, so their spectral behavior must be well characterized. A test setup similar to that shown in Figure 4.34 is usually used for multiplexers. The setup uses an ASE broadband source and a wavelength meter.

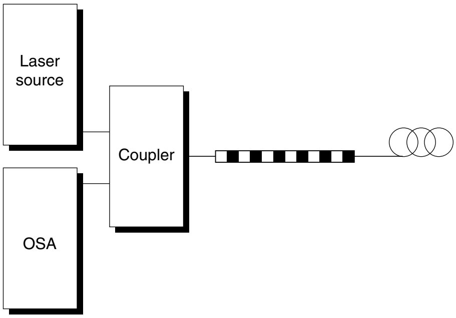


Figure 4.34 Typical setup used for Bragg grating reflectivity measurement

Typical setup loss per channel would be around 7-8 dB. The insertion loss measured would be twice the one-pass value.

4.4.7 Isolators

Optical isolators are needed throughout fiber networks to block backreflections or back-generated ASE, either of which can disrupt signal integrity. Both insertion loss and, especially, return loss must be determined throughout the wavelength band. These measurements may be carried out using either a tunable laser and a power meter, or an ASE broadband source and an OSA.

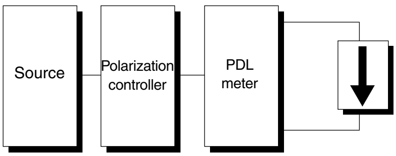


Figure 4.35 Setup for PDL measurement of an isolator

PDL can be a significant factor in isolator performance, but since it generally does not vary with wavelength across the 1550 nm DWDM window, a single measurement suffices (Figure 4.35).

Isolators are subject to other effects that are generally wavelength-dependent, however. Because common isolators split and subsequently recombine the optical path internally, they are subject to PMD. Their mechanical construction also leaves them susceptible to small defects that lead to internal etalon effects, causing multipath interference in the link. PMD analyzers are available to characterize both phenomena and to provide Pass/Fail ratings (Figure 4.36).

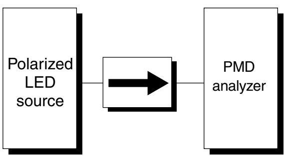


Figure 4.36 PMD measurement of an isolator

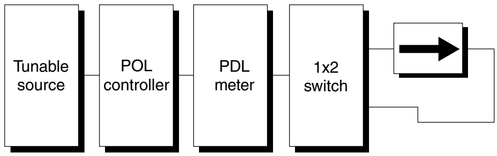


Figure 4.37 PDL is measured as a function of wavelength with this setup.

Many of the wavelength-dependent characteristics of isolators can be measured in a single test setup using a bidirectional switch (Figure 4.37).

4.4.8 Fiber

Chromatic Dispersion

Chromatic dispersion is one of the most fundamental properties affecting the performance of fiber in a communications link. Although it can be measured in a variety of ways, a method particularly suited to the investigation of behavior in the 1550 nm band is illustrated in Figure 4.38.

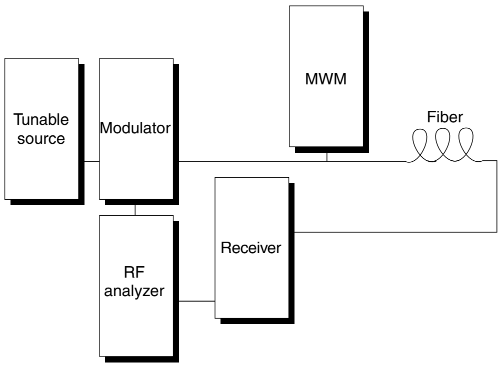


Figure 4.38 Typical chromatic dispersion measurement setup

A signal from a tunable laser is modulated externally at as high a frequency as is practical. The source wavelength is monitored by diverting a small fraction of the signal to a wavelength meter. The signal transmitted by the fiber under test is received and the RF modulation is detected. The group delay at that signal wavelength may then be derived by comparing the phase of the demodulated signal with that applied to the source. Stepping the source through the wavelength range of interest completes the chromatic dispersion picture.

Polarization Mode Dispersion

It is not practical to try to measure PMD in real time because of the very high frequencies involved. There are four main indirect methods. Two are wavelength-scanning procedures: extrema counting and Fourier transform. The others are the interferometric method and two closely related polarimetric techniques: Jones Matrix Eigenanalysis (JME) and Poincaré Sphere Analysis (PSA).

There are two common ways to express the results of a PMD measurement: the mean square deviation of time of flight and the mean DGD. The first applies to the Fourier transform wavelength-scanning method and the interferometric method, the second to extrema counting and JME.

Wavelength-Scanning Methods

Both of the wavelength-scanning techniques— extrema counting and Fourier transform—are performed using either of the two setups shown in Figure 4.39.

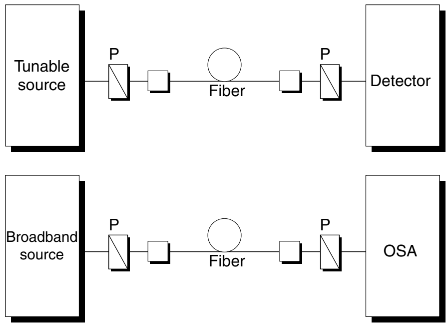


Figure 4.39 Wavelength-scanning setup

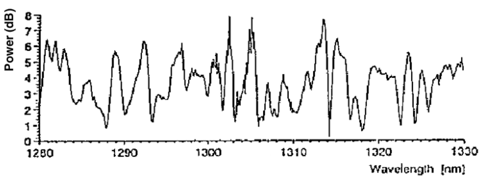


Figure 4.40 Source amplitude as a function of wavelength

Transmission versus wavelength is plotted with both source output and analyzer polarizers fixed at the same orientation. In the absence of birefringence in the fiber, polarized light from the source would always reach the analyzer polarization at the same angle, and the output power measured would be constant. But if the fiber is birefringent, the output polarization will vary cyclically with wavelength and this variation will show up in the output (Figure 4.40).

The two measurements differ in the treatment of the output information. In the first, the extrema over a given wavelength range are counted and related to PMD mathematically. In the second, a Fourier transform (the square of the second moment of the Gaussian fit) is applied to the wavelength scan to extract the PMD parameter.

Limitations of these techniques include:

- Measurements of large PMD values require small wavelength steps and high resolution.
- Increasing the wavelength resolution reduces the dynamic range.
- For accurate results, the wavelength range must be wide enough to give at least one complete oscillation in the output.
- The determination of the number of oscillations can be susceptible to noise and is often a matter of interpretation.
- The coherence of the source must be much greater than the polarization mode group delay.
- The measurement is both time-consuming and sensitive to vibration in the fiber.
- The methods are sensitive to launch polarization.

Interferometric Methods

PMD can be measured using a broadband, polarized source and analyzing the transmitted radiation with a Michelson interferometer, as shown in Figure 4.41.

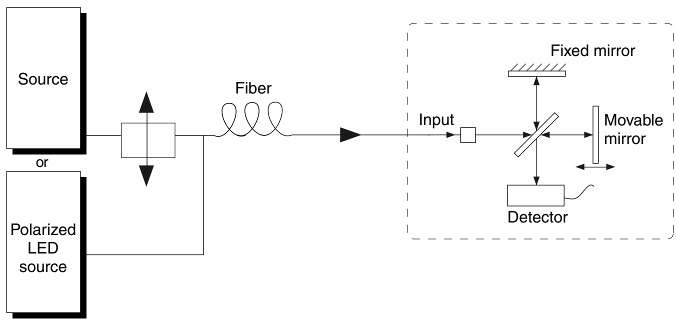


Figure 4.41 PMD measured using a polarized signal and the interferometer

The source is chosen to have a central wavelength appropriate to the measurement (1550 nm for modern DWDM systems) and a coherence time much smaller than the PMD of the fiber under test. The interferometric method determines the autocorrelation of the time broadening of this source, giving the PMD directly on the graph. The analysis assumes that the spectral shape of the source is approximately Gaussian, without significant ripple, and this condition should be verified using an OSA.

The necessary condition that the source coherence time be sufficiently smaller than the PMD of the fiber can be verified by observing the output interferogram: there should be at least two output peaks on each side of the autocorrelation peak, and both should be used in deriving the Gaussian fit.

Source polarization is assured over the full spectral range by a separate polarizer, which may be included in the source module. The detector must have adequate signal-to-noise ratio and dynamic range to cover the measurement conditions, possibly with some manual intervention. The fiber under measurement should be treated appropriately: supported in a strain-free manner and held steady. Temperature control is not usually needed, as the measurement can be made quite quickly.

A test-sample measurement is usually preceded by a source measurement—directly coupling the polarized source to the interferometer to check that it provides a single, smooth, nearly symmetric autocorrelation peak. A "real" measurement can then be made on a PMD emulator—either fixed or variable. This device is deliberately configured to prove a fixed amount or range of PMD.

The fiber itself can then be measured, generally for a number of different input polarization states (some of which will couple better to the principal axes of the test fiber). If results are needed over a range of temperatures, steps of at least 5ºC are recommended to produce significant variation.

PMD can be calculated from the resulting interferogram in two ways. The one to use will depend on the level of mode coupling in the test fiber. If this coupling is negligible, as will usually be the case for a short fiber or one designed to maintain polarization, the interferogram will show a strong central peak that represents the autocorrelation of the source, and two satellite peaks symmetrically displaced from it by the group delay of the fiber (Figure 4.42). Thus, the PMD value is this displacement (or half the total displacement between the two satellites) converted to time. The figure quoted is usually normalized to a unit length of fiber by dividing by the sample length, giving units of ps/m or ps/km.

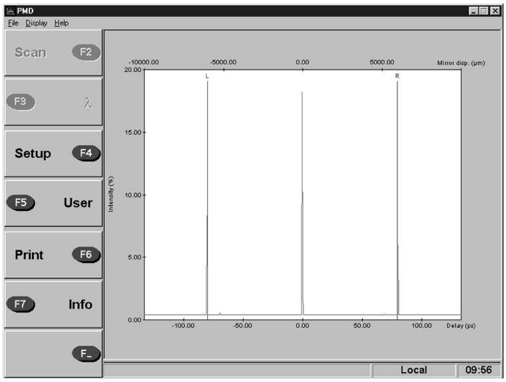


Figure 4.42 Weak mode coupling PMD trace

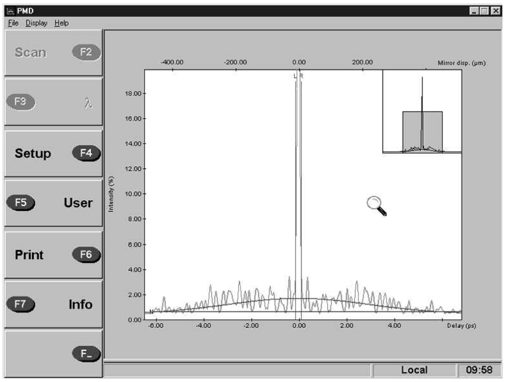


Figure 4.43 Strong mode coupling PMD trace with the Gaussian fit curve

Appreciable random mode coupling in the test fiber will wipe out the satellite peaks, and the PMD must be determined by analysis. The second moment (the rms half-width) of the autocorrelation function is observed (Figure 4.43):

$$\sqrt{\langle \Delta\tau^2 \rangle} = \sqrt{(3/4)}*\sigma$$

where <Dt> is the PMD delay and rms half-width of the autocorrelation function, and σ is the Gaussian standard deviation.

Because of the random contribution of mode coupling, the "normalized" value is referenced to the square root of the length unit, resulting in units of ps/$\sqrt{m}$ or ps/$\sqrt{km}$.

The accuracy of both analysis measurements depends on the number of points used and, thus, on the size and accuracy of the possible displacements of the movable arm of the interferometer. Accuracy of the second analysis method also depends on the ability to extract an appropriate approximation from the noisy signal. Experience based on many repeated measurements indicates that accuracies of 5 to 10% are possible as long as the output signal-to-noise ratio is reasonable and the PMD measured is 1 ps or more, but that accuracy can easily slip to 20 to 25% for PMDs of 0.1 ps or less.

The total displacement range of the movable interferometer arm determines the largest measurable PMD delay. In practice, sufficient displacement should be provided to cover a PMD value three times that expected.

The minimum measurable PMD is determined by the source coherence time (its spectral width) and on the number of peaks observable in the interferogram.

Second-order PMD, which is the change of PMD with wavelength, is closely related to the first-order phenomenon and can be estimated from:

$$PMD_2 = 2\pi c\,(PMD_1)^2 / \lambda^2 \sqrt{3}$$

where PMD_1 is the first-order PMD coefficient.

Thus, for example, a first-order PMD coefficient of 0.5 ps/√km will be accompanied by a second-order effect of about 0.15 ps/nm.km.

Requirements of the interferometric techniques

- Handling large PMD values requires extensive movement of the interferometer mirror.
- Source coherence must be much less than the delay to be measured.

Characteristics of the interferometric techniques

- Very rapid measurement that is insensitive to fiber vibration
- Suitable for field use, because the method does not require simultaneous, co-sited access to both fiber input and output
- Wide dynamic range
- Sensitive to launch polarization condition

Polarimetric Methods

The PMD measurement techniques outlined so far are sufficient for many practical applications, in particular to characterize fibers exhibiting strong, random mode coupling with at least moderate levels of PMD. The coverage of all ranges of PMD in fibers exhibiting arbitrary levels of coupling requires a much more detailed look at the underlying polarimetric parameters that describe the medium. Two methods are currently known: the Jones Matrix Eigen analysis (JME) and the Poincaré Sphere Analysis (PSA). Both methods involve injecting a specified set of polarized signals into the fiber or other DUT and fully characterizing the polarization state of the output signals to obtain the corresponding (normalized) Stokes vectors as a function of the optical frequency.

In the JME method, all the input signals are linearly polarized, whereas in the original PSA technique, one of them must be circularly polarized. However, the PSA method, recently revised by EXFO has been shown to require only the same three linearly polarized input signals as the JME. In fact, it is now recognized that the two methods are fundamentally equivalent and they are in the process of being consolidated as a recommended test method at the international level. Indeed, both methods determine the DGD as a function of wavelength from the same set of raw data (output Stokes vectors).

The JME method is commonly implemented using the tunable laser source configuration, whereas the PSA method (as implemented by EXFO) is based on a combination of a broadband source and an interferometer. A linear polarization state adjuster, the fiber or component under test, and a four-port polarimeter complete the setup.

This setup record the Stokes parameters as a function of wavelength. From the Stokes parameters, the output state of polarization (i.e., the output Stokes vectors) as well as the degree of polarization can be calculated as a function of wavelength.

In the JME method, the measured Stokes vectors are first transformed into Jones vectors. The Jones matrix (i.e., the transmission matrix that represents the conversion by the device of the input polarization state into the output polarization state) is then calculated as a function of optical frequency. The DGDs are finally obtained from the properties (Eigen values) of a composite matrix made up of two Jones matrices at neighboring wavelengths. In the PSA method, DGDs are directly obtained through a combination of the finite differences between two sets of output Stokes vectors acquired at neighboring wavelengths. The formal equivalence of the two methods of analysis is established through an expression of the polarization dispersion matrix (in the Jones vector representation) as a function of the polarization dispersion vector (in the Stokes representation). Both methods yield identical results in the absence of measurement noise. In the presence of noise, results are no longer identical, but the same accuracy can be reached with either methods.

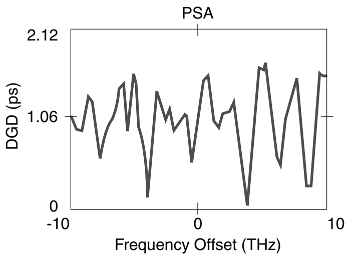


Figure 4.44 JME and PSA give the same DGD vs. f *trace*

Finally, the PMD from a single measurement is the average of the DGDs over the wavelength range of interest.

Main limitations of the polarimetric techniques

- Small wavelength steps (~0.01 nm), or a large interferometer course, are required when measuring large PMD values and/or measuring through narrowband devices and/or when DGDs show strong variations with respect to wavelength.
- Increasing the wavelength resolution reduces the dynamic range.
- A wide wavelength range and small wavelength steps are required in the case of long, strongly-coupled fibers to obtain good output statistics.

Additional limitations when based on a tunable laser source

- Source coherence has to be much greater than the delay to be measured to avoid depolarization.
- The measurement can be very time-consuming (several minutes) depending on wavelength range and step size.
- The measurement is very sensitive to movement (vibrations and thermal effects) when testing devices with small PMD or when using small wavelength steps.

Additional limitations when based on a broadband source and interferometer

- The residual PMD and PDL of the interferometer
- The coherence of the source has to be much smaller than the delay to be measured to avoid unwanted coherence effects within the interferometer.

Traditionally, the JME method has been more commonly used, because it avoided the complication of inserting circularly polarized input signals and it was less demanding as regards the step size needed for the input wavelengths. This is no longer the case with the new PSA formalism. In fact, the new PSA formalism, together with an implementation using a broadband light source and an interferometer in the receiver, considerably reduces the main limitation of the tunable laser source approach. Because of its very fast measurement capability, the DGD distributions obtained with the PSA method are much less susceptible to change in launching and environmental conditions. This opens the door for high-accuracy PMD measurement for production-testing as well as field-testing applications.

4.5 AUTOMATED TEST SYSTEM FOR COMPONENT TESTING

In order to accelerate component testing and receive all the advantages of current automation possibilities, optical testing companies have to exploit the full potential of testing systems. The passive component test system is an innovative approach to DWDM component characterization. The system sweeps a very low-noise, tunable laser source across the spectral band of the DUT and, at the same time, measures power on multiple channels, thus providing a quick testing time that is practically independent of the number of device ports. Because of the low SSEs of the tunable laser source, a dynamic range of 60 dB is easily attained. The wavelength reference module ensures accuracy by providing a fast and continuous wavelength reference across the sweep range.

The system design offers the possibility of testing almost every specification: insertion loss, flatness, ripple, crosstalk, isolation, central wavelength, channel spacing, peak power, bandwidth, and PDL. PDL measurements in accordance with the Mueller Matrix method are optional on different systems and provide PDL vs. wavelength across the complete range. The attenuation and PDL sweeps are completed without any fiber manipulations.

The modularity of the system and the flexibility of the software enable the user to easily expand to a higher number of channels. The user can start with a single channel system for measuring filters or gratings and expand to 32, 64, or more channels simply by adding the necessary plug-in modules.

Throughout most of the system, a high-level software will control all instrument functions from start to finish. A step-by-step approach will also offer a systematic test procedure that ensures accurate and repeatable results. Numerous features—including automatic Pass/Fail detection, filter masks, and part number database—make the job of DWDM component characterization a simple task.

The following components may be part of the test system:

- Platform: This is the system controller and is used to control the measurement process as well as the data interpretation and data storage. The controller will be supplied so that the system can be connected to a local area network (LAN).
- Source: A tunable laser source may be used as the high-resolution light source for performing the spectral attenuation measurement. The ASE source is another option for broadband applications depending on the DUT and the characteristics under investigation.
- Wavelength reference module (WRM): This module is used to perform numerous functions. Its main purpose is to ensure excellent wavelength accuracy. Its secondary functions are to provide a continuous dynamic power reference, provide synchronization of all power measurements, and take the ORL measurement.
- Detector: The power meter is the first choice and is synchronized with the WRM. It is used to perform the transmitted power measurement, which is compared to the WRM reference power to calculate the DUT spectral attenuation. The OSA can be used for wavelength monitoring and large spectrum analysis.
- Polarization state adjuster (PSA): The PSA is used to produce four known states-of-polarization (SOPs). A measurement scan is performed at each state and based on the attenuation values for each SOP, and the PDL vs. wavelength is calculated in accordance with the Mueller Matrix algorithms. The time required for a PDL measurement is the time necessary to perform four sweeps.
- Depolarizer unit: This component is used to condition the tunable laser signal when PDL measurements are being performed. It could also be used for attenuation measurements where unpolarized light conditions are required.

The system software stores data in a separate database for each device type using a database with commercially available software. These databases can be stored on each local machine or can be connected to a LAN for storage on any network drive. Test data can also be exported in a delimited .TXT format, which is then compatible with many different storage and analysis programs. This automated testing system uses a must-have software that offers component and system manufacturers the chance to add reliability, repeatability, and speed to their testing procedure whether the tests are performed in a laboratory, a central office, or an environmental room.

4.6 ENVIRONMENTAL QUALIFICATION

All the components previously discussed will eventually be used in the field, where they may be subject to a wide range of environmental conditions: temperature, humidity, electric and magnetic fields, and more. Procedures to establish the environmental characteristics of the electronic components and modules used are well established, and appropriate care must be taken to qualify each item in the expected conditions.

Fortunately, the very nature of optical communications gives fiber-optic components considerable immunity to many disturbing environmental conditions, in particular electric and magnetic fields. Hermetic packaging protects against humidity.

Temperature is the principal disturbing environmental factor. Many of the important optical characteristics of fiber-optic components depend on physical dimensions—the spacing of grating lines or Bragg etalons, the lengths of the individual fibers in an AWG, the thickness of the layers in a thin-film filter—and these dimensions change in accordance with the thermal expansion coefficients of the materials used. Although in some cases temperature compensation can be built into the device (temperature-insensitive biconic couplers are available, for example), in general the variation of device performance with temperature must be measured and appropriate measures taken either to compensate for temperature effects or to provide temperature-stabilized equipment enclosures.

Many EDFA characteristics are sensitive to temperature, including time-varying ones. The temperature dependence of time variations in the gain spectrum must be investigated over the expected temperature range and for all—or at least a representative sample—of the wavelengths to be used. These measurements are usually made for small signals and for those either at the point of 3 dB compression or at saturation, depending on the ultimate use to be made of the amplifier (booster, in-line, or pre-amplifier).

A set of individual fixed sources, one for each channel wavelength, or a broadband ASE source covering the entire band may be used to allow all channels to be measured simultaneously. A tunable laser can be used for sequential measurement. The choice will determine the appropriate receiver for the measurement: a multiwavelength meter, a singlewavelength meter, or an OSA.

Such EDFA testing is usually carried out in an environmental chamber, with appropriately controlled temperature and humidity.

The critical parameters of all of the many passive components used in WDM systems may vary with temperature or humidity, and the task of ensuring that these variations will not affect system performance is daunting. To maintain testing at a manageable level, methods must be sought that test as many parameters of as many individual devices as possible at the same time or using the same test setup. Where appropriate and available, full use must be made of automated test procedures and computerized data collection, processing, display, and interpretation facilities.

Fortunately, modular approaches to test-equipment design now simplify the task. Modules that share a command language and structure can be interconnected in many ways to meet most measurement needs, and knowledgeable control software allows test procedures to be programmed in high-level languages. Go/no-go test criteria can be handled completely automatically and detailed spectral characteristics can be extracted without operator intervention.

4.7 FIELD TESTING

Some of the complications that differentiate production-line or laboratory test procedures from those appropriate to field use have been hinted at in the previous sections. Some measurements simply cannot be performed reliably anywhere but in a stable, controlled environment. Also, many measurements require capabilities that, until recently, have simply not been available in instruments intended for use in the field. Although conventional field installation and test equipment is still needed to deal with many of the basic attributes of links that are independent of the transmission mode used, new requirements now exist for fiber-optic test instruments to deal with dense WDM components and the complex optical phenomena that affect them.

4.7.1 Optical Loss Test Set

The optical loss test set (OLTS) used in dense WDM systems must be calibrated at precisely defined channel wavelengths in the 1525 to 1565 nm band. This means that accurate power measurements of individual channels can be taken at the output of demultiplexers.

These test sets will also be used at the wavelengths used for optical supervisory channels (OSCs): 1480 nm, 1510 nm, and 1625 nm, depending on the system design. Dedicated DFB light sources will be needed to check the loss budget when the fiber is installed. The longest OSC wavelength, 1625 nm, requires particular attention since it lies outside the range in which the fiber or cable manufacturer guarantees the performance of his product. Optical loss test sets that include capabilities at this wavelength are now on the market.

4.7.2 Optical Time Domain Reflectometer

Modern optical time domain reflectometers (OTDRs) often offer capabilities in the fourth window region, at 1625 nm. In addition to the ability to test and troubleshoot the important 1625 nm optical supervisory channel, using this wavelength presents other important advantages. In particular, in many circumstances, live fibers may be tested at the 1625 nm wavelength while normal dense WDM transmission continues uninterrupted in the EDFA spectral region. In addition, because optical losses due to fiber bending are more pronounced at 1625 nm than at the shorter DWDM operational wavelengths, OTDR testing at the long wavelength can reveal critical points in the installed fiber, that is, points where the performance of the fiber is acceptable at the time of installation but could degrade over time (Figure 4.45).

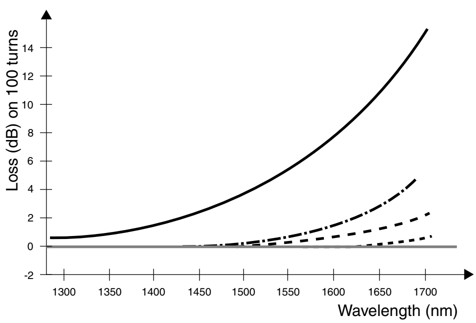


Figure 4.45 Comparison of bending loss for different fiber types as a function of wavelength

4.7.3 Backreflection Meter

In a conventional non-dense WDM network, optical return loss (ORL) can be determined with a single measurement using a backreflection meter at the operating wavelength. This solitary measurement may not suffice for dense WDM systems in the field. There are two possibilities: an aggregate measure covering the entire wavelength band in use or a detailed one giving results for each channel wavelength. Although the first is obviously quicker to perform and may provide enough information to satisfy a go/no-go acceptance test, ORL can vary considerably from channel to channel. This variation with wavelength may be caused by defective Bragg gratings or, more often, by bad connectors at the output port of a multiplexer or demultiplexer. Excessive back reflection can cause instability in DFB source lasers, which affect the overall system performance. Therefore, the ability to perform the more complex wavelength-dependent measurement will often be needed.

An aggregate measurement is made with a broadband source and an independent power meter, in the same way the measurement is carried out in a single-wavelength optical link. The measurement result is a single value: the total ORL power at the test point over the entire transmission spectrum.

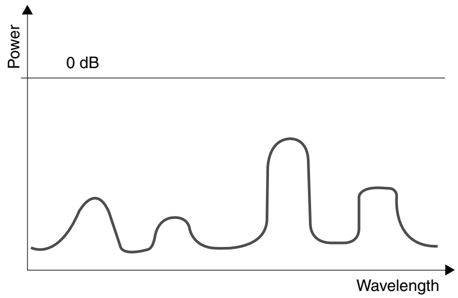


Figure 4.46 Schematic representation of ORL spectral measurement

The value of the ORL as a function of wavelength is often a more useful parameter intrinsically, and it may be essential to determine it if the simpler, aggregate test should fail on a particular link. The value is determined using a high-power broadband source, usually an ASE source. High power is needed to provide enough power in each measurement band (which may be as narrow as 0.1 nm) to give an adequate signal-to-noise ratio at the detector for the lowest ORL of interest. The receiver is an OSA of adequate spectral resolution and sensitivity. The result is an individual ORL reading for each dense WDM channel: often just the information needed to guide a troubleshooting session (Figure 4.46).

