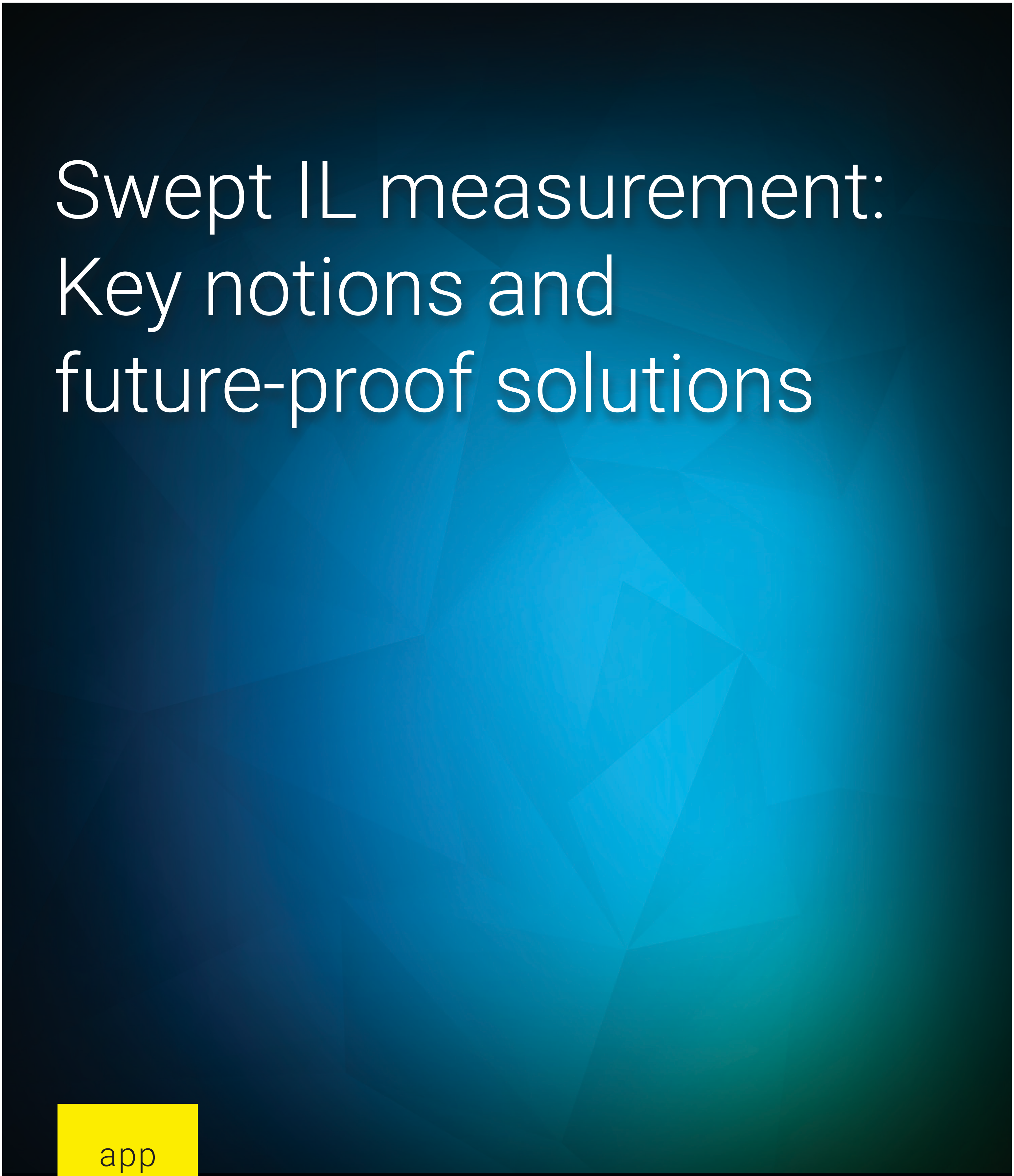

Swept IL measurement: Key notions and future-proof solutions

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EXFO

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Introduction

Passive components are at the heart of any network—from longhaul to access—and must meet increasingly stringent requirements to accommodate the bandwidth explosion triggered by the deployment of 5G and FTTx. So, component manufacturers, system integrators and operators must have a way to quickly and reliably characterize optical components.

Optical characterization usually starts with measurement of the insertion loss (IL) as a function of wavelength for the device under test (DUT). This provides critical information, such as the minimum loss. For wavelength-dependent filters (multiplexers/demultiplexers, wavelength selective switches, etc.), additional parameters such as central wavelength, width and isolation are equally important characteristics derived from the insertion loss measurement.