4.7.4 PMD Test Set

Field measurements indicate that it is not uncommon for the PMD in installed cabled fibers to be much higher than that of uncabled fibers. Having the manufacturer test, the fiber may provide some degree of confidence, but there is no guarantee that the network will provide the required specifications.

The instantaneous PMD for a specific wavelength can vary over time. However, tests performed with the interferometric technique in the field show that the average PMD is relatively stable. This suggests that the second moment calculated by the interferometric technique, which gives the average PMD value, is the best parameter to characterize PMD in fibers. Having such a stable parameter allows comparison among fibers in the same cable and it permits the use of a Pass/Fail criterion, which depends on the network speed and the bit error rate (BER) that can be tolerated.

It is particularly important to measure PMD in conditions that are in accordance with the real operation of the network. For example, some PMD measurement methods require that the source and analyzer be at the same location, not at opposite ends of a link. To meet this requirement for a single link, one might be tempted to provide a return path through a parallel link that returns to the test site. This practice presents two difficulties. First, one of the tests is necessarily made in a direction that does not correspond with its real-life use. Second, because the results from the two separate links are combined into a single measurement, deduced Pass/Fail results for either may be incorrect. A simple numerical example explains this phenomenon:

With strong mode coupling, the total PMD for two cascaded links is:

$$PMD_{1+2} = ((PMD_1)^2 + (PMD_2)^2)^{1/2}$$

where PMD_{1+2} is the total PMD of the optical link, which is composed of links 1 and 2.

If the maximum allowable PMD for a link length of say, 40 km, is 2.5 ps (0.4 ps/km$^{1/2}$); and if two 40 km links are tested together, one with 1.5 ps (0.24 ps/km$^{1/2}$) PMD and the other with 3 ps (0.47 ps/km$^{1/2}$), the result for 80 km will be 3.35 ps (0.37 ps/km$^{1/2}$). Both links will be declared "good," although one of them clearly is not.

Similarly, if one link has a PMD of 2 ps (0.32 ps/km$^{1/2}$) and the other, 4 ps (0.63ps/km$^{1/2}$), an 80-km result of 4.47 ps (0.50 ps/km$^{1/2}$) will be obtained, indicating that both links are bad; another incorrect conclusion. Care must be taken to test the links in the configuration in which they are used.

There is no doubt that PMD will become critical in high-speed communication networks like SONET. Although manufactured cable may be measured for PMD in the plant, cabling and installation will often introduce mechanical bends and pressure points that will alter its value. With the increasing use of EDFAs to increase fiber span, all sources of dispersion must be controlled and minimized, otherwise the gains these devices offer will be compromised by PMD effects.

The interferometric technique is best suited to measurements of PMD in the field. It is fast, it requires no hardware communication or loopback, its wide dynamic range allows large PMD values to be measured over long distances, and it is insensitive to fiber vibration.

Manufacturing and qualifying DWDM components require new test instruments and techniques. The most important ones have just been described. Nevertheless, rapid developments in technology will certainly increase the number of new measurements and methods. Also, some of these measurements will become more relevant as technology evolves (i.e., PDL). These specialized techniques and equipment are rapidly evolving from the quality-control laboratories and manufacturing verification environment to the field-testing arena. The next chapter will deal with key testing issues for system verification before final exploitation of the system begins.

WDM GUIDE

CHAPTER 5

SYSTEM INSTALLATION AND MAINTENANCE

The rapid evolution of WDM technology and the need to quickly apply it in the field have led to a requirement for new and advanced test procedures. WDM technology has the potential to dramatically increase the capacity of existing networks, reduce the cost of network upgrades by increasing the bandwidth of existing links, and offer new options for all-optical network design. These goals can be met, but only by confirming the correct operation of all the network components through extensive testing during installation, and by checking ongoing performance through appropriate maintenance procedures.

In the previous chapter, we discussed different WDM technology components. In this chapter, we will focus on what links all these components, i.e., the WDM system.

Measuring the optical and electronic parameters of the link is vital to ensure that each channel is operating at the specified wavelength and that all network elements are spectrally aligned according to the design specifications. Obviously, once all critical components are installed, they must be tested again to ensure that they still conform to the system provider's requirements. They will have to be tested before the system is put into operation (commissioning) and on a regular basis after that (maintenance).

After the network is in service, operation, administration, and maintenance tests are still necessary to confirm the proper working of network operations and all management functions. Critical parameters must be monitored to ensure that they do not stray from design limits. These system parameters are particular to the system used and depend on several factors, including the length of the optical link, transmission rates used, number of wavelengths, and channel spacing.

This chapter, thus, is relevant for system operators, installers, maintenance teams, and all other personnel who want to know more about test systems.

5.1 CRITICAL SYSTEM PARAMETERS

Critical system parameters are different from individual components, since, when everything is assembled and installed on one fiber, the parameters must be characterized at each end of the network. The effects induced by the different components are hard to foresee because, in certain cases, they are added, in other instances, increased, and sometimes, they are removed. Furthermore, external environmental conditions, physical and optical distance, as well as connectors and patchcords can create unforeseen problems on one single component. The overall performance of a WDM network system is based on the following major factors:

1. Laser transmitter output power level, which should be as high and as stable as possible to increase the transmission span length, but not to the detriment of non-linear effects

2. Number of channels (The number of channels times the modulation rate defines the total system bandwidth; for example: 40 wavelengths at 2.5 Gbps (STM-16 or OC-48) gives a total system bandwidth of 100 Gbps.)

3. The channel spacing capability in GHz (ITU-T has defined a standard channel spacing of 100 GHz—about 0.8 nm—in the ITU grid; 50 GHz is also proposed in the grid—about 0.4 nm—and eventually lower values will be added.)

4. Laser transmitter modulation rate in Gbps (Long-haul communications are presently at STM-16 or OC-48 2.5 Gbps and STM-64 or OC-192 10 Gbps rates; metropolitan communications are usually at much lower rates.)

5. EDFA gain (Both amplitude and spectral width; small signal gains of 30 to 40 dB are typical, while spectral widths of 40 nm are typical in non-extended-range EDFA.)
6. Receiver gain (as high and as stable as possible)
7. Fiber type and specifications (critical for data rate, dispersion, and maximum channel possibility)

Even though it is possible to characterize system performance with the previous parameters, many more considerations have to be taken into account to carry out a complete study of the system performance.

5.1.1 Bit Error Rate (BER)

Suppose the installer has a tentative design for a fiber-optic data link of the type dealt with in this chapter, that is, the type illustrated in Figure 5.01. How does the installer analyze it to see if it will meet requirements?

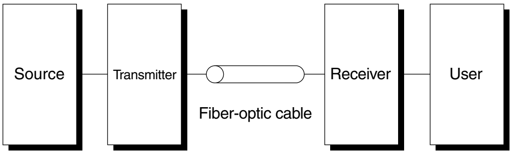


Figure 5.01 Typical point-to-point link from the source to the user

Performance requirements are usually characterized in terms of an acceptable bit error rate (BER), whose value generally depends on a specific source-to-user application. It might be as high as 10^{-3} for applications such as digitized voice or as low as 10^{-12} for scientific data. The tendency is towards lower and lower BER requirements.

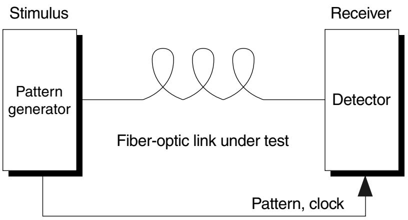


Figure 5.02 BER setup using a traditional pattern generator

Will the tentative link design provide the required BER? To answer this question, we must look at the receiver sensitivity. This specification indicates how much optical power the link must receive if it is to deliver the required BER.

To determine whether the tentative link design can deliver this power, the installer must analyze it, i.e., step through the components of the link to determine just how much power will reach the receiver. This is done with a fiber-optic data-link power budget.

A power budget for a particular example is presented in Table 5.01. The fiber-optic link in question has the following attributes:

LINK	ELEMENT VALUE	COMMENT
Transmitter LED output power	3 dBm	Value specified by vendor
Source coupling loss	-5 dB	Accounts for reflections, area mismatch, etc.
Tranmiter-to-cable connector loss	-1 dB	Transmitter to fiber-optic cable with ST connector. Value accounts for misalignment.
Splice loss	-0.25 dB	Mechanical splice
Fiber-optic cable attenuation	-20 dB	From other specifications or measurements
Cable-to-receiver connector loss	-1 dB	Assumes an ST connector and includes misalignment
Total loss	-27.25 dB	Sum of the five loss figures
Optical power delivered to the receiver	-24.25 dBm	Source power reduced by the total loss
Receiver sensitivity	-40 dBm	Specified in link design
Loss margin	15.75 dB	

Table 5.01 Sample power budget for a fiber-optic data link

The entries in Table 5.01 are self-explanatory. Clearly, the optical power at the receiver is greater than that required to achieve the necessary BER. The loss margin entry is significant since it specifies the amount by which the received optical power exceeds that required. In this example, it is 15.75 dB. Good design practice requires that it be at least 10 dB. Why? Because no matter how carefully the power budget is estimated, some entries are always forgotten and some are too optimistic. In other cases, vendor specifications turn out to be inaccurate and an allowance must always be made for future maintenance.

5.1.2 Loss Tests

Losses depend on components and are a function of optical signal distance. They are to be expected in each component or subsystem, even with top-quality products. Losses are inevitable in connectors, multiplexers, demultiplexers, and in the fiber itself.

The loss test is the principal evaluator of the performance of a system or link. Individual losses can be measured or interpreted according to a variety of procedures and criteria, but the primary result of loss testing is to provide an overall performance figure for the link in question.

5.1.3 Optical Return Loss

When light is injected into a fiber-optic component, some of the energy is reflected. The optical return loss is directly associated with bad connectors or splices and defective components. We can also attribute the loss to the reflections that occur at discrete interfaces as a result of air gaps, misalignment, and mismatched refractive indices.

The signal will lose power, the integrity of the data will be damaged by multipath interference, and the stability of the source will tend to become lower.

The loss is a function of the component quality and accuracy. It fluctuates from one channel to another and this is the main reason why tests must be performed over the entire spectral range. The high-performance lasers used in DWDM systems are very sensitive to reflected light, which can degrade the stability of the laser and the signal-to-noise ratio, or even damage the source. Reflections can appear in the EDFAs and cause major increases in the noise figure. All these problems must be measured before and after the decisive signal is put to the network.

Optical Return Loss versus Reflectance

The terms optical return loss—often abbreviated to return loss—and reflectance are both commonly used to quantify reflected power. The two are often confused.

Optical return loss or ORL is generally used to describe the total reflection in a fiber-optic network system or subsystem, measured at a specific location.

ORL (dB) = 10 $\log_{10}$ (incident power/reflected power)

ORL, measured in dB, is always positive (the incident power is always greater than the reflected power). For example, if, at a system interface, there is 1 mW of incident power and 1 μW of reflected power, the return loss is 30 dB. A higher value means less reflected power and, thus, better performance.

Reflectance is usually used to describe a reflection at a single interface or other site at the component level, for example at a connector.

Although ORL and reflectance are defined differently, each represents a ratio between the incident and reflected power. As both are commonly quoted in decibels, conversion from one to the other is simply a matter of changing the sign.

Reflectance (dB) = 10 $\log_{10}$ (reflected power from specific interface/incident power).

Reflectance, measured in dB, is always negative (reflected power is always smaller than incident power). For example, if, at a connector, there is 1 mW of incident power and 1 μW of reflected power, the reflectance is –30 dB. A greater negative value means less reflected power and, thus, better performance.

5.1.4 Optical Signal-to-Noise Ratio

Although the BER is the best single parameter to characterize the performance of a link, it is determined principally by the optical signal-to-noise ratio (OSNR). Therefore, the OSNR is invariably determined whenever a dense WDM system is installed. It characterizes the "head room" between the peak power and the noise floor at the receiver for each channel. It is an indication of the readability of the received signal; a parameter of increasing interest as the limits for long distance applications are pushed farther and farther.

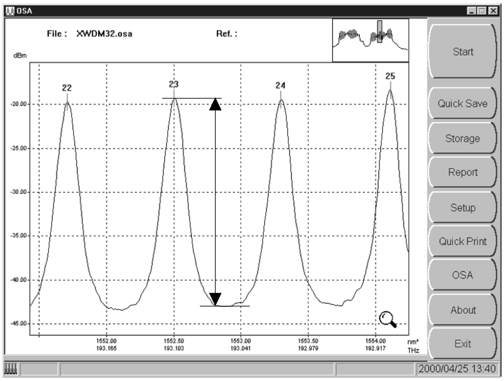


Figure 5.03 SNR is measured half-way from the adjacent peak.

OSNR is graphically represented (Figure 5.03) as the ratio between signal and noise power as a function of wavelength. The value, measured at the output of the first multiplexer, should be greater than 40 dB for all channels. It will be greatly affected by any optical amplifiers in the link and will drop to about 20 dB at the end of the link depending on the link length, the number of cascaded EDFAs, and the bit rate. An individual EDFA should not degrade the OSNR by more than 3 to 7 dB.

Optical noise, which has taken on new importance since the introduction of optical amplifiers in transmission systems, is due mainly to amplified spontaneous emission (ASE) in the EDFAs. Although the manufacturer has almost certainly tested the EDFAs individually, it is important to check their performance on-site, with all optical channels in operation and all cascaded amplifiers present, to confirm that overall performance expectations are being met. Gain variation merits special attention in multi-amplifier systems, as it will directly affect system power flatness. ASE noise figures can be particularly significant in some configurations, since this phenomenon degrades the signal-to-noise ratio in all optical channels.

System gain will vary over time because of temperature changes, local stress, component degradation, and network modifications.

The OSNR must be determined for each populated channel in a WDM system. Referring to Figure 5.05, it is defined as:

$$OSNR = \text{worst-case value of} \left(10 \text{ Log } \frac{P_i}{N_i} + 10 \text{ Log } \frac{B_m}{B_r} \right) \text{dB}$$

where P_i is the optical signal power in the *i*th channel. B_r is the reference optical bandwidth. (B_m and B_r may be either frequency or wavelength); B_r is typically 0.1 nm. N_i is the interpolated value of noise power measured in the noise equivalent bandwidth, B_m, for the ith channel:

$$N_i = \frac{N(\lambda_i - \Delta\lambda) + N(\lambda_i + \Delta\lambda)}{2}$$

where $\Delta\lambda$ is the interpolation offset equal to or less than one-half the channel spacing.

Deficiencies in ONSR must be dealt with by configuration changes, generally by adding optical amplification at appropriate points in the link. ONSR is obviously a particularly significant parameter to be determined at links between connected operators as a measure of the quality of the signal supplied.

5.1.5 Gain

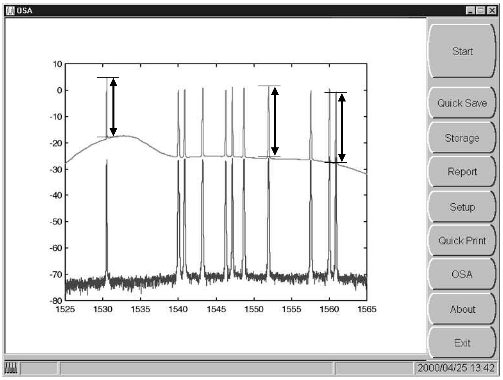


Figure 5.04 Gain is not flat over the EDFA bandwidth.

Optical signals are modified many times in passing from a source to an ultimate receiver in a network. In an optical network using EDFAs, the gain for individual channels depends on the channel population at that particular point, so means must be available to check that the signal-to-noise ratio of every channel remains adequate at the receiver; aggregate measurements are not sufficient. And, of course, means must be available to determine the cause of any discrepancies. Although the overall go/no-go criterion may be based on total power and the power in each channel, tracing the cause of weak channels may well require an ability to chek gain flatness at individual amplifiers, as well as to investigate a variety of polarization and non-linear effects. All require accurate spectral information about the signal.

5.1.6 Central Wavelength

The central wavelength of each channel in the signal is probably the most important single characteristic, given that its accuracy ultimately determines the ability of the source to communicate with the receiver.

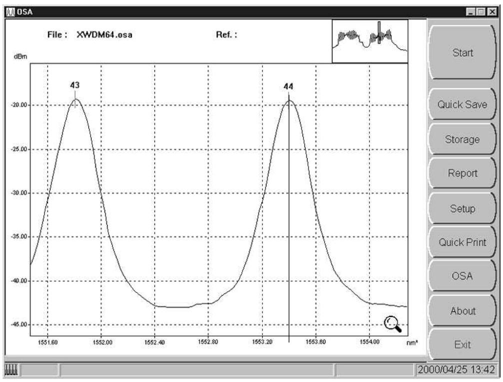


Figure 5.05 Central wavelength measured on a 50 GHz system.

The precise value of the central wavelength of each channel must be measured when the network is first installed to ensure that design specifications are met. These values must also be monitored during maintenance programs to detect unacceptable drift. The accuracy of central-wavelength measurement increases in importance as channel bandwidths and spacings are reduced.

In a switched dense WDM optical network, a comprehensive, carefully planned policy is needed to govern wavelength usage, eliminate conflicts in wavelength assignment, and minimize possible interaction between wavelengths. The international standard for channel spacing now defines integer multiples of 100 GHz (about 0.8 nm). This spacing was chosen because it offers a good compromise between high capacity and tight component specifications, but it still represents a demanding tolerance for all the equipment in the transmission path. Spacing of 50 GHz is commonly used for new installations.

Since a 100 GHz channel separation implies very narrow channel bandwidths, spectral drifts in the distributed feedback lasers used as transmission sources can have devastating effects on signal levels at the receiver end. Therefore, source stability and spectral purity are of paramount importance. Sidelobes are also of particular concern, since they can add noise to adjacent dense WDM channels. Although older, unstabilized lasers used in SONET networks cannot meet these requirements, existing transmission equipment can be upgraded for dense WDM use by replacing these sources with spectrally stabilized DFB models. In some cases, installed equipment can be converted to dense WDM by directly inserting OC-48 laser signals into the stabilized, modulated DFB.

5.1.7 Drift

Real optical sources are not absolutely stable because both their output power and central wavelengths can be expected to drift. Figure 5.06 shows a typical result of monitoring a source over a 12-hour period. Drift is caused by such factors as temperature changes, backreflection, and laser chirp phenomena.

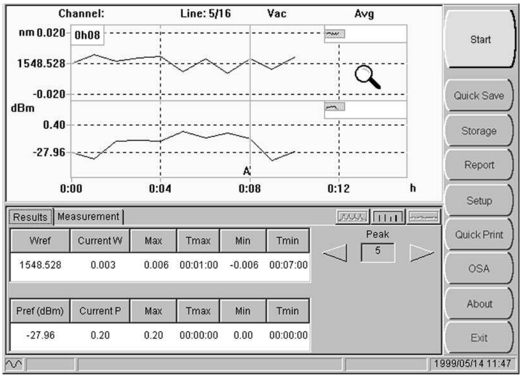


Figure 5.06 The wavelength and power vary over time.

The primary concern with drift is that the signal must remain within the acceptable channel limits at all times, under all operating conditions. Excessive drift may cause the loss of the signal in the affected channel. The drifting source may even spill over into an adjacent channel and interfere disastrously with the information transfer there. Drift must be measured and controlled to avoid loss of data.

5.1.8 Crosstalk

Crosstalk—the unwanted contribution of energy in one channel to others—is another effect whose magnitude is difficult to accurately predict from pre-installation data; it must be observed in real life, with real (or at least simulated) signals present.

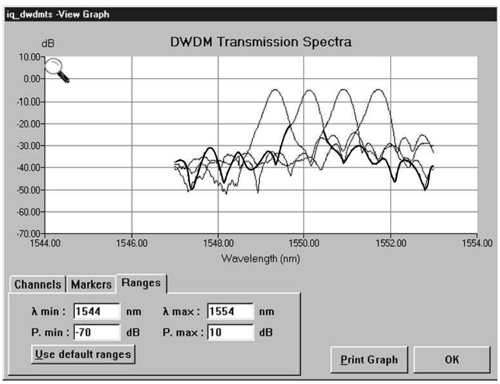


Figure 5.07 The bold portion of peak 2 represents crosstalk in adjacent channels.

Crosstalk calculations were discussed in section 4.4.1. They involve a detailed examination of the shape of the passbands of two adjacent channels to check that the amount of signal leaking from one to the other is negligible. Normally, a minimum of 25 dB is required between channels (Figure 5.07), but 13 dB might suffice for a submarine link, and 17 dB values have been tolerated in very long haul applications.

Calculations based on pre-installation measurements cannot give accurate values; crosstalk must be checked when all the components of a network are assembled. Crosstalk must also be checked periodically during maintenance to assure the quality of signal transmission.

5.1.9 Non-linear Effects

Non-linear effects that are not apparent when fibers are tested can become important only once a network is put into operation. The changes brought on by interconnecting equipment and installing it in the field can bring any of the effects outlined in section 3.3.4 to the fore, and care should be taken—especially during installation, but also at appropriate maintenance intervals—to check for non-linear perturbations.

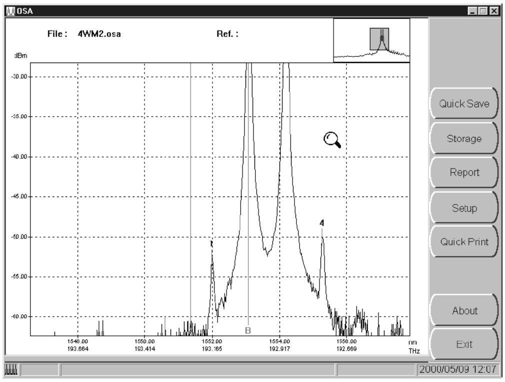


Figure 5.08 The two side peaks are due to four-wave mixing.

Four-Wave Mixing

Although four-wave mixing is also a non-linear effect, it requires special attention because of the seriousness of its consequences on a network. When two optical signals interact in this way, energy extracted from them can turn up at wavelengths in use by other channels, thus seriously disturbing network operation. Although the effect is similar to crosstalk, its effects are not limited to the two conflicting channels. Its magnitude depends on the relative polarizations of the two interacting signals as well as their magnitude and channel spacing.

Four-wave mixing can be reduced by increasing channel spacing or by using unequal channel spacing; either is difficult to achieve after a network design is finalized. For networks not already in place, using a fiber with an appropriate amount of chromatic dispersion can reduce four-wave mixing. Since four-wave mixing can at least potentially be counterbalanced, it is important to know its exact magnitude.

5.1.10 Polarization Mode Dispersion

In the long fiber spans typical of real networks, polarization mode dispersion will arise from a number of causes such as inherent inhomogeneities in the fiber, mechanical perturbations from bends and stress-producing supports, and a variety of temperature effects. Because of the quasi-random nature of all these effects, the most useful characterization of the phenomenon is the expected value of the group-delay variation (<DGD>), the root-mean-square value of pulse broadening. Although <DGD> is a function of both wavelength and temperature, in most cases a single mid-range value will suffice to predict the point at which its effects will degrade network performance.

We noted earlier that the character of PMD—and even the units most useful to express it—depends upon the degree of mode coupling in the optical fiber. In practical terms, the transition between the two states occurs at distances equaling the coupling length, Ic, of the fiber, that is, the length of fiber at which energy transfer between the polarization states becomes appreciable. Values of Ic seldom exceed a kilometer, and values below and around 300 meters are common, so most real-life networks operate under conditions of strong random mode coupling, in which PMD is expressed as an expected time delay per square root of the unit length (e.g., ps/$\sqrt{\text{km}}$).

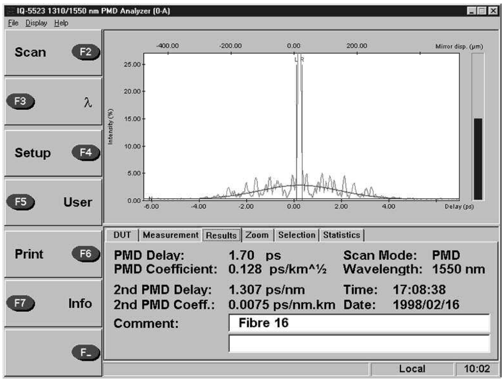


Figure 5.09 Typical PMD measurement

PMD is of particular significance in old cables laid in the late 80s when manufacturing techniques and processes were not as advanced as they are now and the phenomenon and its causes were not well recognized or understood. Now fiber manufacturers are aware of the importance of maintaining near-ideal core geometry throughout the length of fiber, and cable manufacturers take care to avoid placing undue stress on the fiber when winding cable. Finally, carriers and installers now appreciate the effect that the operating environment can have on PMD. But these kilometers of cable laid in the late 80s—with different types and ages intermixed—create complexity and difficulty for network operators who are planning capacity upgrades to OC-192/STM-64.

5.1.11 Chromatic Dispersion

When judiciously selected and properly controlled, chromatic dispersion can minimize certain non-linear effects in optical fiber or even take advantage of them (as in dispersion-aided or managed fibers). In some situations, not only can the total dispersion be controlled, but various non-linear effects can also be minimized, even within and along a single fiber. Field measurement of chromatic dispersion will be more and more important in the future, though, as existing networks and infrastructures are investigated for their upgrade possibilities.

5.1.12 Other Phenomena

A number of other phenomena are important to the characterization and performance of the components of a fiber-optic link. They include

- Optical signal-to-noise ratio degradation (dB)
- Optical-crosstalk-related parameters
  - In-band crosstalk ratio (dB)
  - Out-of-band crosstalk ratio (dB)
- Frequency-response-related parameters
  - Ripple (dB)
  - Insertion loss (dB)
  - Channel width (GHz)
- Polarization-related-parameters
  - Differential group delay (ps)
  - Polarization dependent loss (dB)
  - End-to-end PDL measurement (dB)

Most of these subjects are dealt with in Chapters 3 and 4.

5.2 INSTALLATION AND PRECOMMISSIONING

Before installing and turning on the system, certain tests must be carried out on the optical link that will be used. If the new WDM system will be using the equipment already in place, it is essential to check that the new system is compatible with this equipment. Several types of tests will allow the operator to ensure that the system works properly.

From the network operator's perspective, it is desirable to keep to a minimum the number of system tests needed to demonstrate overall system functionality and signal-transmission integrity. Although procedures to test and deploy SONET/SDH single-channel optical transmission systems are well documented, emerging technologies such as WDM lack such detailed support. Optical component properties and cable characteristics that could safely be neglected in systems using simpler transmission techniques must be considered. Recent advances such as add/drop optical multiplexers permit wavelength routing over complex networks, complicating installation, acceptance, and maintenance test procedures. Optical cross-connects, although still on the drawing board, will radically change the configuration of future telecommunications networks and will probably entail even more intricate testing.

An effort is underway to define a set of system-level tests to characterize the end-to-end network functionality of DWM systems, with due regard to optical signal transmission, multiplexing, supervision, performance monitoring, and survivability. These tests fall into five categories:

- Network compatibility
- Commissioning
- Maintenance and monitoring
- Inter-vendor operability
- Architecture interconnections

5.2.1 Network Compatibility

Network compatibility tests ensure that signals from existing non-WDM networks are compatible with the fiber interfaces to the WDM network elements and that the electrical power specifications of the WDM components are equivalent to those in existing networks. Essential field tests include those to measure end-to-end attenuation, optical reflections at the network interfaces, and dispersion when systems are being upgraded.