To this day, external cavity lasers offer unsurpassed performance for measuring IL as a function of wavelength, with a fast tuning speed, high output power and narrow linewidth. External cavity tunable lasers are future proof, readily available for all major telecom bands and cover most applications in the field of optical telecommunication. In addition to the tunable laser, the standard configuration for measuring IL also includes one or several optical detectors to measure the transmitted light for each channel, as shown in Figure 1.

Figure 1. Schematic representation of the standard configuration to measure insertion loss using a tunable laser and one or several optical detectors.

Two complementary measurement techniques are possible based on the configuration of Figure 1:

- Step-by-step measurement
- Swept measurement

Figure 2 schematically represents the difference between the two methods.

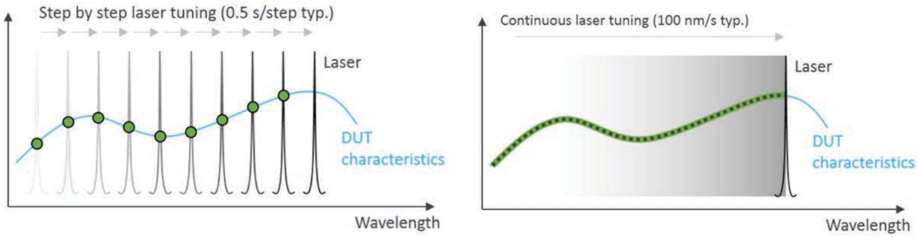


Figure 2. Schematic representation of a step-by-step (left) and swept (right) measurement.

In the case of step-by-step measurements, the tunable laser is successively tuned to the different wavelengths of interest, followed by an acquisition on the optical detectors. Each step typically takes 0.5 seconds, resulting in an overall measurement time proportional to the number of data points. For instance, a 60-nm span with a 50-pm resolution would require 1,201 data points and take approximatively 10 minutes. Although slow, step-by-step measurements are still a viable option when coarse sampling resolution is acceptable or when measurement speed is not a concern. Step-by-step measurements typically require less expensive test equipment (low CAPEX) but the longer measurement time results in high OPEX. However, as the industry is steadily moving towards 100-GHz spaced channels and looking at 25 GHz channel spacing or less, highly resolved measurements become necessary, and the swept method is preferred because of its high throughput with high resolution.

Swept measurements offer uncompromising performance and the possibility of achieving high resolution with excellent measurement speed, resulting in low OPEX.

Swept measurements offer uncompromising performance and the possibility of achieving high resolution with excellent measurement speed, resulting in low OPEX. Synchronous wavelength and power acquisitions are performed as the laser is tuned continuously across the wavelength range. This results in a drastic improvement in measurement speed, typically below 4 seconds for a 100-nm span with 1-pm sampling resolution (100,001 data points). The swept method is therefore ideal to overcome current and future bottlenecks in R&D and manufacturing.

However, swept measurements are more complex compared with step-by-step measurements, and details matter when it comes to getting it right. This application note explains three key notions relevant to swept measurements that are rarely put forward:

1. Power-range-dependent and range-free optical detectors
2. Accurate slope characterization
3. Electrical and optical triggering

The influence of each point on important specifications such as measurement speed, wavelength accuracy, sampling resolution or dynamic range is also discussed.

Power ranges and dynamic range

Depending on the electronic design of the optical detector, power detection may be based on power ranges. Detectors that use power ranges have different settings to adjust the gain of the electronic amplifier circuit to the input optical power. Measuring high optical power would require low electronic gain and vice versa.

This section presents some characteristics of power-range-dependent and range-free detectors relevant to swept measurements.

Power-range-dependent optical detectors

Most optical detectors that use power ranges have between 3 and 5 different settings to select the proper amplification gain for the input optical power. Each range setting can measure power within a certain power range, as shown in the figure below.

> Depending on the electronic design of the optical detector, power detection may be based on power ranges.

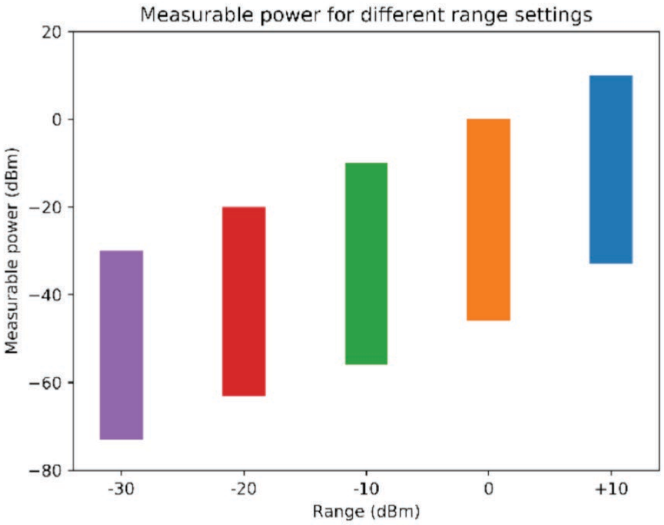


Figure 3. Example representation of the measurable power for 5 different range settings at -30, -20, -10, 0 and +10 dBm.

Prior to starting a swept measurement, the optical detector must be set to a given range, restricting the power values that can be measured during the swept measurement to this range. Each range setting typically has a 45-dB dynamic range (difference between the maximum measurable power and the noise floor), which is insufficient to simultaneously measure the passband and the rejection bands of a filter. This represents a major limitation since both the passband and rejection bands are essential for assessing characteristics such as the central wavelength, minimum loss and isolation.

The only workaround to increase the dynamic range is to perform additional measurements with complementary range settings, for example using the +10 and -20 dBm settings. Typically, you need 2 or 3 consecutive measurements to achieve the desired dynamic range. Figure 4 shows 2 measurements obtained by measuring the same CWDM filter with the -20 dBm and +10 dBm range settings.

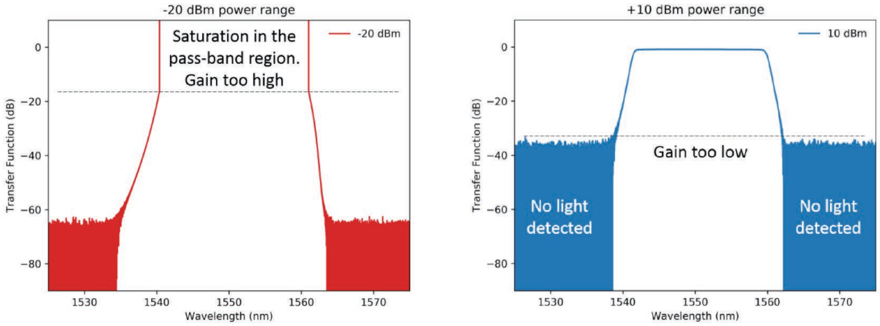


Figure 4. CWDM filter measured with a power-range-dependent optical detector using the -20 dBm (left) and +10 dBm (right) range settings. With the -20 dBm range, the detector saturates in the passband section. With the +10 dBm range, the passband region is properly measured but the noise floor is around -35 dBm.

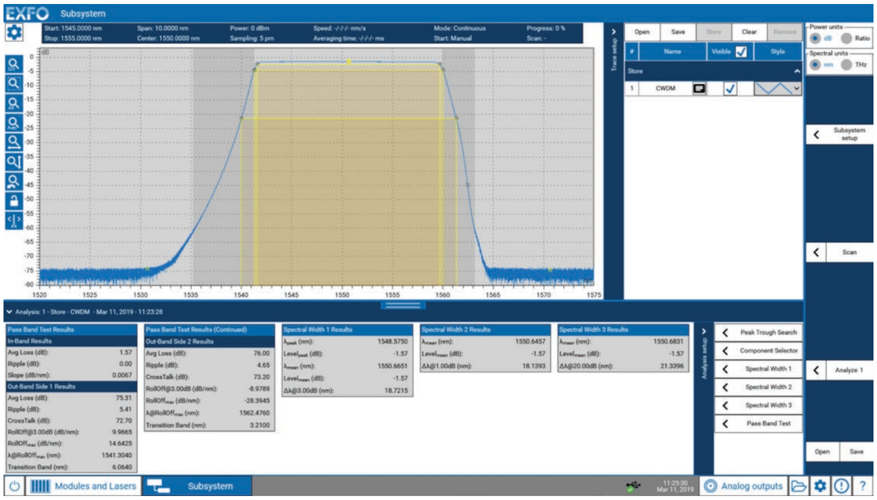
However, this approach comes with several inherent limitations and challenges. First and foremost, the need to perform several consecutive measurements to increase the dynamic range to an acceptable level strongly affects the overall measurement time and reduces throughput proportionally. Then, data processing is required to compile the different results into a single trace, a step usually called *trace stitching*. Although trace stitching is relatively simple in principle, it also raises a number of questions, such as how to handle wavelength or power offsets between traces, in relation to the repeatability of the test equipment, for example.