End-to-end attenuation testing at 1310 nm and 1550 nm examines the fiber path for optical discontinuities and determines whether the fiber conforms to system requirements. Testing for reflected power from individual components, such as connectors and fiber joints, determines whether the effects of single and multiple reflections are within specified tolerances.

Chromatic and polarization-mode dispersion testing is not routinely done on newer fiber during installation (unless dispersion compensators are present in the system), since these parameters are generally specified by cable manufacturers. However, these tests should be conducted on older installed fiber under consideration for high bit rate (OC-192/STM-64) use, or whenever fiber distances are sufficient to approach system dispersion limits.

5.2.2 Commissioning

Transmission performance tests measure transmitter and receiver performance, optical amplifier performance, error behavior, and related effects that accumulate through WDM network elements. Laser wavelengths may vary because of manufacturing variations, thermal shifts, or frequency broadening. When a spectrally broadened signal propagates through a dispersive medium, such as conventional fiber, error rates rise.

End-to-end optical testing should be performed at the system level, with all the building block components working together in the optical link. The net dispersion between the transmitter and receiver for all channel wavelengths, including those added or dropped at intermediate points, should be checked to ensure that it is within specified levels. Optical power and OSNR at the receiver should be measured. To achieve balanced OSNR levels among all the channels in DWDM systems, an OSA can be used to monitor the changes in OSNR as the transmitter levels are varied.

The number of wavelengths available to a WDM system is limited by amplifier, passband, crosstalk, component drift, fiber non-linearity, and cascaded filter alignment tolerances. Optical amplifiers are widely used to compensate for component and transmission losses, and the impact of noise accumulation and cross-gain saturation needs to be carefully considered to minimize signal power variations. Transmission performance tests check end-to-end optical system performance. Channel wavelength, channel drift, optical signal-to-noise ratio, channel spacing, channel isolation, insertion loss, amplifier noise, gain flatness, bit error rate, jitter, and transmission delay are all critical parameters to be measured. Each of these tests will be defined in greater detail in section 5.3 where we will discuss commissioning tests.

5.2.3 Maintenance and Monitoring

Operations, administration, and maintenance tests confirm the capability to perform network operations and management functions, to communicate with management systems and other network elements, to monitor the end-to-end performance of a link, and to isolate faults in replaceable or repairable components.

Maintaining a WDM system means ensuring that the optical carriers remain within specifications, that the channel wavelengths are stable, and that the optical power level does not fluctuate more than the system can tolerate. Testing these parameters makes use of optical service channels that communicate among the WDM network elements (NE/NE) and the operation systems and network elements (OS/NE) via the embedded data communications channel (DCC), a local area network (LAN), or an optical supervisory channel (OSC). Maintenance tests are discussed in detail in section 5.4.

Alarm surveillance and performance monitoring are included in this category. Access to key features and parameters—including system administration and security functions—must be checked, both locally and remotely, according to the specifications. These tests should be comprehensive enough to ensure that the network operator is able to monitor and control the state of the network. It is possible to use a channel dedicated to performing surveillance or transmitting information about the system's status. This supervisory channel, as well as a complete supervisory system (RFTS), will be looked at in more detail in section 5.5.

5.2.4 Inter-Vendor Operability

Inter-vendor operability tests demonstrate the ability of the system to inter-operate with equipment from other vendors. Often, optical transponders must be incorporated at interfaces between differing equipment. To avoid this costly and potentially troublesome addition, both the physical properties of the optical signal and its content (e.g., wavelength, line rate, coding format) must be standardized at the network interface. The ITU and other standards bodies are actively defining such standards for optical interfaces, architectures, and management, and tests are required to ensure that the standards applicable for each interface are met.

5.2.5 Architecture Interconnections

Architecture interconnection tests corroborate the functionality and survivability of network interconnections. Recent WDM systems have been designed primarily for point-to-point connectivity over long distances, and optical network survivability is provided almost exclusively in the electronic layer by SONET. But present-day systems, which allow static wavelength, add/drop, and recently OADM capabilities, have become dynamically reconfigurable. High-performance switches and routers will route wavelengths over complex networks. Optical cross-connects and other advanced optical technologies will support topologies that are more flexible. Restoration architectures based on self-healing rings, diverse routing, or mesh-based distributed algorithms are receiving considerable attention. In light of all these advances in technology, service protection is becoming increasingly difficult to investigate exhaustively. Nevertheless, it is an essential aspect of the architecture that must be tested to ensure network reliability, survivability, and service consistency.

The evolution of WDM technology will undoubtedly allow operators to approach more and more closely the intrinsic capacity of fiber-optic networks. However, the techniques used by system designers to increase capacity may differ from vendor to vendor. Increasing the number of carriers might be preferred by some (by expanding the operating WDM window and/or by reducing the channel spacing), while increasing the data rate of each carrier could be the choice for others. Whatever the path taken, the need for testing will evolve as fast as the technology, and testing procedures will have to be adapted continually to respond to changing realities.

5.3 COMMISSIONING

A number of critical parameters should be measured and recorded when a network is first commissioned to check start-up performance and to provide a base line for future troubleshooting or upgrade planning. This testing period is so crucial that system vendors supply their own test sequences. The tests will be carried out on individual components and also on the system in operation. The objective of the commissioning tests is to demonstrate the general performance and integrity of the system. Basically, there are three series of tests. The first step consists of testing each system component to check their performance and optimize data. The second step focuses on the complete system. We ensure that its performance conforms to requirements. The last step is often forgotten, but is, however, a very important function. It involves disruptive tests. Once all these tests have been carried out and when we can confirm that the entire system and its components conform to standards, we are ready to start operating the system and take advantage of WDM technology.

5.3.1 Transmitters

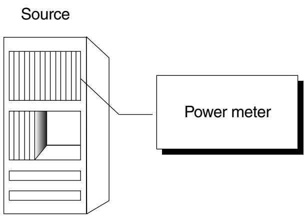


Figure 5.10 The power meter provides source power levels with great accuracy.

The transmitter output power should be measured, using a power meter or an OSA and, possibly, a calibrated variable attenuator. An estimate should be made of the probable error and the result quoted appropriately; i.e., X±Y dBm.

The central frequency should be measured using a calibrated wavelength meter and the result related to the ITU grid.

5.3.2 Receivers

The receiver sensitivity parameter of most value is the input power for a specified BER. It is measured using a BER test set, a variable attenuator, and a power meter. It should be measured for all the ITU channels likely to be used in the application.

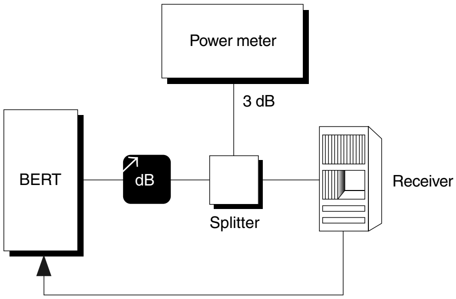


Figure 5.11 BER tester provides the receiver's sensitivity limit.

Receiver crosstalk is usually described in terms of the spurious output present in each channel in turn, in the absence of an input signal in that channel, while signals are present in all other channels. Many modern OSAs include the capability to measure this integrated value of crosstalk directly.

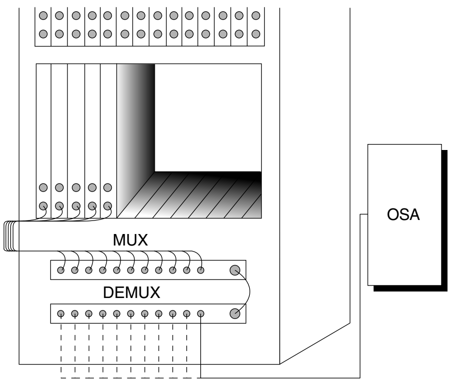


Figure 5.12 The OSA measures crosstalk at the receiver end.

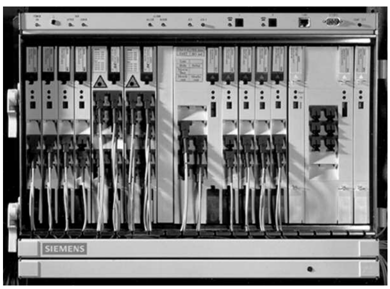


Figure 5.13 Transponder (transmitter/receiver) courtesy of Siemens

5.3.3 Optical Amplifiers

The output power of an EDFA is measured at saturation; i.e., when an increase in input power produces no increase in output power. The measurement is taken at 1550 nm using a tunable laser and a calibrated power meter.

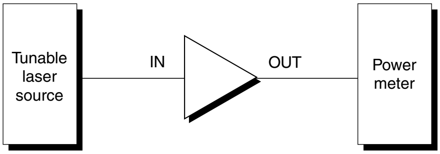
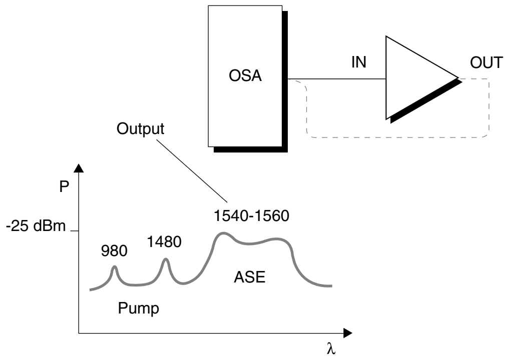


Figure 5.14 The tunable laser sweeps the EDFA bandwidth.

The gain flatness for large signals can be measured with the same setup, varying the input wavelength through the 1550 nm window in 1 nm steps and noting the output power at each wavelength.



The bandwidth of an EDFA is the range between the wavelengths at which its gain falls by 3 dB, measured using an OSA. It should normally exceed 32 nm (i.e., 1530 to 1562 nm).

Figure 5.15 Bandwidth measurement with an OSA

Remnant pump power is a measure of pump energy that escapes from the EDFA. It is measured separately at the input and output of the unit, using an OSA. The input measurement is made at 980 nm, the output at 1480 nm.

Amplified spontaneous emission (ASE) is measured similarly, at both the input and output, using an OSA and scanning the complete gain band. The result is generally given as a power spectral density, i.e., in dBm/nm (or, often, in dBm/0.1 nm).

5.3.4 Multiplexers and Demultiplexers

The proper operation of multiplexers and demultiplexers is obviously central to obtaining useful network throughput, and quite a number of parameters are significant. All should be measured in a stable environment, in combination with other components whose behavior has been checked. In general, tests must be made at every channel wavelength used—or likely to be used—in the link.

The input power-handling capabilities of demultiplexers should be tested to confirm that the output BER is acceptable when they are fed directly from an EDFA. In an installed network, this measurement is accomplished using a BER test set at one end of the link.

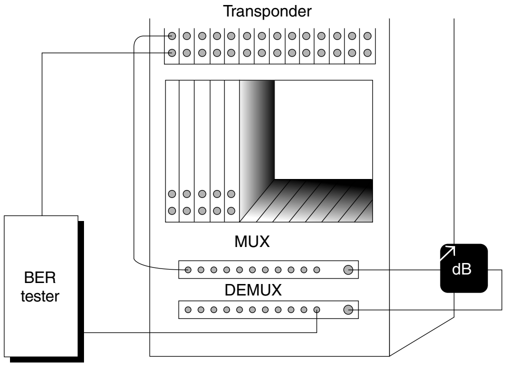


Figure 5.16 BER testing on a single WDM rack with an attenuator to simulate the link losses

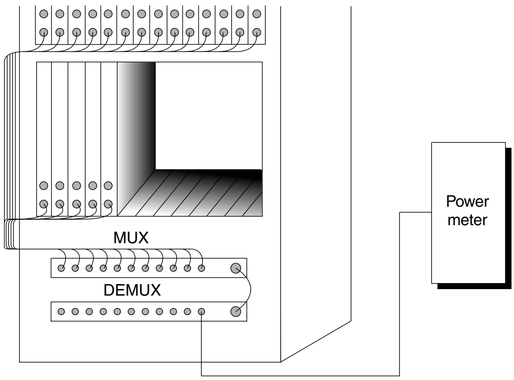


Figure 5.17 The power meter provides the power uniformity of all output ports.

The output power uniformity of a multiplexer is the peak-to-peak variation in power across all channels, with all transmitters active, measured with an OSA. The maximum variation should be less than 3 dB, to avoid introducing serious inconsistencies among the characteristics of different signal channels.

The corresponding parameter in a demultiplexer is the output power level for each channel, measured using a calibrated power meter. The usual acceptance level is –20 dBm.

Insertion loss is closely related to power uniformity. For a multiplexer, it can be measured using either a tunable source or a set of individual channel transmitters and an OSA, looking alternately at the input ports and the output port, to obtain an insertion-loss figure for each channel. An alternate technique uses individual channel transmitters, activated one at a time, and a power meter at the output.

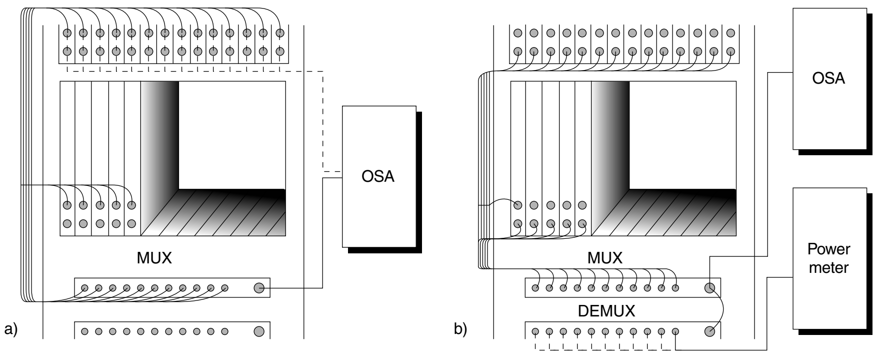


Figure 5.18 Insertion loss is measured using a) an OSA at the mux level and b) a power meter at the demux level.

The central wavelengths and the bandwidths of the individual channels of both multiplexers and demultiplexers are important characteristics, and crosstalk can be estimated from them. These spectral qualities are measured using an OSA, with a wavelength meter for calibration. In most applications, the central wavelengths should correspond with ITU grid values. The bandwidth of each channel (the width at –3 dB) should be less than 0.2 nm.

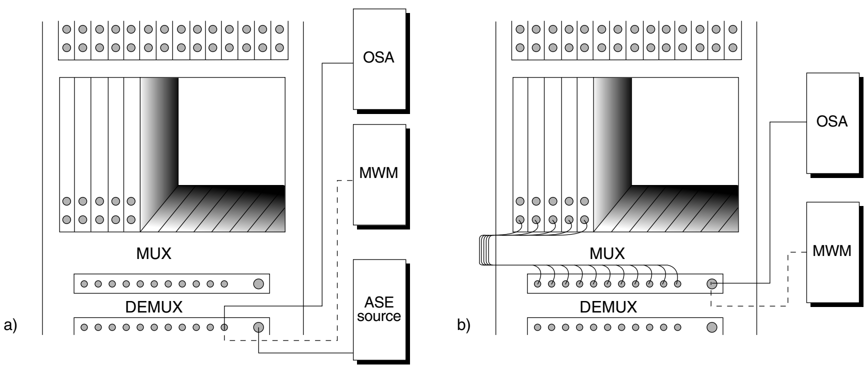


Figure 5.19 Channel central wavelengths are measured using a) an ASE source and an OSA for the demux and b) the OSA with the system sources for the mux.

Directivity is of particular importance in multiplexers, and it is usually checked during commissioning by connecting a laser to an input of the multiplexer and by connecting an OSA at every other input port.

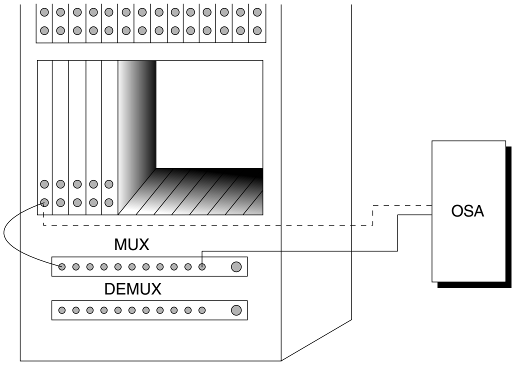


Figure 5.20 Mux directivity is analyzed with the OSA.

5.3.5 System-Level Testing

In addition to the various component and sub-assembly tests already outlined, a system-level performance test is obviously an essential part of commissioning a network. Its purpose is to demonstrate overall functionality and the integrity of data transmission in all the channels provided.

A typical DWDM multiwavelength composite signal passes through one or more optical amplifiers before arriving at its destination, where it is demultiplexed and the original information channels are retrieved.

The single most useful parameter characterizing such a system is the optical signal-to-noise ratio (OSNR), and two different measurement points are suggested. First, a single, time-averaged measurement is taken at the input to the demultiplexer. An OSA is used to examine the signal at this point and the OSNR is determined at different spacing depending on the system vendor requirement (by comparing the channel peak signal with the noise just outside the channel). An average value exceeding 18 dB is usually acceptable.

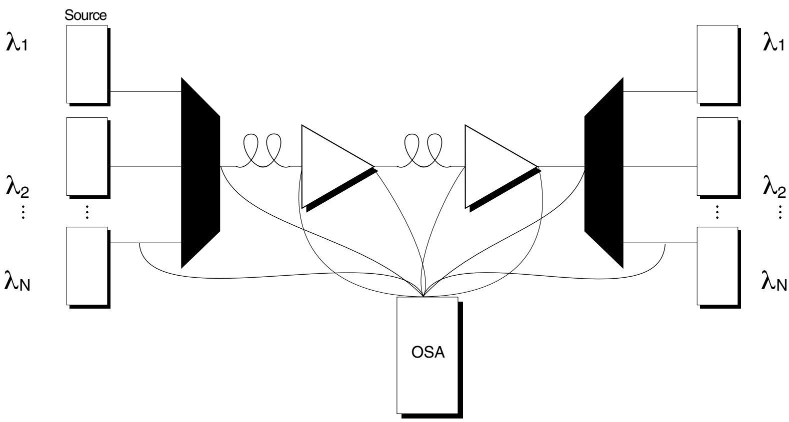


Figure 5.21 The OSA is used at any point along the link to characterize the system.

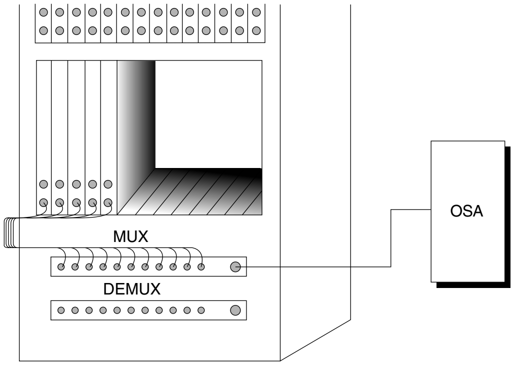


Figure 5.22 The OSA is the best instrument to measure OSNR.

Second, SNR is measured at the inputs and outputs of each of the optical amplifiers in the link, and uses the value to describe the overall link performance. A figure exceeding 21 dB is generally required for a 2.5 Gb/s system.

The uniformity of the transmitter power is also of interest. It is generally quoted as the difference in power between the strongest and weakest channels, measured with an OSA at the output of the first optical amplifier (fed by the multiplexer). The OSNR should be high at this point (>28 dB for a 0.1 nm bandwidth) and the power variation among channels should not exceed 2 dB.

Both the short- and long-term error performance should be checked. A standard link configuration is used to measure the short-term rate: six channels spaced at 50 GHz, each having a span loss of 25 dB, for example. Using a BER test set, the user can confirm that the bit error rate in each channel is acceptable (under 10^{-12} for a 25 dB span loss).

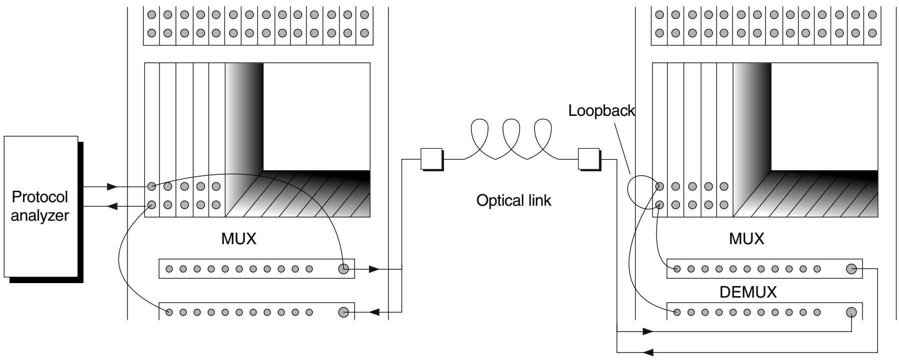


Figure 5.23 A protocol analyzer displays the performance of every channel over a loopback optical link.

The long-term error performance is also checked with a BER test set, at a realistic signal level (–15 dBm). The test should span a 24-hour period, so it is usually impractical to check every channel individually. Two good candidates are the channel that exhibits the lowest OSNR and the one with the highest power.

An idea of the fragility of the link can be obtained by disturbance testing: removing and reinserting modules from channels at random while observing the signals in the remaining channels. Only the signal in the channel suffering the disturbance should be affected.

The wavelength or frequency stability of the channels should be checked using a wavelength meter. The frequency of each channel should stay within ±5 GHz of the nominal frequency for systems using a channel separation of 50 GHz.

A system-level cold-start test should also be performed. With BER monitoring equipment on a suitable number of channels, all the power should be turned off. After a suitable period (which will depend on the time constants of the power supplies and the maximum possible delays in control paths, but which should be at least a minute) the power should be restored. It is important to note the time taken for the signal paths to be restored and for all appropriate management functions to return to normal. There should be no spurious alarms.

5.3.6 Alarm Processing

Most of the modules used in optical networks—transmitters, amplifiers, etc.—include one or more alarms, which are triggered by variations of various parameters from specific operating conditions. In some cases, alarms of graded levels are provided to give an indication of the urgency of repair.

Alarm testing in general implies the deliberate modification of one or more operating parameters in a system that is otherwise in proper working order, to verify that appropriate alarm signals are generated.

For a transmitter, parameters monitored include the output power, the temperatures of the heat sink, the laser itself, and the grating, if present, as well as the laser and thermo-electric cooler (TEC).

The same parameters may trigger alarms on the laser pump module of an EDFA. In addition, loss of either the input or output signal should generate an alarm.

In a receiver, the presence of an output (electrical) signal is monitored, as is the grating temperature, if there is one.

Analogous monitoring should be performed in the supervisory channel, including all the relevant signal levels, drive currents, and temperatures.

Another set (or level) of alarms deals with disruptive failures: the complete loss of a signal, for example, rather than a value that is not in line with specifications. The alarm system should respond appropriately to disconnecting such things as the input to a transmitter, the input and output of an amplifier, all channels entering a demultiplexer, or a single channel at a receiver. It should, of course, react properly to loss of power at any point in the link.

The safe shutdown of EDFAs is a special case of disruptive failure. When the input signal is lost, not only must the appropriate alarm be triggered, but the pumping lasers must also shut down within the time period allowed by the technical specifications for the unit.

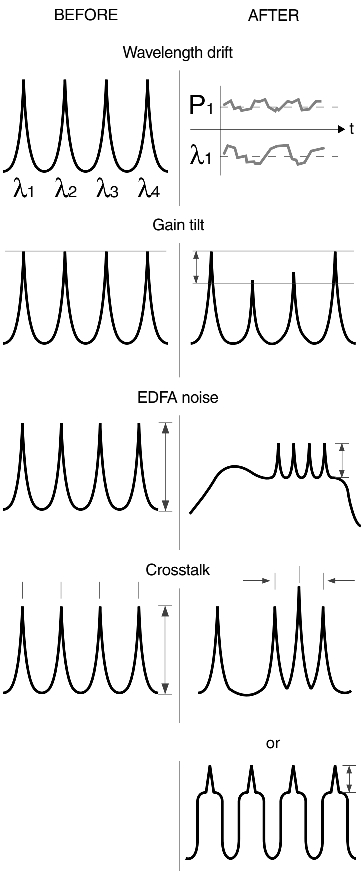


Figure 5.24 Problems that might occur during transmission

5.4 MAINTENANCE

Dense WDM systems have been around only since the mid 90s, so it is still difficult to identify with any certainty the new maintenance issues that will arise. High among problems likely to be encountered, however, is an increase in the bit error rate in a single transmission channel, a situation that could arise because of a drift in the wavelength of a distributed feedback laser source, an uncorrected gain tilt (variation of gain with wavelength) in an EDFA, an increase in EDFA noise, or an unexpected variation in the spectral transmission characteristics of some other component. In the extreme, single-channel degradation may reach the point at which the signal of a particular wavelength is lost completely. Whatever the extent of the loss, field test equipment and procedures must be available to identify the offending part or sub-system quickly and unambiguously.

All of the parameters encountered in the manufacture, qualification, and installation phases of network management are of potential concern during maintenance, but several of them in particular are good candidates for frequent monitoring, as they are direct indicators of possible performance degradation.

5.4.1 Optical Signal-to-Noise Ratio

Most degradations in transmission quality will be accompanied by a drop in the observed signal-to-noise ratio, so measurements of this parameter, for each transmission channel, are certainly among the most important to be taken during both routine maintenance and troubleshooting operations. The optical signal-to-noise ratio is relatively simple to obtain using an OSA. It is the ratio (or difference, when the values are expressed in dBm) between the peak channel power and the noise power within the channel bandwidth. Most power-measuring test instruments will give OSNR values automatically.

5.4.2 Losses

Losses in WDM systems must be examined channel by channel, and the best instrument for the purpose is the OSA, possibly backed up by a wavelength meter for spectral calibration and verification.

Standard methods of characterizing optical return loss have been discussed, using a source, coupler, and photodetector to measure the power reflected by the link, which would not be useable during the test. An OSA may be used as a detector to investigate wavelength dependence. However, in the field, useful results can usually be obtained more simply, using a small, portable backreflection meter or at the system level with the remote fiber test system (RFTS) working with actual network signal traffic as much as possible.

5.4.3 Polarization Mode Dispersion

Of the three methods to measure polarization mode dispersion—Jones Matrix Eigenanalysis, wavelength scanning, and interferometry—only the third is well suited to field use. It is fast, does not require simultaneous access to both ends of a link, and can measure large values of PMD over long distances.

5.4.4 Chromatic Dispersion

Although several methods have been described to measure chromatic dispersion, all four require specialized equipment and care in interpreting results, so the routine measurement of this parameter during maintenance operations is unlikely. The long-term impact of chromatic dispersion on dense WDM systems is not yet well understood, and major developments in field equipment to manage it in installed fiber may yet be needed.

By using a programmable variable optical attenuator and a BER test set, parameters such as receiver sensitivity, input power range, signal degradation, and loss of signal thresholds can be checked.

5.4.5 Optical Gain

The optical amplifier—almost certainly an EDFA in a dense WDM system—is a key component of any optical link, and maintenance personnel must be able to check its performance in the field.