> Optical detectors that do not rely on power ranges use a specially designed electronic circuit to measure a wider dynamic range without having to switch between ranges.

Range-free optical detectors

Optical detectors that do not rely on power ranges use a specially designed electronic circuit to measure a wider dynamic range without having to switch between ranges. For swept measurements of filter-type components, these optical detectors can typically measure a dynamic range wider than 65 dB in a single sweep, offering a significant speed improvement compared with power-range-dependent optical detectors. In addition, with range-free optical detectors, there is no need to postprocess the data, simplifying the procedure and ensuring better measurement accuracy and reliability through less data-processing.

EXFO has developed innovative swept solutions based on range-free optical detectors for the test and measurement industry. EXFO's CT440 and CTP10 are two component testers that can measure passive components with a wide dynamic range in a single scan, providing a two- to threefold improvement in measurement speed as compared with power-range-dependent optical detectors, which require several successive scans to achieve a similar dynamic range.



Start: 1545.0000 nm
Stop: 1555.0000 nm
Span: 10.0000 nm
Center: 1550.0000 nm
Power: 0 dBm
Sampling: 5 pm
Speed: -/-/-/- nm/s
Averaging time: -/-/-/- ms
Mode: Continuous
Start: Manual
Progress: 0 %
Scan: -

Analysis: 1 - Store - CWDM - Mar 11, 2019 - 11:23:28

Pass Band Test Results	
In-Band Results	
Avg Loss (dB):	1.57
Ripple (dB):	0.00
Slope (dB/nm):	0.0067
Out-Band Side 1 Results	
Avg Loss (dB):	75.31
Ripple (dB):	5.41
CrossTalk (dB):	72.70
RollOff@3.00dB (dB/nm):	9.9665
RollOff$_{max}$ (dB/nm):	14.6425
λ@RollOff$_{max}$ (nm):	1541.3040
Transition Band (nm):	6.0640

Pass Band Test Results (Continued)	
Out-Band Side 2 Results	
Avg Loss (dB):	76.00
Ripple (dB):	4.65
CrossTalk (dB):	73.20
RollOff@3.00dB (dB/nm):	-8.9789
RollOff$_{max}$ (dB/nm):	-28.3945
λ@RollOff$_{max}$ (nm):	1562.4760
Transition Band (nm):	3.2100

Spectral Width 1 Results	
λ_{peak} (nm):	1548.5750
Level$_{peak}$ (dB):	-1.57
λ_{mean} (nm):	1550.6651
Level$_{mean}$ (dB):	-1.57
Δλ@3.00dB (nm):	18.7215

Spectral Width 2 Results	
λ_{mean} (nm):	1550.6457
Level$_{mean}$ (dB):	-1.57
Δλ@1.00dB (nm):	18.1393

Spectral Width 3 Results	
λ_{mean} (nm):	1550.6831
Level$_{mean}$ (dB):	-1.57
Δλ@20.00dB (nm):	21.3396

Figure 5. Graphical user interface of the CTP10 test platform showing the insertion loss of a CWDM filter and analysis results. The range-free optical detectors in the CTP10 platform can characterize the filter down to -75 dB in a single sweep, with a measurement time of 4 seconds for a 100 nm span at 100 nm/s.

Accurate slope measurement

As passive optical components follow the newly adopted standards driving the industry towards increasingly close-spaced channels, filters must have increasingly steep profiles to provide good isolation while maintaining low insertion loss in the passband region. Figure 6 below illustrates the difference in width between a CWDM and a 100-GHz DWDM filter. The transition from the rejection band to the passband (and reciprocally) is referred to as filter slope and usually expressed in dB/nm.