Gain and gain redistribution can be measured using an OSA, preferably one with memory. Input power is measured for each channel and the data is stored. The EDFA output is then examined and the channel levels compared with the stored values, giving both gain and the distribution of gain among the channels. Usually, noise levels (OSNR) can be checked at the same time. The total power can be calculated by integrating the individual channel contributions, or a separate power meter can be used.

5.4.6 Wavelength

Accurate measurement of central wavelengths calls for interferometric techniques, i.e., a wavelength meter. For field use in dense WDM systems, the absolute wavelength accuracy should be better than about 0.005 nm. Signals may be weak, so a wide dynamic range, 30 to 40 dB, is needed. An OSA may be needed, in addition to the wavelength meter, to meet this requirement.

A wavelength meter can also be used to monitor channels over time to detect wavelength and power drifts.

5.4.7 Crosstalk

Measurements of crosstalk in the field are facilitated by the data-storage capability of modern OSAs. By using an optical switch, the operator can test each channel in sequence without changing connections between measurements. The power within each channel is stored and used to calculate crosstalk after all channels have been probed.

5.5 MONITORING

Monitoring is not a test in itself, but rather the continual verification of live channels through whatever individual tests are feasible and appropriate. It is used both to detect variations in any optical characteristic of the network that might affect system performance and to gather statistical information. Monitoring functions range from the scheduling and management of tests to the analysis of the data acquired.

Monitoring is particularly important in dense WDM systems, which are very sensitive to optical phenomenal such as dispersion, crosstalk, central wavelength drift, and so on. The ability to perform repeatable tests on critical parameters is essential if the user is to be able to recognize and respond quickly to indications of instability. A good live-channel monitoring system provides constant information about system performance, both specific and statistical.

5.5.1 Optical Supervisory Channel

An optical supervisory channel (OSC) may be used, rather than monitoring a live channel, to test a system. An OSC is a single channel dedicated to the continuous observation of operations and transmission efficiency. It is used to detect failures, power losses, or any significant change to signal integrity. Instead of specific—possibly disruptive—tests at scheduled times, the OSC is used to transmit appropriate tests and control signals continuously. Because it can carry control information, its continuity must be assured, so a wavelength outside the EDFA operating band is usually assigned to it.

OSC monitoring normally does not result in routine reports or statistics: if the system is operating correctly, no such reporting is needed. The OSC is simply a means to keep a constant eye on the overall network behavior, not to perform individual component tests. A functional and reliable OSC test helps the system controller to maintain constant optical power and to guarantee the quality of network transmission for the most efficient use of network resources. If the OSC detects a variation in signal integrity, a flag is raised to notify the operator.

Although binding standards for the OSC do not exist, and a number of possible approaches are under study and in actual use, a consensus in the industry presently favors a wavelength of 1510 nm or 1625 nm. This is because it lies outside the EDFA operating band, yet is close enough to it to provide useful monitoring. Because components for use at 1510 nm are not yet readily available, other wavelengths have been considered, such as 1480 nm and 1310 nm, for OSC functions, depending on the system vendor.

In itself, an OSC calls for no specific test equipment; the additional equipment it requires depends entirely on the parameters one chooses to monitor. If losses at splices or connectors are of concern, a power meter or—even better—an OTDR is needed. An OTDR can also check for certain potential fiber problems. Certain fiber strain defects may be easier to detect at the OCR wavelength than in the EDFA band. And optical loss budgets can be monitored with a variable attenuator and an optical loss test set.

Another supervisory approach dedicates one of the DWDM channels to the monitoring function. Although this technique lacks the invulnerability to EDFA failure of a separate OSC, it does allow standard SONET/SDH protocols to be used to detect routing errors and transmission defects.

One solution to the problem of invulnerability to EDFA failure is to monitor the spectral characteristics of one or several channels in parallel. The addition of spectral measurement instruments to the remote test unit (RTU) of an RFTS would allow easy and appropriate monitoring of transmission systems.

5.5.2 Remote Fiber Test System

A variety of instruments can be used to monitor networks. The most usual are the multiwavelength meter and the OSA, but in many circumstances, a PMD analyzer, an optical time domain reflectometer (OTDR), or smaller testing tools, such as a power meter, reflectometer, or backreflection meter, may be called for. Many of these capabilities are combined in the RFTS: probably the best solution for a complete monitoring of the live system.

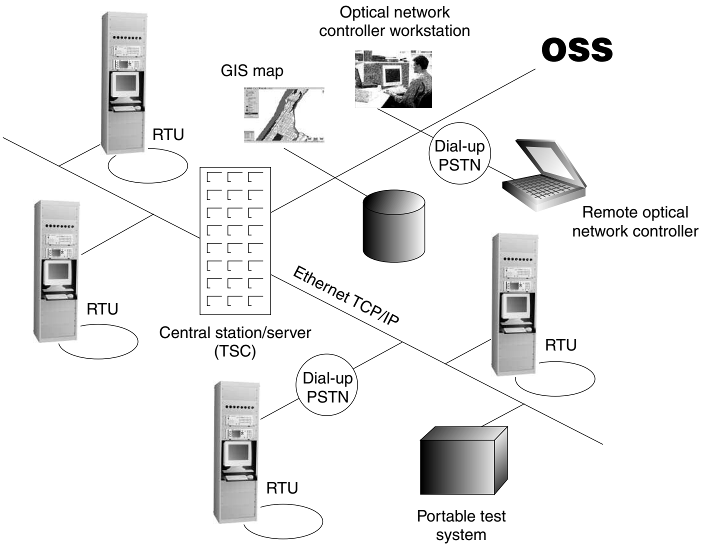


Figure 5.25 Typical deployment of a complete RFTS

RFTS units are seen as key elements in providing many of the supervisory and maintenance functions needed in fiber networks. Their widespread use can be attributed to very real cost/benefit advantages:

- A strong call for quality of service (Q_oS) – continuous monitoring of a network is an important strategic advantage for service providers.
- A significant increase in revenue per fiber – the speed advantages of dense WDM networks (both OC-48/STM-16 and OC-192/STM-64) can be realized in information-carrying terms only if performance can be guaranteed at the channel level.
- The high cost of maintenance – a test system that provides automatic surveillance of the physical network eases the workload of maintenance crews and directs their attention where it is most needed.

Fast and easy fault localization is the key benefit to an effective monitoring system, but the capability to check the suitability of installed fiber before performance enhancements are undertaken can also often be significant.

However, few, if any, of the RFTSs now in use on non-DWM networks are actually used to identify transmission faults. Instead, standard transmission protocols like SONET or SDH perform that function, reacting quite rapidly to interruptions (i.e., in less than 120 ms). SONET switching and network topology protocols can then be used to heal the network without interrupting service to its users.

But dense WDM is not completely covered by protocol-level measures. This new technology brings a new layer—the optical spectrum—into the network hierarchy, and no protection is available for WDM channels at the physical level. In response, system providers are attempting to provide limited spectral supervision of dense WDM transmission systems.

Several different transmission system monitoring techniques, incorporated into RFTS units, could bring a completely new dimension to fiber supervision.

- **Spectral monitoring – In the case of a channel fault**

  As an OTDR detects faulty fiber in a simple link, an OSA can detect and identify a faulty channel in a DWDM system. A diagnosis can be made very quickly on the probable cause of the problem—OSNR, peak power, or channel wavelength—and appropriate corrective action can be taken. Even in the case of a complete loss of a channel, the overview an OSA gives of the other DWDM channels can provide crucial information about potential problems that may be pending because of the automatic redistribution of EDFA gain.

- **Spectral monitoring – Preventive maintenance**

  Preventive maintenance of transmission systems can also benefit from a spectral monitoring system. Although DFBs are very stable over short periods, they are generally considered to be the key issue determining performance in the medium term (over a year or so). Considering the very tight channel bandwidth (0.1 to 0.2 nm) of today's most advanced systems, it is a challenge to maintain adequate spectral stability over the entire life of the system: wavelength variations as small as 0.02 nm can cause loss of a signal channel. With its excellent wavelength accuracy (0.003 nm), an integrated multiwavelength meter is therefore a valuable tool to perform long-term drift measurements on DFBs and to highlight potential problems.

- **PMD monitoring – Optical link evaluation for OC-192/STM-64 bit rates**

Polarization mode dispersion is also increasingly a major limitation to network performance, and its unpredictable nature has led to the need to continuously monitor the PMD behavior of some links used at OC-192/STM-64 bit rates. PMD analyzers are also of interest for long-term spot checks in a network. Integrating their functions into an RFTS would provide an often-needed capability. One can either monitor the average PMD value over the link or monitor the DGD variation as a function of wavelength. The last method offers a great qualification of the maximum and minimum DGD with regards to every channel.

There is tremendous interest in the industry to monitor newly installed systems to recognize symptoms of trouble before they lead to channel or system failure. The optical supervisory channel is now widely deemed to be inadequate to provide the quality of service needed in the competitive world of telecommunications. An evolutionary approach that incorporates needed measurement tools in a self-contained RFTS promises to provide a solution to meet everyone's objective of building and maintaining efficient, reliable transmission networks.

5.5.3 Monitoring and Troubleshooting: An Example

Operators and system maintainers must evaluate transmission quality on the fiber almost continuously. The goal of system testing is to demonstrate overall system functionality and the integrity of data transmission. To minimize the time and effort required, first-stage tests focus on examining the signal at the end of the link to check that optical performance is optimal before testing components individually. The next steps are increasingly specific, as we obtain more information about particular problems. Figure 5.26 outlines the steps in an effective test procedure.

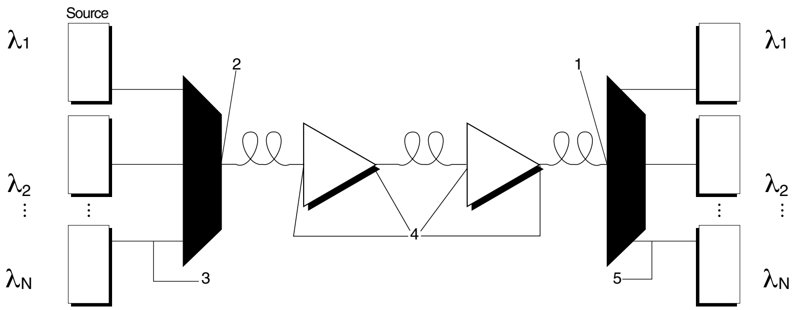


Figure 5.26 Testing points during troubleshooting

1. The first test should be performed at the demultiplexer at the end of the link, to see if any further tests are needed. A wavelength meter can be used to check the OSNR and the wavelength accuracy of each channel. The OSNR at the end of the link should be greater than 18 dB for an acceptable BER (10–13, for example); OSNRs of 22 dB or less are typical. Depending on the system and the detector type, the channel power should be about –8 dBm. The channel wavelength should be within a few tens of pm of the nominal value (a measurement of this accuracy calls for a wavelength meter).

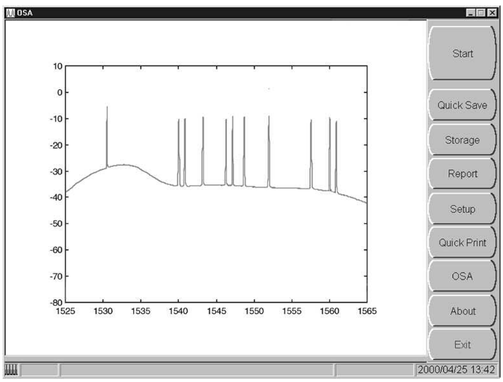


Figure 5.27 OSNR measurement at the end of the link

2. If the first step indicates a problem in the link, the transmitter power level at the output of the multiplexer is the next parameter to test: its specified value might be from –5 to 2 dBm, depending on the system provider. If there is a discrepancy at this level, the multiplexer should be checked for excessive loss.

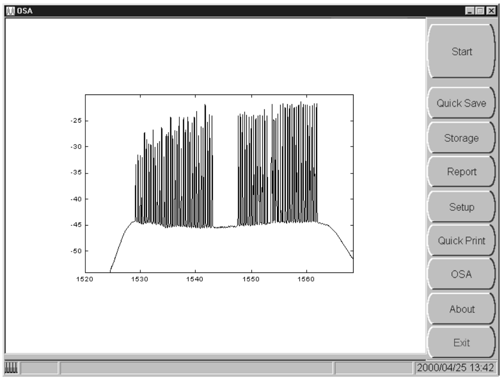


Figure 5.28 High OSNR obtained at the beginning of the link

3. The specific results of the previous tests will probably have identified the channel or channels in difficulty. The power and central wavelength of the appropriate source lasers should be checked.

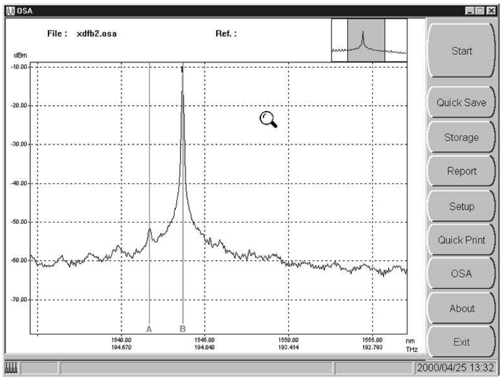


Figure 5.29 Typical DFB spectrum of a WDM system

4. EDFAs are the next candidates: their gain should be linear and uniformly distributed among the channels. A gain tilt of more than 3 dB may exceed specifications.

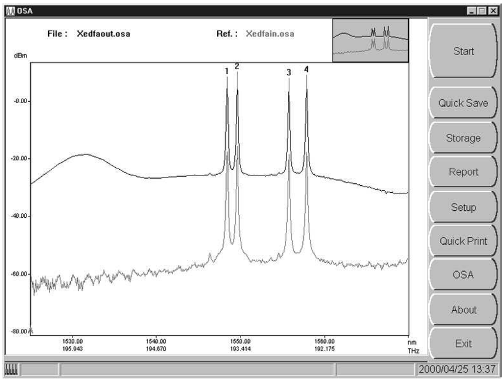


Figure 5.30 EDFA gain characterization with input and output signals

5. Digital test systems (SDH, Sonet, IP, or others) can help ensure transmission quality. The minimum input power for a good BER should be over –20 dBm at the detector level. The test is no longer of optical concern and electrical equipment is needed.

After checking all these previous parameters and procedures, the system integrator is ready to "turn-key" the new DWDM system and fine-tune the last details before final commissioning. Now that the system is working, it will surely be audited by the end user via a quality control procedure. The idea is to check-list client requirements. Those requirements are strongly influenced by both the recommendations of the standardization bodies and industry trends. The next chapter will take a look at these standardization issues and their impact on customer performance requirements.

CHAPTER 6

NEW STANDARDS FOR DENSE WAVELENGTH-DIVISION MULTIPLEXING

6.1 WHY DO WE NEED STANDARDS?

The emergence of standards is a sure sign that a particular technology has progressed significantly in its evolution from birth to widespread use. Timely, well-configured standards protect users from embarking on projects using design parameters or devices that are unlikely to be supported in the long term. Standards also provide guidance to innovative manufacturers on the most promising areas for product development. Although standards often evolve, each generation provides a stable environment in which useful systems can be implemented using devices and equipment whose fabrication is comfortably within the capabilities of providers at that time.

Even more important, adherence to standards permits systems from different service providers to be interconnected and interoperated with relative ease, even though they may use dissimilar equipment and they may serve different needs. Without any standards, interfaces between such systems would be difficult or impossible to achieve; with less-than-optimum standards, performance compromises would be necessary, while with appropriate standards, multi-owner, multi-supplier networks can achieve overall levels of performance consistent with state-of-the-art technology.

Finally, standards benefit both telecommunication providers, by encouraging a multi-vendor environment that fosters healthy competition, and equipment suppliers, by furnishing the basis for high manufacturing volumes that decrease unit costs.

The influence of standards is well exemplified by the success of the Synchronous Optical Network Standard, or SONET, in North America, and the Synchronous Digital Hierarchy Standard, SDH, in Europe and Asia, which today allow the straightforward interconnection of networks using equipment from different vendors. Together, SONET and SDH standards are followed in virtually every optical network throughout the world.

6.2 HOW ARE STANDARDS DEFINED?

International standards in the telecommunication, industry are defined primarily by two organizations. The first, the International Telecommunication Union (ITU), based in Geneva, is concerned with the definition of application standards, while the second, the International Electrotechnical Commission (IEC), deals with product standards. Both work closely with major national and regional standardization agencies such as the Telecommunications Industry Association (TIA) (USA), the European Telecommunication Standard Institute (ETSI) (Europe), and the TTC (Japan). See Table 6.01.

Application-Oriented	Product-Oriented	Level
ITU	IEC	International
ETSI	CENELEC	Europe
TTC	JISC	Japan
EIA/TIA		North America

Table 6.01 Standards development organizations

Voting in these international organizations is by nation, with the vote of each participating country representing the views of an appropriate mix of government and telecommunications industry spokespersons from that nation.

The decision process is based on the circulation and discussion of draft proposals until unanimous approval is reached. The inertia inherent in such a process means that standards usually lag behind technology by several years, but the eventual result is worth the wait, because the standards, once published, usually apply clearly and unequivocally to mature and well-defined technology. These standards can then be used directly to implement new systems, without the iterative steps that would be needed in the absence of such guidance.

6.3 DWDM STANDARDS DEVELOPMENT ORGANIZATIONS

The very rapid development of dense WDM technology and the pressing need to bring its benefits to the field have led to the involvement of many national and international organizations in order to develop the standards needed to govern present installations and to guide future development.

In the United States, the TIA, Telcordia Technologies (formerly Bellcore), and the Institute of Electrical and Electronics Engineers (IEEE) perform standards work for several industries, including fiber-optic telecommunications. Two major bodies develop voluntary standards at the international level: the IEC and ITU, both based in Geneva, Switzerland.

6.3.1 International Telecommunication Union (ITU)

The ITU is a multilateral United Nations organization that brings together governments and the private sector to coordinate global telecommunications networks and services. It deals mainly with applications. The ITU covers three sectors: radio communications (ITU-R), telecommunications standardization (ITU-T), and telecommunications development (ITU-D). The sector most concerned with optical networks, ITU-T, develops voluntary standards to address technical, operating, and tariff issues in global telecommunications. Fourteen study groups, each composed of representatives from member countries, work continually on specific topics and make recommendations for standards. Every four years, the World Telecommunication Standardization Conference (WTSC) assembles members to define general policy for the sector, establish new study groups, and approve a four-year work program.

ITU standards are voluntary, but compliance is widespread, because standards facilitate network interconnectivity and make it possible for telecommunications suppliers to provide services around the world.

ITU-T Study Group 15

The ITU-T sector forms ad hoc groups to address specific issues (and dissolves them when the work is complete). Fourteen such study groups are currently active, and SG 15 (Transport Networks, Systems, and Equipment) is the one most involved in DWDM applications.

SG 15 focuses on developing international standards relating to transport networks, switching, and transmission systems/equipment, including the relevant signal-processing aspects. Recently, for example, it began to address the transport of Internet Protocol (IP) data signals. Areas of major importance, which have attracted a number of new organizations to the ITU-T, are network access and issues related to optical networking. With about 345 participants from 26 countries and 78 scientific and industrial organizations, and with its focus on transport-related standards, SG 15 is one of the largest ITU-T study groups.

SG 15 is currently working on some 89 new or revised recommendations addressing such topics as

- digital subscriber line access (xDSL)
- signal processing (echo control, equipment for interconnecting GSTN, and IP networks)
- SDH/SONET (format, equipment, network architectures, IP over SDH/SONET)
- ATM equipment (including IP-over-ATM equipment)
- optical technology (systems, amplifiers, components, all-optical networking, IP on optics)
- management of transmission systems and equipment (functions, services, and information modeling of network elements, including IP-related aspects)

SG 15 is divided into four working parties (WP): Network Access, Network Signal Processing, Multiplexing, and Switching and Transmission. The last, WP 4/15 (Transmission), is responsible for all the aspects concerning transmission media and systems, with particular reference to optical fibers, systems, sub-systems, and components.

In the optical field, WP 4/15 plays the role of initial leader for the Optical Transport Network (OTN) and is charged with:

- preparing a framework recommendation on optical networking
- preparing and updating of a list of optical networking activities
- coordinating optical networking activities inside the ITU-T
- coordinating activities for IP-over-WDM

Formal questions particularly relevant to DWDM systems that have been the subject of recent WP4/15 recommendations include

- characteristics and test methods of optical fibers and cables (Question 15)
- characteristics of optical systems for inter-office and long distance (Question 16)
- characteristics of active and passive optical components and sub-systems (Question 17)
- characteristics of optical fiber submarine cable systems (Question 18)
- reliability and availability of optical systems (Question 19)
- characteristics of optical networking (Question 20)
- optical interfaces for equipment and systems relating to the synchronous digital hierarchy
- optical safety procedures and requirements for optical transport systems
- optical interfaces for multichannel SDH systems with optical amplifiers (G.692)
- definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems
- generic characteristics of optical amplifier devices and subsystems

Each of these study areas must be examined in considerable depth, with particular attention paid to the way technology is evolving, so that the lag between the leading edge and the commonplace is kept to a minimum. In the area of characterizing optical fibers and cables, for example, the WP recently reviewed and altered recommended test methods to include those pertinent to new fiber types, and added new methods dealing with non-linearity and non-uniformity.

Detailed attention is also paid to the way complex phenomena, such as chromatic dispersion and polarization-mode dispersion, are defined and measured, so that component and system measurements can be exchanged among suppliers and users with confidence.

An area of particular interest—because of the phenomenal growth rate in Internet access—is the use of the Internet Protocol (IP) directly in optical networks. The WP is studying the question and has recommended a structured approach, one aimed to ensure that routing equipment under development or being installed will now be compatible with future steps to provide IP-over-WDM, which promises a dramatic reduction in the bandwidth needed for Internet communication.

Another area under study by the WP is the development of standards for new, high-capacity WDM network applications. A wavelength grid with spacing of 50 GHz has been proposed that is compatible with the present 100 GHz grid. Standards for systems up to 128 channels are included, as are those for lower capacity "inter-office" use and for unequally spaced channels (i.e., partially populated bands).

Work has also been undertaken towards developing specifications for TDM systems operating at bit rates greater than 10 Gbps, with due consideration to the eventual upgrade of these links to WDM. In particular, the status of key technologies to support 40 Gbps TDM transmission systems is under review.

Of particular interest to WDM testers is work currently underway on the uses of the 1625 nm region (1620 to 1660 nm) for remote fiber test systems (RFTSs), which are discussed in section xx, and for other monitoring applications.

6.3.2 International Electrotechnical Commission (IEC)

The ITU addresses application issues: protocols, the definition and characterization of link phenomena, the allocation of compatible channels, etc. The IEC, on the other hand, addresses standards for products. Its concerns are not only limited to telecommunications but also include electronics, magnetics and electromagnetics, electroacoustics, and energy production and distribution.

Approximately 50 countries are full members of the IEC; they have equal voting rights and are represented by National Committees. As much as possible, the National Committees—each of which is responsible for including the voices of public and private electrotechnical interests in its country—work together to provide consensus at the international level. There are also associate member countries, which have observer status but no voting rights. By setting international standards and producing technical reports, the IEC provides a solid foundation for national bodies to set regulatory standards. Adherence to standards is voluntary, even for IEC member countries.

The IEC has formal links with several other international standardization bodies, including the International Organization for Standardization (ISO), the ITU, the World Trade Organization (WTO), and the European Committee for Electrotechnical Standardization (CENELEC). At the telecommunications level, many of the most active members of the North American TIA are also members of the IEC.

Major decision-making at the IEC follows an established chain of command from the governing committee, known as the IEC Council, through other administrative bodies, down to technical committees (TCs), subcommittees (SCs), and WGs. There are approximately 200 TCs and SCs, and about 700 WGs, representing the knowledge of about 10 000 experts worldwide, who prepare the technical documents needed in drafting international standards. Any IEC member country, as well as any organization with official links to the IEC, may contribute to standards.

The TCs cover a multitude of topics, from household appliances to electro-medical equipment to superconductivity. TC 86, Fiber Optics, is a large committee covering fiber-optic communication systems and components including specifications and test and measurement methods. Its structure is outlined in Table 6.02.

STRUCTURE OF IEC TECHNICAL COMMITTEE TC86: FIBER OPTICS
Liaisons
Telecommunication Standardization Sector of the ITU (ITU-T) IEC Subcommittee 100 D (cabled distribution systems)
Working Groups
WG 1: terminology and symbology
WG 4: fiber-optic test equipment calibration
WG 7: discrete/integrated optoelectronic semiconductor devices for fiber-optic communications, including hybrid modules
Subcommittees
SC 86 A: fibers and cables WG 1: fibers WG 3: cables
SC 86 B: fiber-optic interconnecting devices and passive components WG 4: test methods WG 6: interconnecting device specifications WG 7: component specifications
SC 86 C: fiber-optic systems and active devices WG 1: systems and active devices WG 1: systems WG 3: optical amplifiers

Table 6.02 International Electrotechnical Commission (IEC) structure

As one would expect, the interests of those developing standards for products are unlikely to be vastly different from the interests of those developing standards for applications. Therefore, it is not surprising that many of the TC 86 activities are on subjects already mentioned as current ITU areas. Such topics include PMD, WDM, optical amplifiers, and fiber specifications.

The ITU work on choosing a reference test method for measuring PMD is reflected at a more practical level by the development by IEC TC 86 of PMD-related standards. For example, a technical report (IEC 61282-3) on calculating PMD in fiber-optic systems has been prepared. Published standards include PMD Measurement Techniques for Singlemode Optical Fibers (IEC 61941), which discusses all the commercially available PMD measurement techniques for singlemode optical fibers. Proposals for statistical PMD cable specifications, PMD test methods for optical amplifiers, and PMD measurement methods for optical components are currently under review.

Other recent work includes dispersion compensation, PMD in digital and analog systems, and the development of PMD power-penalty relationships.

A recently formed sector board, SB 4, addresses several topics related to the infrastructure of telecommunications networks that are relevant to WDM systems, including

- standardizing installation conditions and instructions
- DWDM techniques for optical amplifiers and fibers
- xDSL techniques for installed and new passive infrastructures
- major changes in fiber types and their influence on standards
- twisted pairs for outdoor applications, optimized for ADSL
- new developments in multimedia home cabling

Another concern is the attenuation (insertion loss) of DWDM devices. Document IEC 61074 from the IEC SC 86B defines terminology in this area. The same committee is working with the ITU-T on a rigorous definition of central frequency.

Generic specifications for optical amplifiers are provided in IEC Document 61291-1. A performance specification template for multichannel optical amplifiers, IEC 61291-4, is under discussion. A "black box" approach is taken to this and other product specifications: specifications that are as free as possible of application detail.

IEC 61291-4 discusses automatic gain control and the relevant operating input power range, gain equalization, clamping criteria and spectral hole criteria. It provides generic specifications and—through related standards—performance specification templates for digital, analog, and multichannel optical amplifiers, specific to various application areas (power amplifier, pre-amplifier, line amplifier, etc.).

The most important performance characteristics of optical amplifiers are covered:

1. Gain (IEC 61290-1)
   a) Small-signal gain in the forward and reverse directions
   b) Maximum value of the small-signal gain (absolute value, spectral profile and variation as a function of temperature)
   c) Overall spectral variation and wavelength band variation of the small-signal gain
   d) Small-signal gain stability
   e) Polarization-dependent gain variation

2. Optical Power Measurement (IEC 61290-2)

   a) Nominal signal output power
   b) Large-signal output stability
   c) Saturation output power
   d) Maximum input and output signal power
   e) Input and output power range
   f) Maximum total output power

Various limitations to the performance of optical amplifiers are included:

1. The noise figure (in dB) or noise factor (a linear value), which is one of the most important factors limiting the performance of EDFAs, can be measured following IEC 61290-3-1 (using an OSA and the interpolation method) or IEC 61290-3-2 (using an ESA and the Relative Intensity Noise (RIN) subtraction method) or IEC 61290-10-2 (the pulse method with a gated OSA).

2. The gain slope, which causes WDM signals on one side of the spectral band to be amplified more than those on the other. It can be tested following IEC 61290-4-1 (using a broadband source).

3. The return loss, critical because it can perturb adjoining EDFAs. It can be tested following IEC 61290-5-1 (using an OSA), or IEC 61290-5-2 (using an ESA), or IEC 61290-5-3 (with the tolerance method using a reflection generator).

4. Pump leakage to output and input, which also can generate interfering signals. It can be tested following IEC 61290-6-1 (optical demux test method).

5. Out-of-band insertion losses in the forward and reverse direction, which limit the total available power. The appropriate test is IEC 61290-7-1 (filtered power meter test method).

Working groups within IEC SC 86C are engaged in defining reflectance and reliability testing, establishing gain and noise figures, and setting performance specifications. One such example is IEC 61290-1-3, Gain by Optical Power Method, which demonstrates that a gain measurement for a single channel made with a power meter and bandpass filter can be as valid as one taken with an optical spectrum analyzer. This is a highly cost-effective approach to gain measurement in production environments, provided that values can be checked periodically with an OSA.

There is a major project to update the way fiber is specified, including standard test methods. Documents in the IEC 60793-1-x series propose fiber specifications organized by attribute and suggest appropriate restructured test methods.

6.3.3 Telecommunications Industry Association (TIA)

The North American standards and conformity assessment body for all areas of telecommunications, the TIA, has two committees dedicated to fiber-optic telecommunications issues: FO-2.0 (Optical Communications Systems), responsible for system and applications level standards and FO-6.0 (Fiber Optics), responsible for product standards. Each has a number of active subcommittees and working groups, among which FO-2.1.1 (Optically Amplified Devices, Subsystems, and Systems), FO-2.1.2 (Working Group on Single-Mode Transmission Design), FO-6.3.5 (Passive Fiber-Optic Branching Devices), and FO-6.6.5 (Single Mode Fibers) are the most involved with WDM-related issues. TIA is an independent organization under the American National Standards Institute (ANSI), with both private and public membership.

Many TIA members are also involved in ITU and IEC, and the Association maintains direct liaison with both.

FO-2.1.1 has recently addressed issues relating to optical amplifiers, including the definition and measurement of noise figure, round-robin test results, and relative intensity noise (RIN) artifacts.

A draft entitled Optical Fiber Standard Test Procedure, OFSTP-6—Measurement of Optical Signal-to-Noise Ratio—produced by FO-2.1.2 proposes a scheme using an OSA based on a Michelson interferometer, a diffraction grating, and/or a Fabry-Perot interferometer. It provides values of the resolution bandwidth required to receive less than 0.1 dB error in the signal-power measurement. For example, for a 10 Gbps channel, a bandwidth of ≥0.2 nm is needed; and for 2.5 Gbps or lower, ≥0.09 nm is required.

Guidelines and methods for the measurement of PMD and PDL have received recent attention from FO-6.3.5, especially for components to be used in WDM systems.

FO-6.6.5 has addressed such issues as non-linear effects in fibers, new low-OH fibers and PMD measurements based on the Jones Matrix Eigenanalysis (JME), and Poincaré Sphere Analysis (PSA) methods.

STRUCTURE OF TIA FO-2.0 AND FO-6.0 COMMITTEES

Liaisons

US Department of Defense (DOD)

Telecommunication Standardization Sector of the ITU (ITU-T)

IEC TC-86, SC86A, SC86B, SC86C, through technical advisory groups (TAGs)

FO-2.1	Subcommittee on Singlemode Systems	FO-6.3.6	Splices & Enclosures
FO-2.1.1	Working Group on Optically Amplified Devices, Subsystems, and Systems	FO-6.3.8	Reliability of Passive Components
FO-2.1.2	Working Group on Singlemode Transmission Design	FO-6.3.10	Connector Specifications
FO 2.2	Subcommittee on Digital Multimode Systems	FO-6.6	Fibers and Materials
FO-2.2.1	Modal Dependence of Bandwidth	FO-6.6.1	Round Robins and Multimode Optical Measurements
FO-2.3	Opto-Electrooptic Sources, Detectors, and Devices	FO-6.6.2	Fiber Specification Documents
FO-2.4	Subcommittee on Optical Terms, Definition, Document Control, and Safety	FO-6.6.3	Sensor Fibers
FO-2.5	Subcommittee on Outside Fiber Cable Plant	FO-6.6.5	Single Mode Fibers
FO-2.6	Subcommittee on Reliability of Fiber-Optic and Active Optical Components	FO-6.6.6	Step-Index Fibers
FO-6.1	Fiber-Optic Field Tooling & Test Instrumentation	FO-6.6.7	Fiber Coating
FO-6.1.1	Working Group on Metrology and Calibration	FO-6.6.8	Long-Term Fiber Reliability
FO-6.3	Interconnecting Devices	FO-6.6.9	International Standards Harmonization
FO-6.3.1	Reliability of Adhesives in Optical Ferrules	FO-6.7	Fiber-Optic Cables
FO-6.3.3	Ferrule/Fiber Geometrical Measurements	FO-6.7.1	Editorial Task Group
FO-6.3.4	Intermateability Standards	FO-6.7.10	Color Coding of FO Cables
FO-6.3.5	Passive Fiber-Optic Branching Devices	FO-6.7.14	Hydrogen Susceptibility
		FO-6.7.15	IEC Liaison/Ribbons
		FO-6.7.16	Cabled Ribbon Special Task Group
		FO-6.7.17	Impact Test Task Group
		FO-6.8	Specification Structure & Processing
		FO-6.9	Fiber-Optic Sensors
		FO6.9.3/6.6.3	Sensor Fibers
		FO-6.9.4	PN Connector Working Group

Table 6.03 TIA subcommittee structure

6.4 OUTSTANDING ISSUES

A number of tricky technical issues remain open, awaiting appropriate discussion and recommendations at the ITU-T and IEC levels. They include

- ITU specification for multichannel systems (one is expected soon addressing compatibility issues)
- upgrade of the ITU grid from 100 GHz to 50 GHz channel spacing; with 25 GHz spacing to come eventually
- standards for extended range DWM operation, from 1528 to 1602 nm
- channel counts of 128 wavelengths, with 256+ to come
- span loss targets of 22 dB to 25 dB
- optical supervisory or service channel specifications for 40 to 80 km point-to-point links
- optical supervisory channel assignment within the DWDM ITU grid, to provide simple optical treatment along with the signal channels
- further discussion of the +17 dBm power limitation, in place to meet Class IIIb laser safety requirements (more powerful lasers are available, up to 1 W, but Class IV laser safety would be expensive to manage and, thus, difficult to sell to investors)
- consideration of the present 1650 nm limitation, which appears to be immovable because of OTDR, fiber attenuation, and macro-bending considerations

As was pointed out earlier, solid standards are a strong contribution for new technology deployment as they provide the required, objective, general overview needed to arbitrate the different industry trends. The newest technology trend for the DWDM system is its movement to metropolitan networks, and even though the standardization organizations are working on this issue, many questions remain open, and new solutions to old problems are appearing every week. In the next chapter, we will take a look at this exciting new application of the DWDM system and will concentrate on its impact on testing issues.

CHAPTER 7

METROPOLITAN AREA NETWORKS

METROPOLITAN AREA NETWORKS

7.1 A NEW ENVIRONMENT FOR DWDM

Most of the deployment of fiber-optic technology in the recent past—especially that of DWDM technology—has been for long-haul service: OC-48 and OC-192 networks spanning distances of 50 kilometers and up. An entirely new area has now opened, however: the metropolitan area network (MAN), which provides communications service within cities and other restricted areas, right down to consumer cable service. Figure 7.01 shows the place MANs occupy in the communications hierarchy.

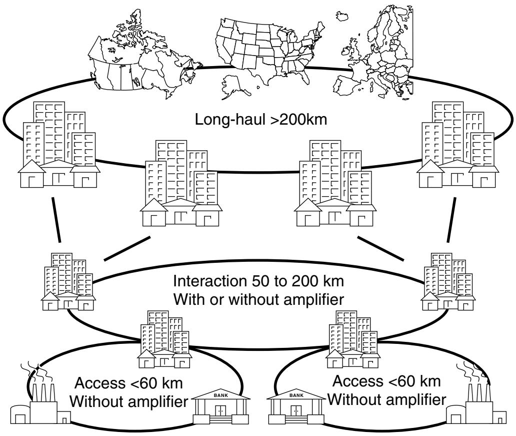


Figure 7.01 The WDM environment

Local exchange carriers face an increasing need for bandwidth, and laying new cable is usually very expensive in the urban environment, in particular for obtaining the rights-of-way, which is complicated by multiple civil jurisdictions and already-taxed cable supports and conduits. Increasing the channel capacity of individual fibers using TDM techniques is often unattractive because of the need for expensive equipment to add and drop low-traffic channels—and thus low-revenue channels— throughout the network.

In principle, DWDM techniques can provide the needed increase in capacity for metro areas. The problem has been to do so at a reasonable cost because of the high quantity of equipment to be installed in the metro networks in comparison with the long-haul scenario. However, DWDM equipment is now available for this new market, whose importance will grow significantly: estimated sales of about US$200 million in 1998 are expected to reach close to $2 billion by 2003.

Although only about 15% of clients in the residential market are expected to require 1.5 Mbps service between now and 2005, with only 20% of that group needing service at 2 Mbps or faster, demand in the small business sector will be more spectacular. By the end of 2005, up to 85% of small-business users will require data rates better than 2 Mbps, with 20% going as high as 45 Mbps.

Copper-based access networks cannot easily accommodate a capacity growth of this magnitude, so, to a significant extent, they are capping the growth in demand and customers are slow to ask for services that are not available for demonstration. Fiber needs to get into the local access network before metro WDM will take off.

7.2 DWDM TECHNOLOGY IN METRO NETWORKS

Metro DWDM technology is particularly appropriate for competitive local exchange carriers (CLECs), because of the reconfiguration flexibility it offers, which the supplier can translate into attractive options targeting a variety of market sectors. The transparency of optical transmission suggests that local transmission can be offered using native protocols (IP, Ethernet, etc.), with only a simple layer of SONET-like protection added. Incremental growth costs should be low, and the DWDM equipment needed for short metropolitan links should be significantly less expensive to buy, install, and maintain than the more complex equipment needed in long-haul operations, which are usually operating close to technological limits.

That is not to say that metro DWDMs will necessarily be simpler than their long-haul counterparts. In fact, flexibility will be much more significant for local carriers, and particular attention will be needed to design-in as many reconfiguration possibilities as can be imagined, with as few assumptions about transmission protocols as can be managed. A great deal of emphasis must be given to providing sophisticated management tools that will allow this flexibility to be used easily, quickly, and—above all—cost-effectively.

Installing metro DWDM does not necessarily imply replacing existing SONET networks: the two can live side by side, with parts of the metro DWDM carrying SONET traffic. Instead, good use must be made of the raw bandwidth offered by DWDM technology. For example, by using the many available channels to deliver services—SONET, IP, or ATM—each in its native format; metro DWDM systems can not only can accept traffic from devices supporting SONET interfaces, such as ATM switches and routers, but can also accommodate other protocols such as Gigabit Ethernet (GigE), FDDI, and ESCON. Although it may not be cost-effective to transmit "time inefficient" signals, such as Gigabit Ethernet, in their raw form on a dedicated long-haul DWDM channel, it may make sense to do so over the short distances typical of a metro system.

As the SONET portion of such a network reaches its limits, it can by converted, link by link, for DWDM use, which can grow as needed, at least while channel space is available. The old traffic can still be handled—SONET channels can be provided—while entirely new business is added at very low incremental costs.

Although metro DWDM link spans are characteristically short, they are not necessarily short enough to avoid the need for in-line optical amplification (by EDFAs, usually). Because needing or not needing EDFAs in the link represents a major cost break-point, metro DWDM networks are usually classified in one of two ways: interoffice or access.

Link distances in the former generally exceed 50 km, and they are subject to many of the optical and equipment constraints typical of long-haul systems. However, the requirement for flexibility remains high. For example, they may provide the top-level service of a CLEC. Although these link distances may require in-line optical amplifiers, they can often operate cost-effectively at low data rates, thus reducing system costs.

The short links of an access metro system provide compound benefits. First, EDFAs are not needed, saving considerable cost. Next, because EDFAs are not present, signal characteristics, such as wavelength tilt, are much less critical, so component selection, qualification, and maintenance are all simpler (although with no in-line amplification, insertion and other losses may actually be more critical in these components). Furthermore, non-linear effects in components or fiber are unlikely to present problems. Finally, the removal of EDFAs frees the system designer from using wavelengths outside the EDFA window, either for additional channels or to provide a wide channel spacing that will further relax the component quality needed. Taking full advantage of the potential simplifications offered in an access metro environment requires the investigation of a set of equipment and configuration options that is quite different from the choices that are relevant to the design of long-haul systems.

DWDM equipment for metro use is often configured similarly to the existing network, whose capacity it is supplementing in rings (either two counter-rotating rings or a single bidirectional cable) that are compatible with the SDH ring network architecture. Monitoring and protection schemes are available to provide rapid path switching (tens of milliseconds) should a component or the fiber itself fail.

In a ring-based DWDM network, channels must be added and dropped at arbitrary points around the circuit, so channel balancing may be difficult, although its importance will be greatly reduced if EDFAs are not present. However, the topology itself may present apparent problems to certain potential new applications. A tree-like network, for example, is most appropriate for the delivery of CATV services to the home, so it most be possible to extract tree-like behavior from the ring net. Fortunately, means have been devised to simulate tree, point-to-point, broadcast, and other distribution topologies on a DWDM ring network through appropriate use of the many channels available. Still, requirements for specific logical configurations may require some alteration to the physical network.

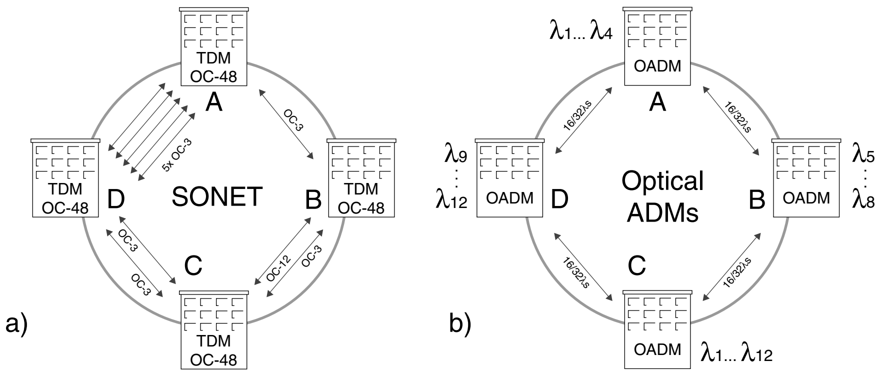


Figure 7.02 a) The TDM metropolitan ring is overloaded between A an D and b) WDM topology is the logical solution.

DWDM MANs (Figure 7.02-b) also offer an economic advantage over traditional links (Figure 7.02-a) because the complexity of equipment needed to add or drop a particular signal depends only on the characteristics of that signal. The add/drop equipment does not have to deal with the full bandwidth of all the information on the link. Costs are, therefore, closely related to actual benefits. And, of course, DWDM services can be added to a network link without disturbing the existing traffic—a consideration that is increasingly important as the need grows to provide day-to-day alterations in service.

7.3 MORE THAN JUST AN INCREASE IN CAPACITY

Whether the electrical-to-optical network transformation takes place suddenly or over a long period, replacing or supplementing single-channel or TDM metro networks with DWDM systems offers much more than an increase in traffic-carrying capacity.

Signals are no longer constrained to specific time slots or to specific protocols—protocols that heretofore have often been determined by network considerations rather than by the needs of the user of the service. A single network can simultaneously carry a variety of protocols—including data that is essentially analog—over a wide range of data rates. User-appropriate protocols—Ethernet, for example—can be handled transparently, without any need for signal conversion and without concern for particular transport-layer needs in the network.

The information on each channel and the integrity of transmission can be protected individually, to suit specific needs. In particular, present-day protection protocols such as SONET can be handled without special provisions. Routing can be flexible, to accommodate applications from point-to-point communications to data collection and broadcasting.

DWDM MANs offer all these advantages, plus the ability, in many cases, to interface signals easily with compatible long-haul networks, without concern for bit-rates and protocols. Components and systems are now becoming available for these applications: two-fiber, interoffice spans cost approximately US$30 000 to $50 000 wavelength, and access metro systems are somewhat less.

Extensive planning is needed to ensure that DWDM upgrades can provide all the SONET-like protection mechanisms that current customers require, while still offering the service-expanding new features inherent to DWDM technology. Price, immediate functionality, and future expansibility are all important considerations.

7.4 IMPACT ON TESTING NEEDS

Regarding the testing requirements for DWDM systems in the metro areas, the parameters to check are the same but the strategic and economic realities will affect the threshold values to be checked and the testing procedures. The first important change is in portability and simplicity. Given the much more populated network structure in the metro regions and the high volume of optical transmission equipment that will be deployed, the testing instrument will be used at a lot of different points, and will be handled by many users. This requires very portable (handheld) instruments and a low price tag because of the number of units that will be needed. Because of the smaller distances and the possibility of non-amplified links working around 1310 nm, the metro DWDM system will demand more relaxed optical specifications when compared with long-haul systems. The impact on test equipment results in simpler instruments that are fast, easy to use, and provide only the required optical measuring performances.

The simpler hardware will be accompanied by a more intelligent and powerful software to speed up testing analysis and reporting. Automatic testing will also be very important, because the need for testing many new parameters will put some pressure on testing crews. Automatic procedures will help the new user avoid the typical first measurement mistakes.

Metropolitan DWDM networks are just one of the new exciting applications of DWDM technology. In the next chapter, we will describe some of the more relevant trends in the industry that will create a new wave of measurement techniques and equipment.

WDM GUIDE

CHAPTER 8

THE FUTURE

THE FUTURE

8.1 WHAT IS NEXT?

Previous sections have described or hinted at some of the leading-edge technologies that are currently influencing the design and assembly of optical networks. How will this evolution proceed?

Practical solutions to, or even the use of, the various optical phenomena that now limit service—polarization mode dispersion, chromatic dispersion, and non-linear effects, in particular—will gradually allow increases to both channel counts and bit rates in WDM systems. The resulting very high aggregate data rates will force service providers in two directions: toward greater "centricity" in raw data handling over common paths in order to take full advantage of the bandwidth that the technology will allow, and toward finer "granularity" in services offered thus tailoring user channels to meet the protocol data rate and reliability needs of specific market segments.

It is certainly impossible to predict future technical developments—or even to predict with much accuracy how well and how long current technology will hold up—but Table 8.01 presents an outline of the technologies and techniques that are expected to play important roles in the near future.

	PAST	PRESENT	FUTURE
Fiber	- NZDSF - Dispersion compensation	- Dispersion-managed fiber - Better compensation - Lower loss	- Multicolor - Ultra-low loss - Solitons
Transmission	- 0.5 Tb/s - 2.5 Gb/s per λ - DWDM 32 λ	-1.2 Tb/s -10 Gb/s per λ - DWDM 128 λ	- 2 to 5 Tb/s - 40 Gb/s per λ - Soliton - UDWDM 200+ λs
Bandwidth Management	- Electrical - Async, SONET - Interfaces <10 Gb/s - STS granularity	- Electrical, optical - Multiprotocol, ITU λ grid - Interfaces up to 10 G b/s STS granularity - DCS	- Optical - Multiprotocol, ITU λ grid - Interfaces up to 40 Gb/s - STS-3c granularity - Fast switching

Table 8.01 Technological progression from yesterday to tomorrow

8.2 FIBER

The theoretical capacity of fiber is enormous—that of a singlemode fiber is perhaps 50 THz, under realistic assumptions. However, these astronomical rates will require considerable technological developments. Deployment of a 400 channel system seems feasible in the near future, and with each operating at a conservative 2.5 Gbps (allowing for an optical signal-to-noise ratio of 20 dB) a total bandwidth of 1 Tbps does seem attainable. Further foreseen developments will soon raise that figure to 2.5 Tbps.

DWDM will continue to be the technology of choice, and the fixed add/drop multiplexers that are now being introduced will give way, first to field-reconfigurable units and later to remotely controllable ones. Network complexity will grow, especially as specialized services requiring specific logical configurations (CATV, for example) are overlaid on traditional services. Channel counts will rise, as will the requirements for laser stability and filter accuracy, and for sophisticated management tools for power and noise. DWDM-based architectures based on packet and cell switching and offering SONET, ATM, SDH, Gigabit Ethernet and IP interfaces will allow large businesses to "own" individual wavelengths on a net, thereby going a long way toward satisfying the growing demand for secure yet flexible communications among company sites.

The transmission of Internet Protocol (IP) via optical fiber is on the immediate horizon, and the dramatic savings in possible bandwidth will spur its eventual adoption at all levels of Internet service.

Over the past few years, the increase in installed fiber has doubled bandwidth capacity about every six months. To maintain this rate, cables containing many hundreds of fibers will be common in new installations, and fully deployed 128-channel DWDM systems will be widespread.

8.3 COMPONENTS

More and more network overhead functions will be built into transmission components: transponders, in particular. Such features as SONET processing, forward error correction, automatic protection switching, bit error rate checking, and signal tracing will be included, all monitored by automated functions provided in an optical supervisory channel.

Networks will become increasingly "all-optical" as research leads to new devices able to provide functionalities now available only in electronic equipment. Removing the need to recover and regenerate user traffic to pass through such a device will reduce the hardware complexity of networks, but it will increase the importance of the effects of various optical phenomena on signal integrity because, over increasingly long distances, signals will exist only as optical pulses.

But a possible damper on the widespread use of all-optical networks exists: it is still too early to say if transparent pipelines can ever satisfy the needs of service suppliers and regulatory agencies to monitor, test, and manage information transfer right down to the bit level.

DFB lasers are expected to be the transmitting sources of choice for dense WDM links for some time, especially as on-chip features are added to improve their performance and to ease their integration into networks. Nevertheless, other technologies are on the horizon.

Multi-electrode lasers have been demonstrated whose operating wavelength can be controlled directly through signals applied to the laser chip. In another approach, a linear array of laser cavities has been produced in a single semiconductor wafer, with each cavity tuned for a specific wavelength and under individual electronic control. A chip incorporating 40 such channels has been reported. In yet another development, the "chirp" phenomenon that is so disruptive of narrowband communications schemes has been harnessed to generate many usable wavelengths—206 in the device reported—simultaneously from a single laser transmitter.

New source techniques often require the development and use of improved multiplexing and demultiplexing techniques, as well as innovative network design philosophies. But despite these complications, upcoming source technologies should decrease the cost of dense WDM applications and increase network design possibilities.

8.4 TRENDS

Even if soliton-based communication systems are not yet commercial realities, many indicators point to a rapid move from the laboratory to the service providers' networks. The strongest force for implementation of this technology comes from the ultra-long-haul submarine cable applications. As this market is increasing, the need for a low-cost ultra-distance solution like soliton technology is expected to strongly increase as well.

These types of systems will lead to a decreased cost per bit because of the elimination of repeaters or optical amplifiers. The soliton-based system will have to wait sometime before becoming a commercial reality because the optical transmission systems are still in evolution, but the volume of publications and research that is being conducted by both universities and industry is a clear indication that this technology is here to stay.

Fiber to the home (FTTH) is a technology in the wings. Its major impediment is transceiver cost: it needs a laser in each home. Although this requirement is currently cost-prohibitive, it is possible that wireless technology ("fiber almost to the home") will overcome at least some of the difficulties in the short term, providing adequate data rates without the need for extensive deployment of a completely new fiber infrastructure. In 10 years, 50% of homes will have FTTH using some form of wireless or fiber final link. Inexpensive vertical cavity surface emitting lasers (VCSELs) are already available for short-wavelength use, and developments are likely for the 1310 nm and 1550 nm spectral regions. Multimode (MM) WDM is another technology with promise for LAN and other short-haul applications, eventually including FTTH. Potentially it offers both lower cost and better reliability than its current competitors.

One thing is certain: the increasing need for bandwidth is not going to abate. The phenomenal growth of Internet traffic has given service providers a taste of what can happen when a totally new service is offered. HDTV is just beginning to demonstrate its appeal to consumers, and millions of home viewers may ultimately decide that an unobtrusive cable is easier to deal with than a rooftop satellite dish. Past attempts to popularize such bandwidth-intensive services as video telephones have failed at least partly because of compromises needed to meet severe bandwidth constraints. When these constraints finally crumble, there is no telling what new conveniences consumers will demand.

Even without considering growth at the consumer level, business use of data networks for everything from inter-office communication to plant monitoring shows no sign of flagging. Indeed, one has only to recall the recent fears of a Y2K "meltdown" to underline the dependence of modern industry on reliable communications. And the ever-increasing cost of travel will make video conferencing a more and more attractive option for businesses large and small, especially if the one-view-at-a-time nature of present techniques can be overcome. Although the ultimate capacity of fiber-optic systems may seem able to meet any conceivable demand safely, we must not forget the predictions made early in the digital computer revolution that, perhaps, half a dozen of these strange devices would serve all the needs of North America.

THE FUTURE

WDM GUIDE

CHAPTER 9

CASE STUDY: AN EXFO TEST SOLUTION

CASE STUDY: AN EXFO TEST SOLUTION

In the previous chapters, we talked about WDM system components as well as important test parameters at the individual component and complete system levels. A multitude of test combinations exists for a wide range of products. In this chapter, we will use a case study to present some of EXFO's equipment as well as complete EXFO solutions.

The examples used will briefly present the most important steps in implementing a WDM system and manufacturing individual components before installing and maintaining the complete system. These include

- qualifying the optical link
- quality control of individual component
- commissioning
- monitoring
- maintenance and re-activation in case of fault

Obviously, the instruments used in these examples vary from one supplier to another and there are alternatives to the choices that we propose. It is also important to note that these are not standards, but EXFO solutions. EXFO instruments are likely to change in the next few years and even months. Therefore, we suggest that you contact one of our representatives or company headquarters to obtain more details about new and existing testing instruments.

A telecommunications company wants to invest in a WDM system to make full use of SONET systems already in place. They have very few optical fibers available and must therefore use several wavelengths on the same fiber in order to increase the bandwidth. They plan a very rapid expansion of their communications network within the next two or three years, which means they will need a system that can be upgraded. They will therefore immediately acquire a 32-wavelength system, but plan to increase to 128 wavelengths in the future. Channel spacing will initially be 100 GHz (0.8 nm), but will decrease to 50 GHz (0.4 nm) with the upgrade. Furthermore, the system will be bidirectional, that is, 16 wavelengths will go in one direction and 16 in the other.

They currently use 2.5 Gb/s transmission speeds. With this project, they will increase transmission rates to 10 Gb/s, fully aware that it will be possible to upgrade when equipment for 40 Gb/s will be less expensive. The network has a point-to-point architecture—a single 180 km link with an optical amplifier placed at around 90 km. The fiber being used was installed at the beginning of the nineties and has never been tested in depth for today's needs.

A system cannot be bought and implemented without it being previously tested. Therefore, before buying the system, the customer must know if the optical link is capable of supporting these new wavelength parameters.

9.1 LINK QUALIFICATION

Qualifying the optical link is absolutely essential before buying and installing a new system. The physical link plays an important role in system limitations and upgrading capabilities. Using an analogy, even the most performing cars could not reach their full capacity on roads that are not made for them. When testing the link, not only current needs but also future improvements must be taken into account. In this case, testing will be carried out in anticipation of the 128 channels at a transmission rate of 40 Gb/s.

CASE STUDY: AN EXFO TEST SOLUTION

In the majority of cases, qualification of the link will be performed inside a central office (CO) or a secondary building, where the space available for test equipment can vary from comfortable to very limited. In this case, the company only has a small space inside a secondary building that is not close by. This is why portable instruments are often the units of choice for this first series of tests. Before deploying the system, the customer will have no instruments in place. Therefore, a company such as EXFO must supply all the necessary testing equipment, i.e., sources, couplers, switches, and a variety of detectors.

To properly qualify the optical link, we suggest the following tests:

- loss
- ORL
- PMD
- chromatic dispersion
- non-linear effects

Since a system is already working on the link, it is not necessary to perform continuity tests. However, the link must be inspected. It is a good idea to take advantage of the fact that the other system is shutting down to perform a full series of tests.

Each test will require connections. It should be noted that the instrument connectors as well as the patchcords connecting the system or the optical link must always be clean. The use of a talk set will facilitate the coordination of testing procedures at both ends of the fiber. All results obtained should be saved for future use or simply for internal use. This is what we propose:

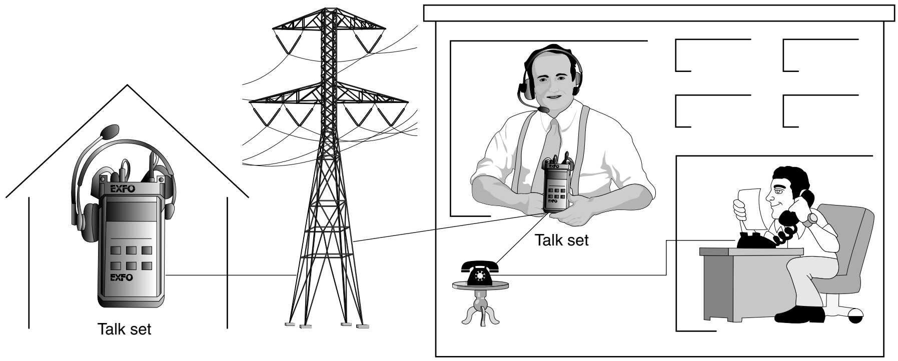


Figure 9.01 The talk set allows two or more operators to communicate over the cable under test.

CASE STUDY: AN EXFO TEST SOLUTION

1. Foot print: The OTDR test is required to establish the link's foot print, ideally at 1310 nm, 1550 nm, and 1625 nm. The OTDR is connected to the patchcord going outside. Users choose parameters in Expert mode or using the one-button testing feature in Novice mode. Once the measurement has been taken in one direction, the operator at the other end can do the same. ToolBox Process software can then be used to perform a bidirectional analysis of the link. The OTDR's bidirectional analysis is useful for qualifying the loss of certain events according to the signal's direction.

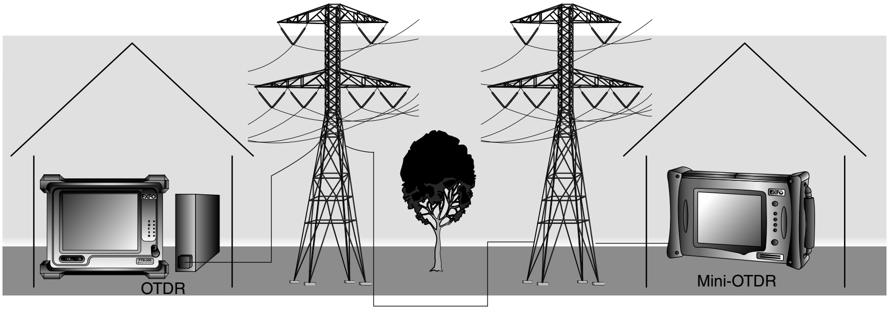


Figure 9.02 OTDR establishes the link's foot print at given wavelength.

2. Loss: The OLTS test is necessary because this technique gives a much more accurate loss measurement than that with the OTDR. It can also take advantage of the bidirectional measurements. Using the MultiTest or MaxTester, 1550 nm and 1625 nm wavelengths are chosen. The source is connected to the detector for auto-calibration; FasTesT should analyze the loss in both directions.

MultiTest report

Job Info

Job ID	: BA-2704	Reason	: NEW BUILD
Contractor	: MCG Inc.	Operator A	: J.V.
Customer	: MMFN	Operator B	: G.G.
Test Date	: 1999/01/09	File	: 1310_1.fta
Custom Field 3	:	Custom Field 4	:

Cable Info

Cable ID	: BALPOP24		
Location A	: 351 CHURCH St.	Location B	: 111 MARKET PL
Cable Mfg.	: LUCENT 432	Type	: COMPOSITE
Custom Field 1	:	Custom Field 2	:

FasTesT Results Table

Fiber	Loss 1310 A->B (dB)	Loss 1310 B->A (dB)	Loss 1310 Avg. (dB)	ORL 1310 A->B (dB)	Loss 1550 A->B (dB)	Loss 1550 B->A (dB)	Loss 1550 Avg. (dB)	ORL 1550 A->B (dB)
Reference	-1.57	-1.86			-3.62	-3.96		
FIBER001	-1.80	-1.75	-1.77		-1.71	-1.89	-1.80	
FIBER002	-1.89	-1.87	-1.88		-1.45	-1.68	-1.56	
FIBER003	-1.89	-1.90	-1.89		-1.44	-1.64	-1.54	
FIBER004	-1.79	-1.80	-1.79		-1.27	-1.54	-1.40	
FIBER005	-1.89	-1.94	-1.91		-1.07	-1.24	-1.15	
FIBER006	-1.81	-1.88	-1.84		-1.10	-1.29	-1.19	
FIBER007	-1.77	-1.72	-1.74		-1.05	-1.21	-1.13	
FIBER008	-1.81	-1.69	-1.75		-1.23	-1.38	-1.30	
FIBER009	-1.78	-1.84	-1.81		-1.97	-2.22	-2.09	
FIBER010	-1.82	-1.82	-1.82		-1.14	-1.32	-1.23	
FIBER011	-1.80	-1.84	-1.82		-1.10	-1.32	-1.21	
FIBER012	-2.01	-2.06	-2.03		-1.75	-2.01	-1.88	
FIBER013	-1.81	-1.83	-1.82		-1.56	-1.85	-1.70	
FIBER014	-2.00	-1.94	-1.97		-1.20	-1.52	-1.36	
FIBER015	-2.45	-2.25	-2.35		-1.55	-1.71	-1.63	
FIBER016	-2.08	-1.94	-2.01		-1.39	-1.63	-1.51	
FIBER017	-2.29	-2.20	-2.24		-1.60	-1.84	-1.72	
FIBER018	-2.53	-2.49	-2.51		-1.67	-1.82	-1.74	
FIBER019	-1.90	-1.94	-1.92		-1.35	-1.51	-1.43	
FIBER020	-2.00	-1.97	-1.98		-1.32	-1.81	-1.56	
FIBER021	-2.03	-2.08	-2.05		-1.50	-1.74	-1.62	
FIBER022	-2.06	-2.11	-2.08		-1.53	-1.79	-1.66	
FIBER023	-1.98	-1.92	-1.95		-1.52	-1.76	-1.64	
FIBER024	-1.85	-1.78	-1.81		-1.80	-1.97	-1.88	
FIBER025	-2.24	-2.31	-2.27		-1.37	-1.65	-1.51	
FIBER026	-1.92	-1.90	-1.91		-1.24	-1.42	-1.33	
FIBER027	-1.91	-1.80	-1.85		-1.56	-1.83	-1.69	
FIBER028	-2.01	-1.99	-2.00		-1.50	-1.68	-1.59	
FIBER029	-1.85	-1.81	-1.83		-1.19	-1.39	-1.29	
FIBER030	-2.08	-2.08	-2.08		-1.15	-1.38	-1.26	
FIBER031	-1.64	-1.63	-1.63		-1.07	-1.26	-1.16	
FIBER032	-1.94	-2.21	-2.07		-1.22	-1.45	-1.33	
FIBER033	-1.76	-1.76	-1.76		-1.15	-1.33	-1.24	
FIBER034	-1.95	-1.90	-1.92		-1.19	-1.32	-1.25	
FIBER035	-1.79	-1.72	-1.75		-0.96	-1.24	-1.10	
FIBER036	-1.80	-1.72	-1.76		-1.31	-1.47	-1.39	
FIBER037	-1.66	-1.60	-1.63		-1.11	-1.30	-1.20	
FIBER038	-1.69	-1.74	-1.71		-1.10	-1.29	-1.19	
FIBER039	-1.89	-1.80	-1.84		-1.08	-1.29	-1.18	
FIBER040	-1.88	-1.92	-1.90		-1.29	-1.48	-1.38	
Average	-1.92	-1.91	-1.91		-1.34	-1.55	-1.44	

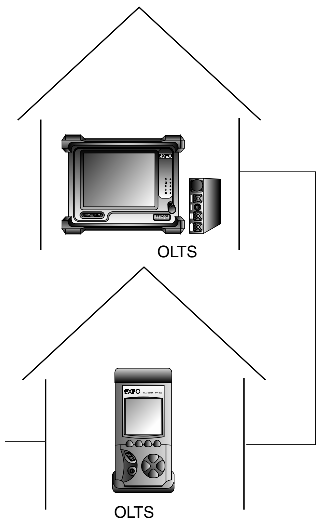


Figure 9.03 Losses are accurately measured using the OLTS and a complete report is given for bidirectional testing.

CASE STUDY: AN EXFO TEST SOLUTION

3. ORL: By using the ORL test set, the user can measure the ORL level. This measurement is very important because when it is too high, ORL can cause problems such as source instability or high BER at the receiver level. The instrument must therefore be connected to the patchcord going outside; the wavelengths employed in the system must be used. For ITU wavelengths, a 1550 nm wavelength should be used.

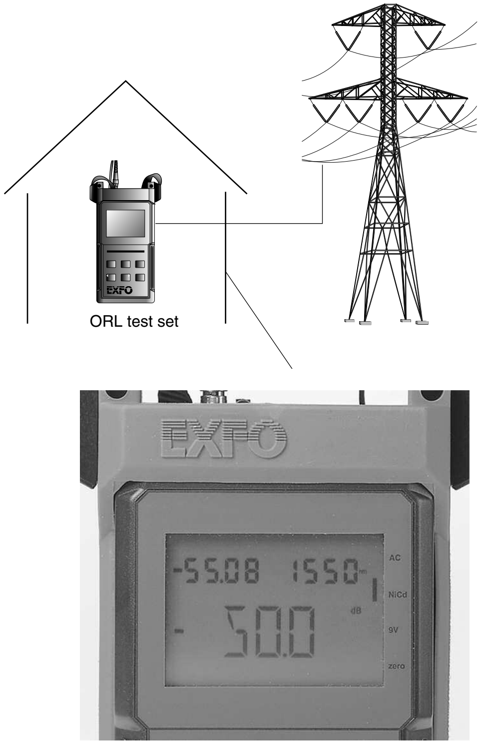


Figure 9.04 Return loss is important for system stability.

4. PMD: Although PMD is a complex phenomenon, the PMD test is made easy with the PMD analyzer. The PMD value is critical to determine the maximum transmission rate that can be used on the link. The polarized source (1550 nm) is connected to the other end of the link and the analyzer at this end. No communication is necessary between the two, but the source must be turned on before taking an acquisition. When the source is turned on, the user must check that there is enough power on the PMD power bar. The total length of the link obtained with the OTDR is entered to obtain the PMD coefficient. The user can personalize the configuration or use Automatic mode, but more accurate values will be obtained by using the exact measurement range.

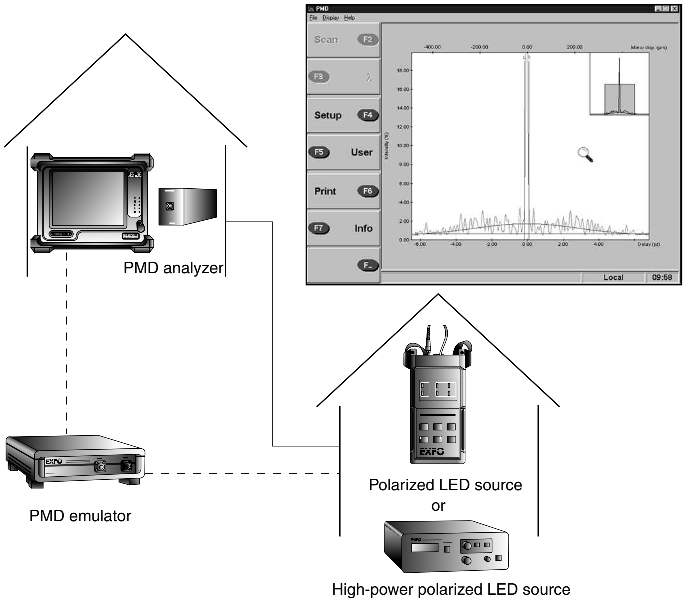


Figure 9.05 The emulator qualifies the PMD analyzer used to characterize optical link performance.

5. Non-linear effects: This phenomenon is crucial with the multitude of wavelengths. To test four-wave mixing (the most important non-linear phenomenon), two sources are used: tunable and fixed sources, along with an OSA. The sources will be installed at the other end of the link with a polarization controller and a coupler; the OSA will be at this end. The test involves using two identical polarized sources with similar power and bringing them close together. At a certain distance, two secondary peaks caused by the non-linear effect will be visible. The power of the secondary peaks and the spacing between them are indicators of the link's quality. If the peaks have a wide spacing or high power, it means that there will be problems with the 128 wavelengths at 50 GHz spacing. In this particular case, the link will have no problems with the 128 wavelengths.

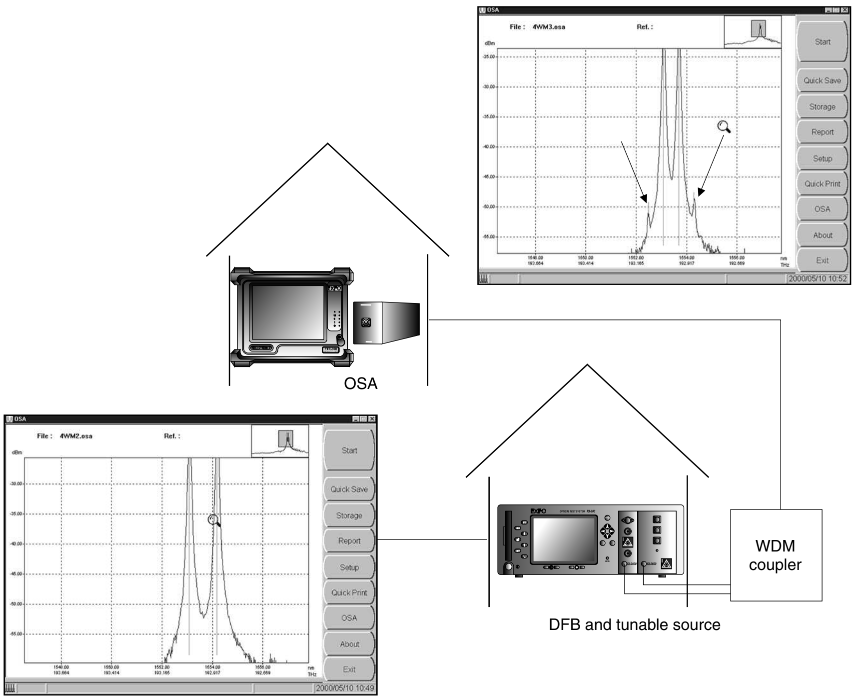


Figure 9.06 Bring signals from the tunable laser and DFB laser close together and check if side peaks appear.

The link seems to be of sufficient quality for the 128 WDM channels, but the transmission rate must be limited to 10 Gb/s, since the average PMD of 8.3 ps is higher than the ITU standard of 2.5 ps for 40 Gb/s rates. An order for the system can now be placed.

9.2 COMPONENT TESTING: MULTIPLEXER

Once the company that manufactures and sells the WDM system has received the order, it must begin to manufacture, buy, and assemble each component to make a complete system. At this stage, several tests will be performed on the components to ensure that they respect the necessary technical specifications. The tests are obviously performed when the components are being manufactured, but also after the purchase and before assembly. A system is composed of numerous types of components that come in various sizes. They may be metal frames or microelectronic chips and may come from all types of domains, i.e., optics, mechanics, electrical, electronic, even magnetic or chemical. The most important final components are the following:

- transmitters
- detectors
- attenuators
- switches
- optical cross connect (OXC) switch
- filters
- couplers
- DCD (dispersion compensation device)
- OADM
- mux/demux
- Bragg grating
- EDFA or any other optical amplifier

The following example concentrates on the tests that should be performed to characterize a wavelength selective filter (multiplexer). The multiplexer is an essential tool for WDM, and several parameters must be tested. This is why we use the mux as an example, but it should be noted that the tests to be performed vary greatly from one component to another. (Refer to chapter 4 for more details.) The following tests will be performed:

- central wavelength and channel spacing
- ripple
- channel uniformity
- bandwidth
- crosstalk
- PDL
- insertion loss
- directivity
- ORL

For all possible component tests, it is preferable to use a laboratory instrument with the highest technical specifications. The following is the preferred assembly for these types of tests:

CASE STUDY: AN EXFO TEST SOLUTION

1- Central wavelength and channel spacing: Since the primary function of the multiplexer is to combine all wavelengths (separate in the case of the demux), it is essential to qualify the component as a function of the wavelength. These two important parameters will be measured by using a broadband ASE source and an OSA. The source is connected to one of the input ports of the mux and the OSA to the output port. The central wavelength is then deduced by taking the halfway distance between the wavelengths where there will be 3 dB less than the maximum power. The spacing between each central wavelength will provide the channel spacing. The measured wavelengths should correspond as much as possible to those that will be used in the system, i.e., those in the ITU grid.

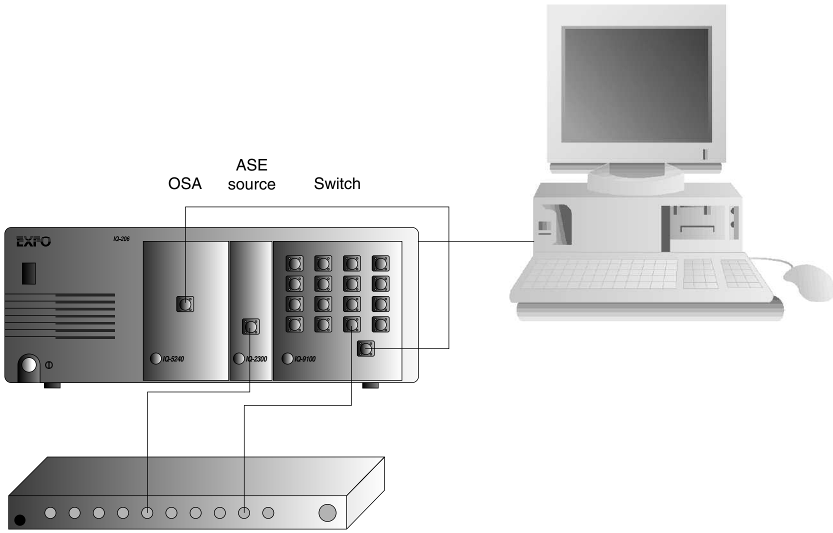


Figure 9.07 Proposed setup to characterize the multiplexer

2- Ripple: The ripple will be measured using the same setup. This time, the analysis will concentrate on the shape of the spectral response. If the mux were perfect, the filter would have a perfectly rectangular shape at the output port, but in reality, there is a deformation at the channel peak that must be examined. Ripples are typically due to parasitical Fabry-Perot etalons that produce different spectral modulation noises. Ripples are usually sensitive to the input light state of polarization. A non-polarized ASE source provides an average measurement of the ripple amplitude. If this variation in power is too great, there will be significant variations in signal power for a small variation in wavelength.

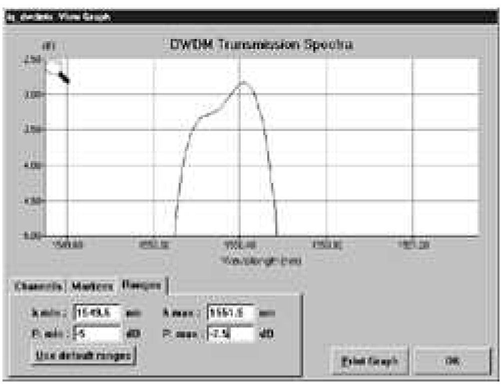


Figure 9.08 Ripple causes variation in signal power.

3- Channel uniformity: To avoid differences in the output power of the different multiplexed sources, it is important to check channel uniformity. By using the same test configuration, we must check that the output power of the channels is almost identical and that the channels have the same width. The highest transmission point will represent the maximum power and the channel width is calculated at 3 dB lower (FWHM).

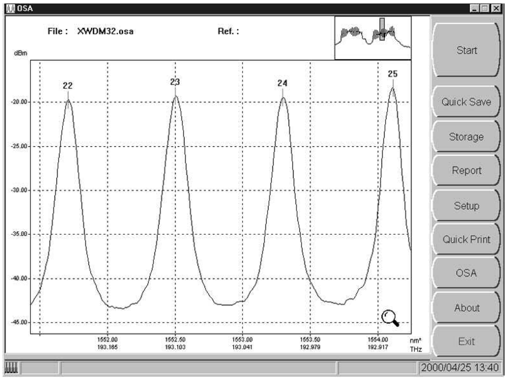


Figure 9.09 Channel width and power must be similar.

4- Insertion loss: The insertion loss of a component is normally defined as the difference between the power entering and leaving a component or optical path:

$$IL \text{ (dB)} = P_{in} \text{ (dBm)} - P_{out} \text{ (dBm)}$$

where IL is insertion loss in decibels, P_{in} (dBm) is input power in decibels referenced to a milliwatt and P_{out} (dBm) is output power referenced to a milliwatt. This equation quantifies the power loss in the device at a particular wavelength or in a given spectral region. Normally, insertion loss should be as small as possible. For components, it is not uncommon to measure insertion loss of 0.10 dB or even less. The critical instruments for accurately measuring insertion loss are a stable light source and a linear power meter. Other important points to consider include the type of fiber, type of source, launching conditions, mode filters, and polarization dependence.

For both manual and automatic testing, EXFO has a wide range of instruments and accessories to simplify the task of accurately measuring insertion loss. We offer several instruments for benchtop use and as part of a modular platform: LEDs; Fabry-Perot and distributed feedback lasers; tunable lasers optimized for passive component testing; and single- and multichannel power meters.

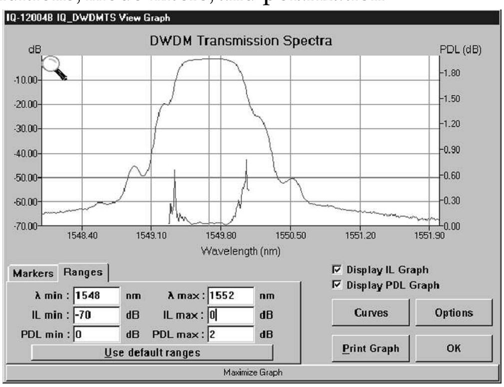


Figure 9.10 Insertion loss must be taken into account for a loss budget.

CASE STUDY: AN EXFO TEST SOLUTION

5- Bandwidth: By using a tunable source and a power meter, it is possible to properly define the band edges of each channel over a large dynamic range. The tunable laser, in this case, sweeps across a predefined wavelength range. The large-count power meters simultaneously measure transmitted power. With appropriate input power reference, it is possible to measure spectral insertion loss on 40 channels with a single sweep.

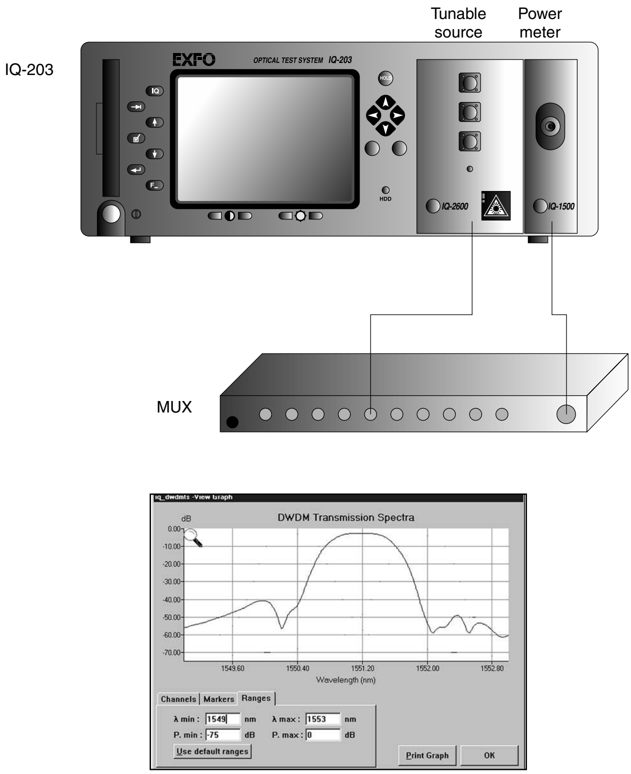


Figure 9.11 Bandwidth is an important specification for a multiplexer.

6- Directivity/near-end crosstalk: Directivity, sometimes referred to as near-end crosstalk, is the measure of a device's ability to block transmission among the input ports of the multiport filter. As shown in the figure below, directivity represents the power returned to the second input. Normally, this value is very small. The setup shown below can measure the insertion loss at ports 1 and 2 and then measure the directivity of inputs 1 and 2. Using a 3-channel power meter, measurements can be taken without any reconnection. It is important to note that the outputs must have low-reflection terminations for directivity measurement. If not, reflections from the fiber endface will transmit back through the filter and lead to poor test results.

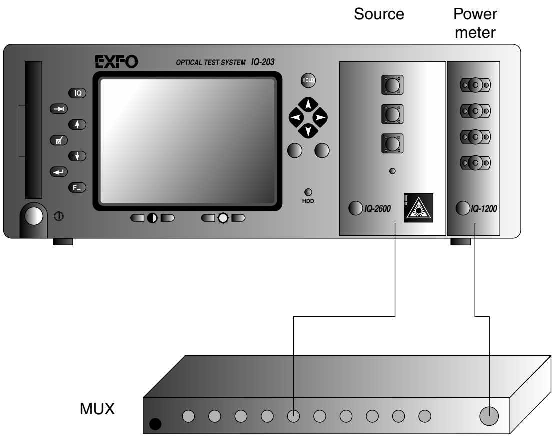


Figure 9.12 Directivity measurement

CASE STUDY: AN EXFO TEST SOLUTION

7- PDL: Polarization dependent loss (PDL) is a measure of component sensitivity to state of polarization (SOP). Normally, it is expressed in dB. When PDL is added to the insertion loss, it represents the worst-case loss for the component. Almost all components are designed to keep PDL to a minimum, and it is not uncommon to see components with PDL specifications at 0.05 dB or less. PDL measurements taken with EXFO equipment are fast and accurate. The modular optical test system enables users to configure their system exactly as they want it. The user can choose between a polarized LED source, tunable laser source, or another external source. The polarization controller randomly scans all SOPs, and the total measurement is performed in five seconds. For PDL measurement using this system, no calibration is required, and the setup is insensitive to fiber movement.

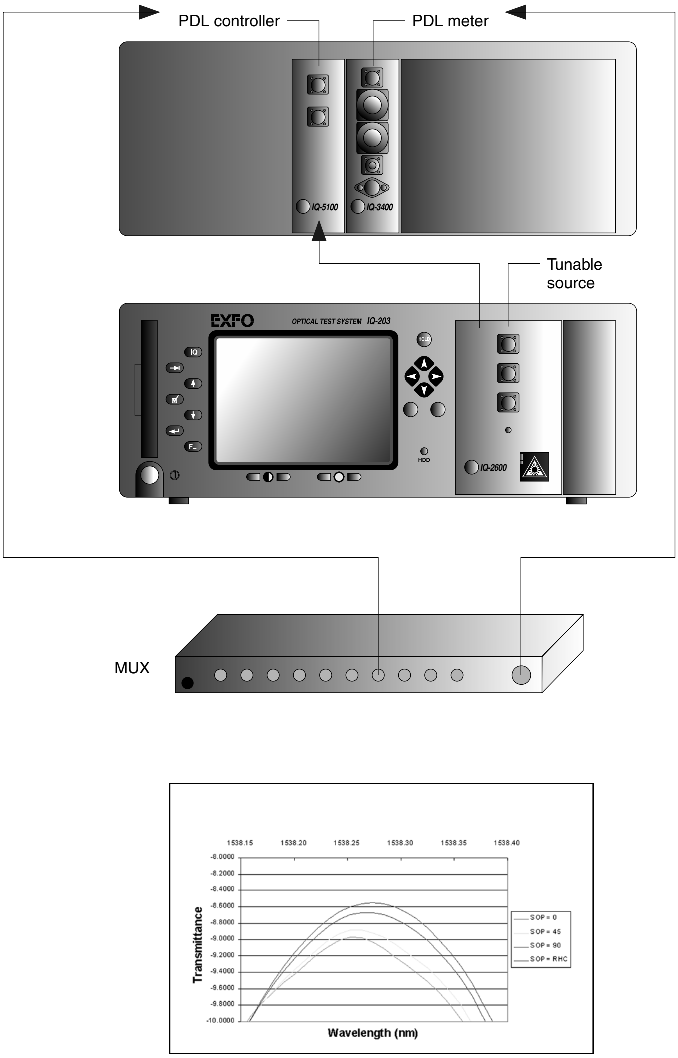


Figure 9.13 Fast, accurate PDL measurement

8- ORL: Optical return loss (ORL) is a measure of the amount of optical power reflected by a component. It is expressed in dB.

$$ORL = 10 \log (\text{incident power}/\text{reflected power})$$

A device that has an ORL of 0 dB reflects 100% of the incident power, while a device with 20 dB ORL reflects 1%. Most passive components are designed to minimize reflected power, and it is not uncommon to have components with >60 dB ORL. At 60 dB ORL only 0.0001% of the optical power is reflected. Because of the low reflected power levels, accurately measuring high ORL poses some interesting challenges for instrument manufacturers. For accurate and stable return loss measurements, it is important to have a high-power, stable, and (ideally) non-coherent light source. High and stable power is important to achieve the required sensitivity (80 dB); the coherence properties of the source are necessary to avoid interference problems. If the coherence properties of the source are inadequate, large fluctuations will be observed on the measured ORL. The return loss meter, when used with the light source (optimized for ORL measurements), can perform stable ORL measurements to 80 dB. When used with the medium-coherence tunable laser source, ORL can be measured across the DWDM wavelength range.

Most of these tests can be carried out automatically and quickly by using a test system dedicated to passive component testing. This assembly includes broadband sources (DFB and tunable) so that all types of tests can be performed, as well as a polarization controller, couplers, switches, a PDL tester, and an enormous capacity to save data for complete offline analysis.

The multiplexer is of very good quality and will be just as efficient in the system as it is alone. Once all the other tests have been performed and the system has been tested in the factory, it will be delivered to the customer, who will have to perform his own series of tests.

9.3 COMMISSIONING

When the company has received the system and installed it, it is important to perform a series of tests to check that the connected components provide the required performance and meet the installation requirements. In certain cases, the sum of all the small losses may introduce significant problems in the system. Therefore, we suggest critical testing procedures that will allow users to determine if they are ready or not to start up the system while maximizing the important parameters. These are the last tests that will be performed before the WDM system is turned on for operation.

When the system is installed, the equipment in place (sources and multiplexer) can be used for testing. The environment in which the tests will be performed may be clean or dusty, very large or very restricted. Therefore, a good battery-operated portable instrument is definitely a must. The following will be tested:

- transmitters
- detectors
- amplifiers (EDFA)
- multiplexers/demultiplexers
- the general system
- alarms

CASE STUDY: AN EXFO TEST SOLUTION

We suggest that users follow the test procedure proposed by the system vendor once the system has been delivered. To give an idea of the types of operations that the user will have to perform, here is an EXFO procedure to test the system's important components:

1- Transmitters: The power and wavelength of each transmitter must correspond to the data supplied by the system vendor and be in accordance with the ITU standards. A power meter is used to accurately measure the power of each laser and a multiwavelength meter for high wavelength accuracy.

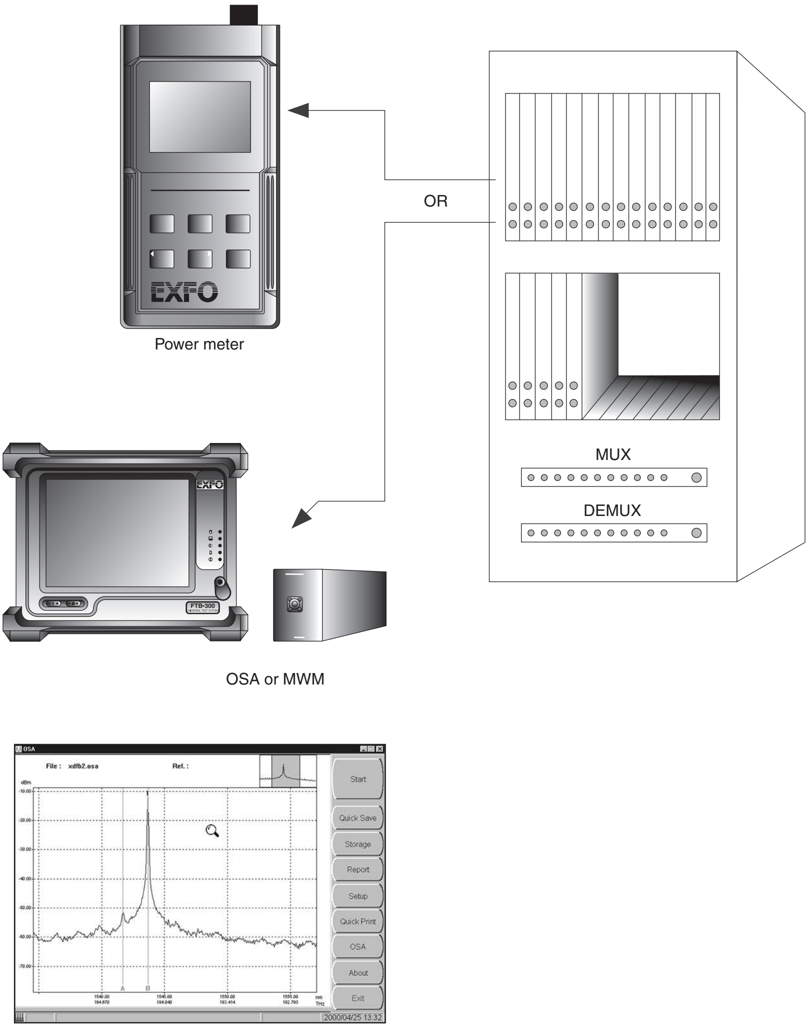


Figure 9.14 Characterize the system source with a power meter, OSA, or MWM.

2- Detectors: Since the detectors must be able to detect the channel power to which they are each dedicated without experiencing crosstalk from other channels, an instrument that can make this type of calculation automatically must be used. To do this, we will use the system sources and an OSA. All the sources are connected and a measurement is taken with the OSA. Then, we terminate a source and measure the power coming from other sources inside this channel.

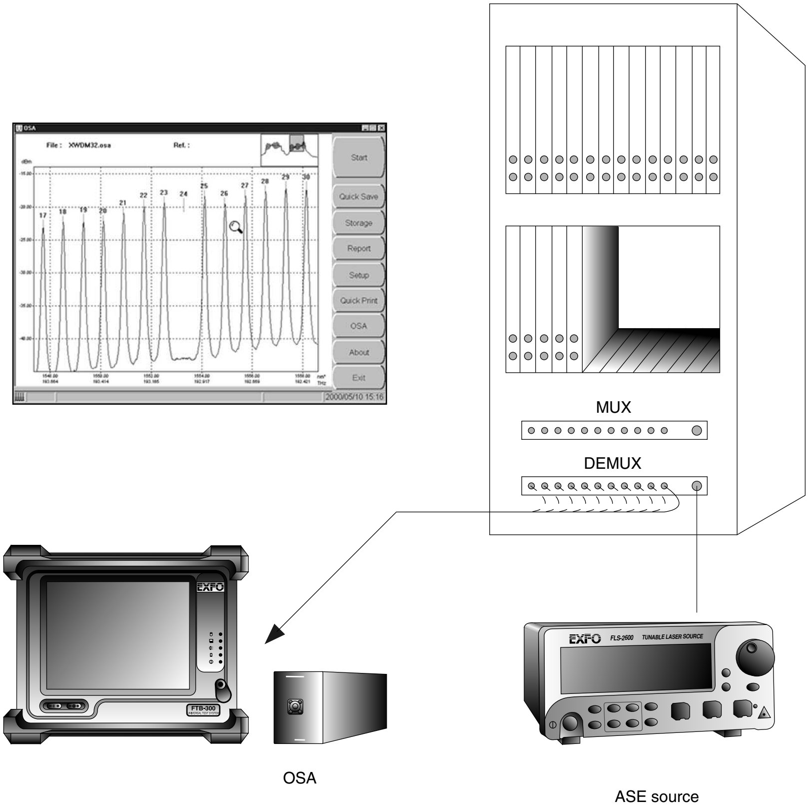


Figure 9.15 Crosstalk measurement at the receiver end

3- EDFA: The amplifier's output power is measured at saturation, that is, when an increase in power no longer produces amplification. This measurement is taken in the 1550 nm region by using a tunable source with a variable attenuator and a calibrated power meter. The EDFA flatness is also measured with a tunable source that is swept across the entire amplification range and an OSA that recuperates the gain values.

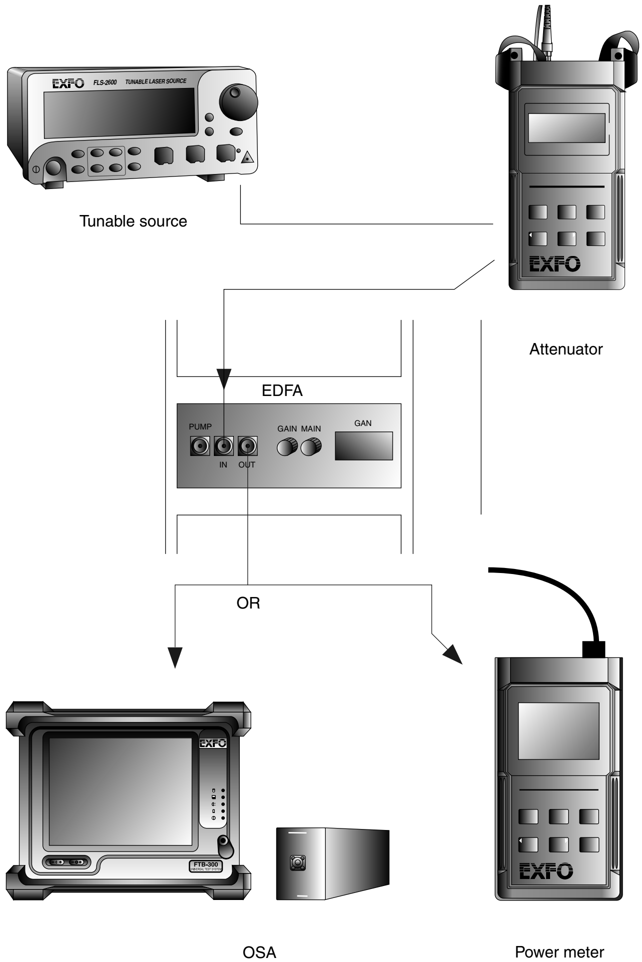


Figure 9.16 EDFA gain characterization

4- Multiplexer/demultiplexer: It is very important that the 32 channels be stable and of equal power at the mux level just before initiating their propagation in the fiber or demux output port after channel separation. To check that the output power is flat, we turn on all the sources and connect the OSA to the mux or demux output port. In this way, we can measure the signal's linearity. Next, by using the multiwavelength meter, we can ensure that the wavelengths conform to those of the ITU. As with the demux at the detector level, we can measure the crosstalk induced during wavelength multiplexing in the mux by using the same assembly: system sources and the OSA. Finally, the insertion loss will be measured by using the system sources and connecting the OSA to the input port and then to the multiplexer output port. The instrument subtracts one trace from the other to provide the insertion losses.

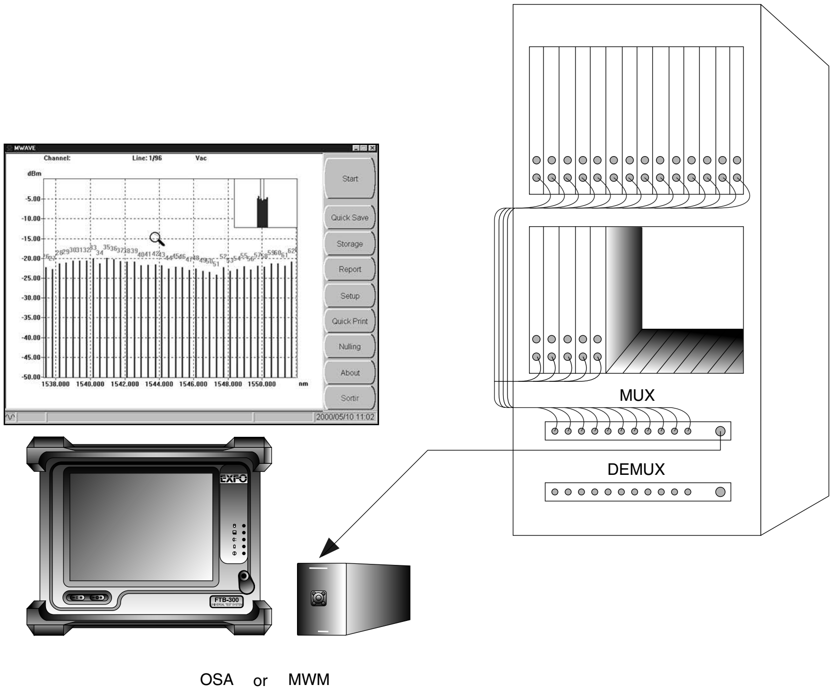


Figure 9.17 The multiwavelength meter (MWM) provides very accurate wavelength measurements.

5- General system: The system tests will be performed with all the new system's components working together. To do this, an OSA is connected to each of the system's physical ports to measure the OSNR of each channel. Depending on the system vendor's specifications and where users perform tests, values will vary between 18 dB at the very end of the system and 40 dB at the beginning. At the EDFA level, a certain gain should be recorded depending on the type of amplifier. Finally, a long-term test is preferable to check channel stability. By using the multiwavelength meter in drift mode, users will be able to follow the system wavelength drift with extreme wavelength accuracy.

6- Alarms: To check that all the system's alarms work properly, simply disconnect each system component one after the other (sources, mux, demux, amplifier, laser pump, and detector) to check that an alarm will be displayed.

All tests have been successful and the results are within the limits suggested by the system vendor. We can therefore start operating the system and take advantage of the significant increase in bandwidth (i.e., 32 wavelengths).

9.4 MONITORING

1- Generic Overview

The basic idea is very simple. The intelligence of RTUs, which used to be the dummy units, is maximized thanks to their PC-based architecture. RTUs are located at strategic points throughout the fiber-optic network to cover the maximum of the user's fiber-optic network.

The RTUs include advanced OTDRs as well as optical switches to maximize the use of OTDRs. Each fiber connected to a port of the optical switch is then monitored 24/7 or according to an established schedule, by comparing OTDR acquisitions to standard OTDR responses, also called reference traces. For each of those fibers, upper and lower limits, or thresholds, are entered, and if one of the OTDR acquisitions exceeds the threshold, an alarm is automatically generated. This alarm usually includes different generic fields such as date and time, optical distance to the fault (OTDR measurement), loss, CO, affected cable and fiber, and much more.

As shown in Figure 9.18, the carefully positioned RTUs report to a central station/server, also called test system controller (TSC). All information sent by RTUs is stored in a relational database for treatment and further SQL queries of all types. This central station also executes all communication functions with RTUs, workstations, and supervisory stations for remote users located anywhere in the field.

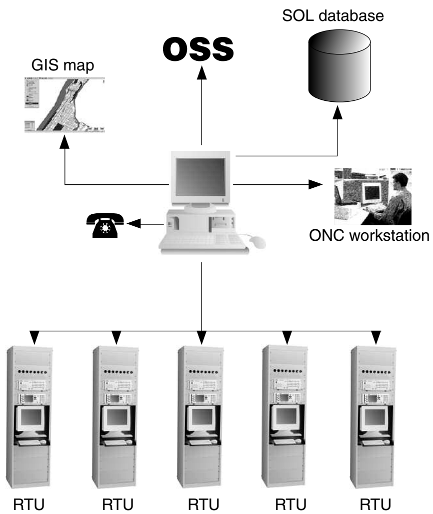


Figure 9.18 Typology of an RFTS system

Locating Faults

This is where the RFTS really shows its strengths. Indeed, through the powerful graphical information system (GIS) embedded in the central station RFTS software, such as GeoMedia or Small World, users have the capability to map their fiber-optic networks and link them to specific data such as

- type of fiber
- manufacturer
- type of connectors
- installation date
- to and from locations
- fiber count
- spare fibers
- clients affected, etc.

Users also have the possibility of entering landmark data, such as manholes, COs, towers, etc., with the exact locations in GPS or other types of coordinates.

The optical distance to the fault allows the system to actually extrapolate the physical location of the fault by calculating the optical-to-physical ratio between every landmark of the network. The optical distance can be extremely different from the physical one (on the map) for many possible reasons:

- fiber slacks left in manholes or poles
- access fiber meandering along streets
- helix factor, etc.

2- Connecting and Operating the System

Physical Monitoring

•Install the RTU (RFTS rack), and connect all fibers to be monitored to the optical switch. These fibers can be active or dark.

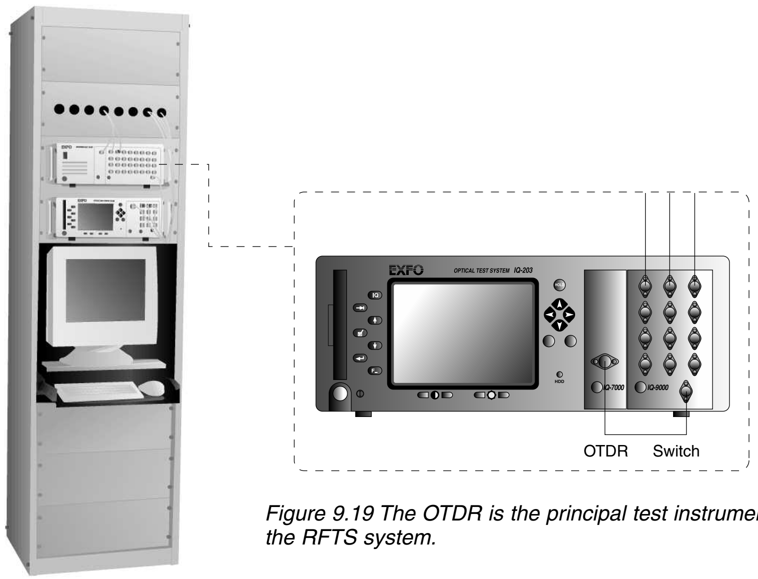


Figure 9.19 The OTDR is the principal test instrument in the RFTS system.

- Take reference traces for all the fibers to be monitored, with the OTDR connected to the optical switch at the RTU level. The reference trace is used to set upper and lower limits, or thresholds, and determine when alarms of different severity (minor, major, critical, etc.) will be generated. These thresholds can be set for
- total link power loss
- reflective event degradation
- non-reflective event degradation
- section attenuation
- new event detection
- launch level degradation, etc.

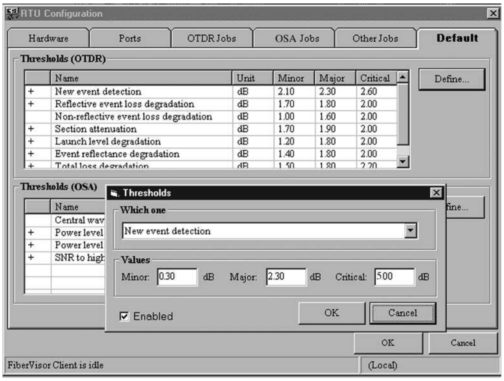


Figure 9.20 Define the limits of the system.

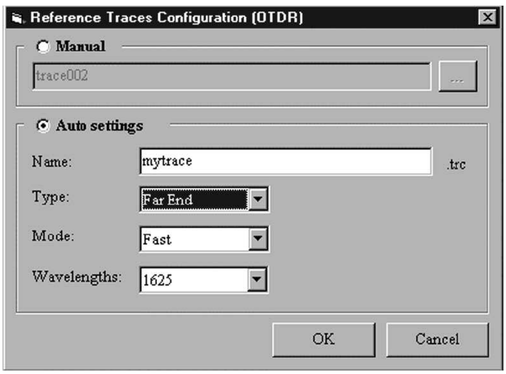


Figure 9.21 The reference trace is the basis for comparative analysis.

- Enter the monitoring sequence.
- Port 1
- Port 12
- Port 42
- Port 13
- …

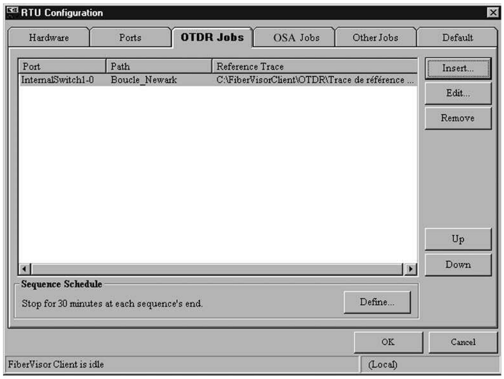


Figure 9.22 Monitoring sequence

- Specify the interval (if any) between each monitoring cycle.
- Start OTDR monitoring.

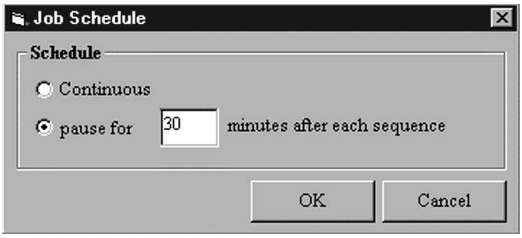


Figure 9.23 Specify the interval between each monitoring cycle.

Spectral monitoring

- Install the RTU (RFTS rack), and connect all fibers to be monitored to the optical switch. These fibers have to be active.

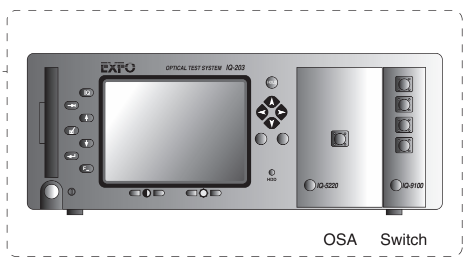


Figure 9.24 The OSA is another test instrument used in the RFTS.

- Take reference traces for all the fibers to be monitored, with the OSA connected to the optical switch at the RTU level. The reference trace is used to set upper and lower limits and determine when alarms of different severity (minor, major, critical, etc.) will be generated. These thresholds can be set for
- central wavelength drift
- SNR
- signal power

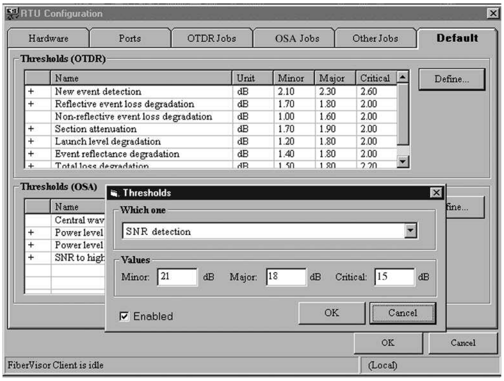


Figure 9.25 Define the spectral limits of the systems.

- Enter the monitoring sequence.
- Port 1
- Port 12
- Port 42
- Port 13
- …

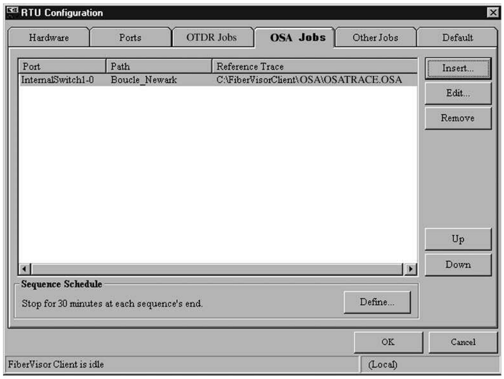


Figure 9.26 The monitoring sequence of the OSA is different than the OTDR's.

- Specify the interval (if any) between each monitoring cycle.
- Start spectral monitoring.

9.5 MAINTENANCE AND TROUBLESHOOTING

There are probably as many maintenance plans as there are system operators. Maintenance can vary in time and in the quantity and choice of tests. In reality, maintenance is very similar to commissioning. The only difference is it can be spread out over a period of six months to two years. During this period, critical specification tests will be performed more often, while less important parameters will be checked less frequently.

The frequency of maintenance can always be changed depending on whether critical parameters drift from their original value. This drift will be visible when monitoring. If the system stops working and troubleshooting must be performed, the tests will be mainly concentrated on the defective component. Complete tests carried out during commissioning may be repeated or the manufacturer's testing procedure borrowed.

The test equipment necessary for maintenance is the same as that used for commissioning, but since the person in charge of this operation must move from one location or room to another, the unit must be portable and rugged to endure transport without requiring calibration. The frequency of the tests that we suggest takes into account the importance of the system's components and the quality of the optical transmission.

- Alarm testing every four months
- System-level and EDFA testing every six or eight months
- Mux/demux testing every 12 months
- Source and receiver testing every 16 to 18 months

Hopefully troubleshooting will represent only a fraction of the time that you will spend working with this system!

WDM GUIDE

GLOSSARY

ACRONYM INDEX

FURTHER READING

Absorption
Loss of light in fiber caused by impurities, resulting from conversion of optical power into heat.

Accuracy
Defines how close a measurement is to its true value.

Add/drop multiplexer (ADM)
A component used to multiplex lower-speed electrical and/or optical signals into a high-speed optical channel and vice versa. An add/drop multiplexer can support either time-division multiplexing (TDM) or dense wavelength-division multiplexing (DWDM). It also links individual lines to backbone trunks.

Amplified spontaneous emission (ASE)
The light emitted from the decay of the upper level of a lasing transition without stimulated emission. In general, this emission is spectrally broad and unpolarized.

Amplitude modulation (AM)
Transmission technique where the information is encoded in the amplitude of the carrier.

ANSI
American National Standards Institute.

Arrayed waveguide grating (AWG)
Also known as a phasar. An integrated optical component which serves as an optical multiplexer/demultiplexer. It is based on the phase differences experienced by different input wavelengths to separate the channels, much like the classical diffraction grating.

ASCII
American Standard Code for Information Interchange.

Asynchronous transfer mode (ATM)
A high-speed transmission scheme providing bandwidth on demand for multimedia (voice, video, or data).

Asynchronous transmission
Occurs when the beginning and end of the data unit being transmitted is individually signaled by the transmitter with start and stop bits.

Attenuation
The diminution of average optical power. Attenuation results from absorption, scattering, and other radiation losses. Attenuation is generally expressed in dB without a negative sign.

Attenuator

An optical device that reduces the intensity of a light beam passing through it.

Avalanche photodiode (APD)
A photodiode that produces current through internal amplification. This is referred to as avalanche multiplication.

Backbone
A network designed to interconnect lower-speed channels.

Backscattering
The portion of scattered light that returns in a generally opposite direction to that of propagation. See Rayleigh scattering.

Bandpass
Defines the range of frequencies that pass through a filter or other devices.

Bandwidth
Measure of information-carrying capacity; the greater the bandwidth, the greater the information-carrying capacity.

Bend loss
The result of macrobends (curvature of fiber) or microbends (small distortions in the fiber) producing increased attenuation by coupling light energy from the fiber core to the cladding.

Birefringence
The property whereby the effective propagation speed of a light wave in a medium depends upon the orientation of the electric field (state of polarization) of the light.

Bit error rate (BER)
The number of digital highs on a transmission link that are interpreted as lows, and vice versa, divided by the total number of bits received. In modern networks, BERs much better than 10-9 are expected.

Brillouin scattering
In stimulated Brillouin backscattering (SBS), the laser signal creates periodic regions of altered refractive index, that is, a periodic grating that travels as an acoustic wave away from the signal. The SBS effect can result in a very noisy and unstable forward-propagating signal, since much of the optical energy is backscattered.

Broadband
Supporting a wide range of carrier frequencies (e.g., voice, data, or video).

Buffer coating
Protective material that covers and protects a fiber. The buffer has no optical function.

CATV
Acronym for cable television.

C-band (conventional band)
The spectral window from about 1525 nm to 1565 nm corresponding to the strong amplifying range of the silica-based erbium fiber.

Central office (CO)
Building that houses a telephone company's communications equipment.

Central wavelength
Wavelength of a source's peak power.

Channel isolation
The ratio of the light in an optical channel that corresponds to the desired spectral range against the contribution due to light at other wavelengths.

Chirp
A change in the characteristic optical frequency of a device as a function of time (e.g., modulated diode laser) or position
(e.g., chirped fiber Bragg grating).

Chromatic dispersion
A phenomenon caused by the wavelength dependence of group velocity in an optical fiber. Since any practical light source has a certain spectral width, chromatic dispersion results in pulse broadening. The coefficient describing chromatic dispersion per unit length is generally given in units of ps/(nm.km).

Cladding
Low refractive index material surrounding the core of a fiber.

Coherence
A phenomenon whereby the phases of the photons (or constituent wave trains) of a light beam maintain a definite relationship with each other. A narrow linewidth laser is said to exhibit a high degree of coherence.

Connector
Hardware installed on cable ends to connect cables to a transmitter, a receiver, or another cable.

Connector adapter
A device that allows a connectorized fiber to interface with a power meter.

Core
Center section of the optical fiber carrying and guiding light.

Coupler
Optical device containing several input and output ports to distribute optical power.

CPU
Central processing unit.

Crosstalk
Undesirable signals in a communication channel due to leakage or coupling from another channel.

Cutoff wavelength

The shortest wavelength for which an optical fiber can only support the propagation of a single transverse mode.

Dark current
Thermally induced current of a detector in the absence of incident light.

dB–Decibel
: Standard logarithmic unit for the ratio of two quantities. In fiber optics, the ratio is optical power and represents loss or gain.

dBc
: Decibel referenced to the carrier optical power.

dBm
: Decibel referenced to a milliwatt.

Demultiplexer (Demux)
: Separates X different channels (wavelengths) of a signal into X different signals.

Dense wavelength-division multiplexing (DWDM)
: WDM technology where channels are closely spaced and typically concentrated within the 1550 nm wavelength region (C-band).

Detector
: Transducer that converts incident optical energy to an electrical signal at a receiver device.

Differential group delay (DGD)
: There are two mutually orthogonal input states of polarization. These are known as the input principal states of polarization, one of which corresponds to the fastest and the other to the slowest pulse propagation time through the fiber. The difference in these two propagation times is known as the differential group delay (DGD).

Diffraction grating
: A bulk optical element that causes a reflection often at one or more wavelength-dependent angles. This element is based upon coherent scattering from an array of fine, parallel, equally spaced reflecting or transmitting lines.

Directivity
: The ratio of light that passes through the desired port against the light that leaks through to an undesired output port in a multiport device (e.g., optical circulator).

Dispersion
: Signal distortion caused by differing path lengths of the modes in the fiber, which results in the broadening of an input pulse along the distance of the fiber and limits the bandwidth.

Distributed feedback laser (DFB laser)
: An injection laser diode that has a Bragg reflection grating in the active region to suppress multiple longitudinal modes and enhance a single longitudinal mode.

DSn
: The hierarchy of channel capacity for the transmission of digital signals used in North America. A DS1 channel supports 1.544 Mb/s and holds 24 DS0 channels at 64 Kb/s. A DS3 is made up of seven DS2 channels (four DS1 channels) that are multiplexed and transmitted at 44.736 Mb/s.

Dynamic range

For an optical instrument, generally defined as the ratio (in dB) of the smallest signal that can be observed (at a specified wavelength separation) in the presence of a strong, nearly saturating signal.

EDFA

Erbium-doped fiber amplifier.

Edge-emitting LED (EELED)

A type of LED that emits via a rectangular-shaped edge facet. Designed for WDM component manufacturing and testing.

EIA

Electronic Industries Association.

Electromagnetic interference (EMI)

Any electrical or electromagnetic interference that causes degradation, failure in electronic equipment, or undesirable response. Optical fibers neither emit nor are affected by EMI.

Erbium-doped fiber amplifier (EDFA)

An optical amplifier that uses active erbium-doped fiber and a pump source (laser) to boost or amplify the optical signal.

ESA

Electrical spectrum analyzer.

Fabry-Perot (FP) laser

Laser with multi-longitudinal modes.

Fault

Break in the continuity of the optical fiber's normal performance.

Fiber Bragg grating

A spectral filter based on a periodic variation in the refractive index in an optical fiber's core. It is a key component in devices such as optical multiplexers, dispersion compensators, and gain-flattened EDFAs.

Fiber coating

Material immediately around the cladding covering the optical fiber to preserve the integrity of the fiber.

Fiber distributed data interface (FDDI)

ANSI architecture for a metropolitan area network (MAN); a network based on the use of optical fiber to transmit data at 100 Mb/s.

Fiber in the loop (FITL)

Deployment of fiber cable in the local loop, that is, the area between the telephone company's central office and the subscriber.

Flatness

Spectral uniformity of the WDM optical signal.

FOA

Fiber-optic adapter.

Frequency modulation (FM)
: Transmission technique where information is encoded in the frequency of the carrier.

Fresnel reflection
: Reflection of a portion of the light incident on a planar interface between two homogeneous media having different refractive indices. For a perpendicularly-cleaved fiber terminated in air, the Fresnel reflection is -14.6 dB if the fiber's index of refraction is 1.46.

Fused biconic tapered (FBT) device
: A type of optical coupler based on the melting together of two optical fibers along a certain predetermined length (typically 2 to 5 mm). This fusing of fibers results in a certain transfer of energy from one fiber to the other.

FWHM
: Full width half maximum.

Gain
: Gain is the ratio between the average output and input powers, omitting the contribution of the amplified spontaneous emission (ASE) of the amplifier itself.

GPIB
: General purpose interface bus.

Graded index fiber
: An optical fiber whose core refractive index uniformly decreases from its center out to its edge. Normally used to refer to multimode fibers.

Group index
: Ratio of speed of light in a vacuum against the speed of propagation of a light signal in a fiber.

HeNe
: Helium-neon laser.

HiBi
: High birefringence fiber.

IEEE
: Institute of Electrical and Electronics Engineering. It is a professional body that is very active, among other fields, in fiber optics and opto-electronics.

Index-matching gel
: Material with an index of refraction that is almost equal to that of the fiber core; used to reduce Fresnel reflections.

Index of refraction
: Ratio of the speed of light in a vacuum to the speed of light in a given material.

Insertion loss (IL)
: Loss of optical energy resulting from the insertion of a component or device into the optical path.

International Telecommunication Union (ITU)
International standards development body for telecommunications, and the source of many network standards.

L-band (long band)
The spectral window from about 1568 nm to 1610 nm.

Local area network (LAN)
A communications network that links data processing and telecommunications equipment within a confined geographical area. Different elements include servers, workstations, a network operating system, and a communications link.

Laser
Acronym for light amplification by stimulated emission of radiation. Source of highly coherent light via stimulated emission. Semiconductor lasers find widespread use in the fiber-optic industry.

Light-emitting diode (LED)
A semiconductor device that emits incoherent light.

Linearity
For optical measurement instruments, generally used to refer to the deviation of a measured change of a performance parameter (e.g., power, wavelength) from the expected change.

Loss
See attenuation.

Mach-Zehnder interferometer
A device that divides an optical signal into two optical paths having different, generally variable, path lengths. When these two beams recombine, they interfere. These devices are often used as external intensity modulators.

Macrobending
Curvature of a fiber that causes loss of light.

Mandreling
Wrapping an optical fiber or cable around a cylinder to induce changes in optical propagation (e.g., loss in singlemode fiber, mode mixing in multimode fiber).

Material dispersion
Dispersion caused by the wavelength dependence of the optical fiber's index of refraction.

Measurement range
Difference between the launch signal level at the interface to the fiber under test and the minimum level at which an event can be accurately identified and measured within defined limits.

Metropolitan area network (MAN)
A stretched LAN providing data communication over a distance of about 50 km, generally associated with the IEEE 802.6 MAN standard.

Microbending
Microscopic bends or bumps in fiber; these cause loss of light by transferring light energy from the guiding core to the cladding.

Mode
Distribution of electromagnetic energy in an optical fiber, which satisfies Maxwell's equations; path followed by light in an optical fiber.

Mode coupling
Energy exchange between modes of light propagating in an optical fiber.

Mode field diameter
Characteristic diameter of optical energy in an optical fiber.

Mode stripper
Device used to fully attenuate modes of light propagating in the cladding of the optical fiber.

Multimode fiber
Optical fiber supporting more than one spatially propagating mode.

Multipath interference (MPI)
Interference that arises from multiple reflections in an optical path. These reflections cause part of a detected signal to be dephased, which leads to pulse spreading and degraded system performance.

Multiplexer (Mux)
A device that combines several different signals (typically at different wavelengths) on a single fiber.

Narrowband wavelength-division multiplexing (NBWDM)
Type of WDM technology where channels are concentrated around the 1550 nm wavelength. See DWDM.

Network architecture
Description of how communication is established by its terminals, protocols, and software between data-processing equipment at remote sites.

National Institute of Standards and Technology (NIST)
American national standards laboratory that maintains standards for a variety of industries including fiber optics. One such example is standard setting for optical power.

Node
Termination point for two or more communication links.

Noise floor
Optical power level where the signal cannot be distinguished from noise. SNR=1.

Nominal wavelength
An approximate or target wavelength that is characteristic of an optical device (e.g., filter, laser). It is not guaranteed to be its true wavelength.

Numerical aperture (NA)
Light-gathering capabilities of a fiber described by the relative maximum half angle (in units of radius) at which light is accepted and propagated through the fiber. It is a function of the refractive indices of the fiber core and cladding. Standard singlemode fiber has an NA of about 0.12.

Optical carrier (OC)
The main unit used in SONET (synchronous optical NETwork). OC denotes an optical signal and the number following OC represents increments of 51.84 Mbps (capable of holding DS3 signals), which is the minimum transmission rate. The standard SONET format for this transmission rate is called OC-1. Higher transmission rates are exact multiples of OC-1 (e.g.,OC-12, OC-48, and OC-192) Transmission is typically carried out using the protocol at the following rates: OC-3, OC-12, OC-48, and OC-192.

OH-peak
A wavelength range of around 1390 nm—corresponding to an absorption peak of the hydroxyl ion (OH-)—where silica-based optical fibers tend to exhibit enhanced attenuation. This is caused by water contamination in the manufacturing process. Some manufacturers have managed to reduce this peak, permitting newer fibers to be used across a wide spectral range.

Optical cleave
The breaking of an optical fiber to predictably produce flat end surfaces that are perpendicular to the longitudinal axis of the fiber. Sometimes referred to as a mirror-like surface across the entire end surface.

Optical continuous wave reflectometer (OCWR)
An instrument for measuring the total backreflection returning to the source along an optical fiber. For optical components (e.g., isolators, filters, etc.), the OCWR is used to measure return loss (the fraction of light reflected versus the fraction of light transmitted). It can also be used to measure Fresnel reflections of mated connectors.

Optical cross connect (OXC)
Generally refers to a non-blocking NxN, reconfigurable optical switch where the optical signal entering any input port can be directed to any desired output port.

Optical fiber amplifier (OFA)
A term used to include all optical amplifier technologies, including EDFA.

Optical fiber
Fiber made of dielectric material and consisting of the core (light-carrying medium), and the cladding (protective layer) allowing total internal reflection of the light for propagation.

Optical loss test set (OLTS)
An instrument used to measure end-to-end loss in an optical fiber. It is composed of an optical light source and optical power meter, either as an integrated test set or individual test equipment.

Optical return loss (ORL)
Ratio of reflected power against incident power from a fiber-optic section or link; measured in positive dB units.

Optical time domain reflectometer (OTDR)
An instrument used to characterize an optical fiber wherein an optical pulse is launched into the fiber and the resulting backscatter and reflections are measured as a function of time. It is used to identify faults and other localized losses and to estimate loss.

Photodiode
Device that absorbs light energy and produces a photocurrent.

Photon
The packet or element of light exhibiting features of both particles and waves, also referred to as quantum of electromagnetic energy.

Peak wavelength
The wavelength corresponding to the maximum value of a spectral performance characteristic (e.g., the peak wavelength of an optical source, bandpass filter transmission, etc.).

Pigtail
Short length of fiber attached to a connector, source, detector, or coupler.

p-i-n photodiode
A type of photodiode (positive/insulating/negative) with a large intrinsic region in between p- and n-doped semi-conducting regions.

Poincaré sphere (PS)
A three-dimensional graphical representation of the state of polarization of a light beam.

Point-to-point
A two-station communications system that directly links two terminals.

Polarization
A term used to describe the orientation of the electric and magnetic field vectors of a propagating electromagnetic wave.

Polarization controller
A device that transforms the input state of polarization (SOP) of a light beam into a different, adjustable output SOP.

Polarization dependent bandwidth
The dependence of the spectral width on the incident state of polarization.

Polarization dependent central wavelength
The dependence of the peak transmission or reflection wavelength on the state of polarization of the incident light.

Polarization dependent loss (PDL)
The difference in dB between the maximum and minimum values of loss (attenuation) due to the variation of the polarization states of light propagating through a device.

Polarization mode dispersion (PMD)
Dispersion of light causing a delay between the two principal states of polarization propagating along a fiber or through a device due to the birefringence property of the material.

Polarizer
Device that transmits light having one electric field orientation and blocking all others.

Port
Opening for light traveling to and from a component.

Principal states of polarization (PSPs)
The two generally orthogonal states of polarization of a monochromatic light beam launched into a fiber (input PSP) that will propagate through the fiber without spreading or distortion. The SOP of this light beam as it exits the fiber will be in one of two, generally orthogonal, output PSPs. In general, the output PSPs are not the same as the input PSPs and the orientation of these PSPs changes with wavelength. Not to be confused with birefringence. Only in the spectral case of a single HiBi fiber are the PSPs and the axes of birefringence the same.

Protocol
A set of procedures required to establish, maintain, and control communications.

Pulse width
Length of the optical probe pulse that is directly related to the pulse duration.

Rayleigh scattering
A fundamental, wavelength-dependent scattering process that depends strongly on inhomogeneities in material density smaller than a wavelength in size.

Receiver
Terminal equipment of the fiber network that converts optical signals to electrical signals.

Reference power
Power level set as a datum power level; in loss testing it is the power level of the test light source.

Reflectance
Ratio of reflected power against incident power at a single reflection point, or from a device; measured in negative dB units.

Reflection
A change in the direction of light at an interface between two dissimilar materials so that light returns into the material from which it originated.

Reflection generator
Device that reflects a fraction of the optical power incident on the device back into the fiber.

Refraction
A bending of the light propagation direction at an interface between two materials having different indices of refraction.

Refractive index
See index of refraction.

Relative intensity noise (RIN)
A measure of noise in the baseband frequencies of an optical carrier.

Repeatability
Variation of measured quantity when measurement conditions are changed and restored.

Repeater
Device that regenerates the bits into a digital signal, normally by converting the optical signal to an electronic signal, retimes the bit transitions, and retransmits a new optical signal.

Resolution
Minimum value of the quantity measured by a test instrument.

Responsivity
Ratio of photodetector's electrical output against optical input in amperes/watts.

Retardation
In a birefringent material such as a waveplate, the difference in phase shift experienced by light propagating along the slow and fast axes.

Retardation plate
An optical component with two main axes. They separate an incident polarized beam into two perpendicular polarized beams that recombine to form a particular single polarized beam. A retardation plate generates full-, half-, and quarter-wave retardations.

Ripple
An approximately concentric wave that appears on a surface that has not been polished with an oscillating polishing lap.

Sensitivity
Minimum optical power required for a specified level of performance.

Signal-to-noise ratio (SNR)
Ratio of signal power against noise power for the receiver.

Singlemode fiber
Optical fiber supporting only one spatial mode of light propagation.

SOA
Semiconductor optical amplifier.

SONET
: Synchronous optical network. A network that describes a set of common characteristics for optical transmission of digital signals; a Bellcore-proposed protocol for fiber networks.

Source
: Light-emitting diode or laser diode that emits light for launch into an optical fiber; characterized by its central wavelength and spectral width.

Spectral width
: Measure of the wavelength extent for an optical device. In a source, it is the width of the light at half-peak power (full width at half maximum), and in power meters, it is the detector spectral sensitivity range.

Splice
: Method to join two ends of optical fiber in a permanent or temporary manner. Types include fusion splices and mechanical splices.

State of polarization (SOP)
: The orientation of the electric field vector of a propagating optical wave. In general, this vector will trace an ellipse as it propagates. In special cases, it will remain oriented in one direction (linear polarization) or will trace out a circle (left or right circular polarization).

Step-index fiber
: Fiber having a fixed, flat index of refraction within the fiber core and a lower (step) index at the cladding.

STM
: Synchronous transfer mode.

Switch
: Device that transfers light from one or multiple input ports to one or multiple output ports.

Synchronous
: Digital communication having a constant time interval between successive bits or characters and using no redundant information, such as start and stop bits, to identify the beginning and end of the data unit.

Synchronous digital hierarchy (SDH)
: A worldwide, high-speed synchronous protocol standard transmitting up to 40 GB/s, known as SONET in North America. See SONET.

Talk set
: Test set similar to a telephone that uses an optical fiber to establish voice communication.

Thin film coating-based filter
: A type of spectrally selective filter (e.g., optical bandpass filter) based on the application of thin dielectric layers on a glass substrate.

Time-division multiplexing (TDM)
: Optical transmission technique that uses specific positions in time to send data.

Topology
Physical arrangement of stations on a network.

Total internal reflection
The physical process responsible for keeping a light beam guided within the core of an optical fiber. It arises when light in a higher refractive index medium is incident upon the surface of a lower refractive-index medium at an oblique angle greater than a characteristic critical angle.

Transistor-transistor logic (TTL)
Type of signaling in which a nominal +5 V is equated with logic 1 and a nominal 0 V is equated with logic 0. A common semiconductor technology for building digital logic integrated circuits.

Transmitter
Terminal equipment of the fiber network that emits optical signals in response to electrical signal input.

Trunk
A single circuit between two points, both of which are switching centers and/or individual distribution points.

Tunable laser
A laser capable of having its central wavelength varied to optimize it for a given application.

Wide area network (WAN)
A network that links data processing and telecommunications equipment over a larger area than a single work site or metropolitan area. It usually links cities and is based on X.25 packet switching. It may be implemented by a private corporation or a public telecommunications operator.

Waveguide dispersion
Pulse spreading caused by the dependence of the phase and group velocities on a wavelength due to geometric properties of the waveguide.

Wavelength-division multiplexing (WDM)
Optical transmission technique that uses different light wavelengths to send data. Combination of two or more optical signals for transmission over a common optical path.

Wavelength-independent coupler (WIC)
An optical splitter connecting inputs to outputs having a suppressed insertion loss dependence on a wavelength.

ADM:	Add/Drop Multiplexer
ADSL:	Asymmetric Digital Subscriber Line/Asynchronous Digital Subscriber Loop
APS:	Automatic Protection Switching
ATM:	Asynchronous Transfer Mode
BER:	Bit Error Rate
BDLA:	Bidirectional Line Amplifier
BML:	Business Management Layer (TMN)
CLEC:	Competitive Local Exchange Carrier
CD:	Chromatic Dispersion
CO:	Central Office
CORBA:	Common Object Request Broker Architecture (TMN architecture/object model)
DBFA:	Dual-Band Fiber Amplifier
DCD:	Dispersion Compensation Device
DCF:	Dispersion Compensating Fiber
DCOM:	Distributed Component Object Model (TMN architecture/object model)
DSF:	Dispersion-Shifted Fiber
DWDM:	Dense Wavelength-Division Multiplexing
EDFA:	Erbium-Doped Fiber Amplifier
EML:	Element Management Layer (TMN)
FDF:	Fiber Distribution Frame
FEC:	Forward Error Correction
FTTC:	Fiber to the Curb
FWM:	Four-Wave Mixing
GIS:	Geographical Information System
HDSL:	High-Rate Digital Subscriber Link
HFC:	Hybrid Fiber Coax
IP:	Internet Protocol
IXC:	Inter-eXchange Carriers
LAN:	Local Area Network
MAC:	Media Access Control
MIB:	Management Information Base (SNMP jargon)
NDSF:	Non-Dispersion-Shifted Fiber
NE:	Network Element

NEL:	Network Element Layer (TMN)
NML:	Network Management Layer (TMN)
NOC:	Network Operations Center
NRZ:	Non-Return to Zero
NZDSF:	Non-Zero Dispersion-Shifted Fiber
OADM:	Optical Add/Drop Multiplexer
OC:	Optical Carrier
OC-3:	155 Mb/s (SONET transmission rate)
OC-12:	622 Mb/s (SONET transmission rate)
OC-48:	2.5 Gb/s (SONET transmission rate)
OC-192:	10 Gb/s (SONET transmission rate)
OC-768:	40 Gb/s (SONET transmission rate)
OCH:	Optical Channel
OLTE:	Optical Line Terminating Equipment
ONC:	Optical Network Controller
OO:	Object-Oriented
OPS:	Optical Protection Switching
OSC:	Optical Supervisory Channel
OSNR:	Optical Signal-to-Noise Ratio
OSS:	Operation Support System (management systems)
OTAU:	Optical Test Access Units (Bellcore/Telcordia standard name for central station)
OTDR:	Optical Time Domain Reflectometer
OXC:	Optical Cross Connect
PDH:	Plesiochronous Digital Hierarchy
PMD:	Polarization Mode Dispersion
POP:	Point of Presence
POP3:	Post Office Protocol Mail
PSTN:	Public Switched Telephone Network
QoS:	Quality of Service
RFTS:	Remote Fiber Test System
RTU:	Remote Test Unit
SBS:	Stimulated Brillouin Scattering
SDH:	Synchronous Digital Hierarchy
SMTP:	Simple Mail Transfer Protocol

SNMP:	Simple Network Management Protocol (TMN)
SONET:	Synchronous Optical NETwork
SPM:	Self-Phase Modulation
SQL:	Structured Query Language
SRS:	Stimulated Raman Scattering
STM-1:	155 Mb/s (SDH transmission rate)
STM-4:	622 Mb/s (SDH transmission rate)
STM-16:	2.5 Gb/s (SDH transmission rate)
STM-64:	10 Gb/s (SDH transmission rate)
STM-256:	40 Gb/s (SDH transmission rate)
TCP/IP:	Transport Control Protocol/Internetworking Protocol (layer 4 and 3)
TDM:	Time-Division Multiplexing
TMN:	Telecommunications Management Network
TSC:	Test System Controller (Bellcore/Telcordia standard name for central station)
VDSL:	Very High Speed Digital Subscriber Line
VPN:	Virtual Private Network
WAN:	Wide Area Network
WDM:	Wavelength-Division Multiplexing
XPM:	Cross-Phase Modulation

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Guide to WDM Technology and Testing

Nowadays, the whole world depends on fiber-optic voice and data communication to exchange information, buy and sell goods and services, and simply do business as we know it. With the demand for speed and capacity rising just about every day, telecommunications companies have found a future-proof method to keep up: wavelength-division multiplexing, or WDM.

EXFO's *Guide to WDM Technology and Testing* is the only practical reference handbook designed specifically for system and component manufacturers, installers, service providers, and private network operators.

In this book, you'll learn:

- the most important parameters to qualify before deploying WDM technology
- how polarization mode dispersion (PMD) can harm transmission, and how to prevent PMD-related problems
- the challenges of tighter wavelength spacing
- the most critical factors affecting WDM system performance

Whether you're gearing up for WDM component production, installing or maintaining a system, or responsible for monitoring, the *Guide to WDM Technology and Testing* will provide answers.

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