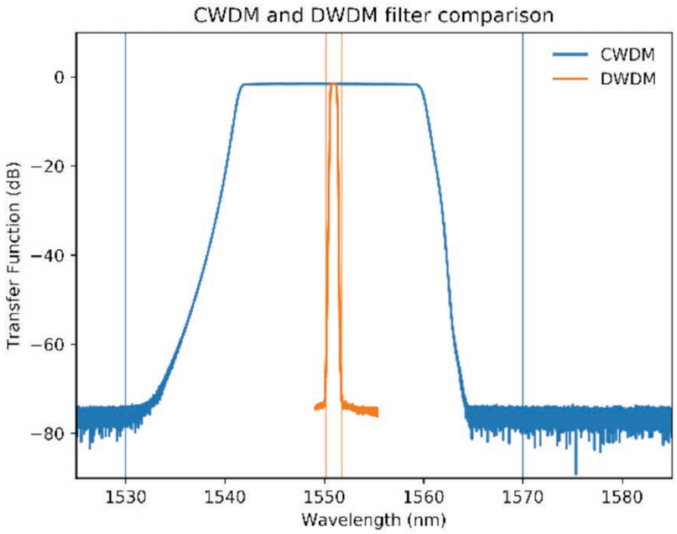


Figure 6. IL measurement of a CWDM and DWDM filter. The vertical lines represent the adjacent channels of both filters. Maximum filter slopes: CWDM, 14.6 and 28.3 dB/nm (left and right); DWDM, 165.4 and 268.7 dB/nm (left and right).

The table below summarizes the grid spacing and some typical slope values for different types of optical components.

	CWDM	DWDM	Next Gen.
Grid spacing	20 nm	100 GHz	100/50 GHz
Max slope (typ.)	< 50 dB/nm	< 350 dB/nm	> 750 dB/nm

Components with steep profiles are challenging to measure accurately because they create fast power variations on the optical detector during the laser sweep. The following equation expresses the power variations in the time domain as a function of the laser sweep speed and DUT slope.

$$\textit{Power variations on the detector}_{[dB/s]} = \textit{Laser sweep speed}_{[nm/s]} \,.\, \textit{DUT slope}_{[dB/nm]}$$

In practice, the characteristics of the optical detector are given by the manufacturer and will determine the maximum slope (i.e., IL variations) that can be measured for a certain laser sweep speed. Power variations that exceed the specifications of the optical detectors will not be accurately measured, resulting in a distorted trace. For filter-type components, this may affect the measured central wavelength and minimum loss, as shown schematically in Figure 7.

> As we move towards reconfigurable, narrower and increasingly complex optical components, test solutions that can accurately measure steep profiles at full speed are key and will certainly be essential in the future.

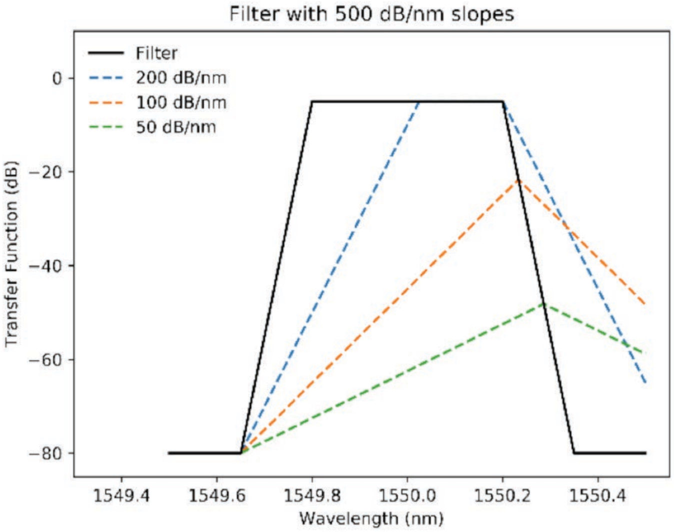


Figure 7. Schematic representation of how a DUT with 500 dB/nm slopes would be measured using an optical detector limited to 200 dB/nm (blue), 100 dB/nm (orange) and 50 dB/nm (green) for a given sweep speed.

In a manufacturing environment with pass/fail criteria on the measured central wavelength, minimum loss or filter slope, this may lead to pass defective components or discard components within specifications.

One way to mitigate this effect is to reduce the laser sweep speed so that you can measure steeper slopes at the expense of measurement time. However, as we move towards reconfigurable, narrower and increasingly complex optical components, test solutions that can accurately measure steep profiles at full speed are key and will certainly be essential in the future.

Several reconfigurable optical components, such as wavelength selective switches (WSS), have been developed in recent years and deployed in the field. A WSS can generate virtually any filter shape and result in extremely steep profiles that can contain dozens of passband regions, adding even more emphasis to slope measurement. Figure 8 shows a typical IL measurement of a WSS.

Start: 1545.0000 nm
Stop: 1555.0000 nm
Span: 10.0000 nm
Center: 1550.0000 nm
Power: 0 dBm
Sampling: 5 pm
Speed: -/-/-/- nm/s
Averaging time: -/-/-/- ms
Mode: Continuous
Start: Manual
Progress: 0 %
Scan: -

Analysis: 1 - Store - WSS - Mar 11, 2019 - 09:47:12

Pass Band Test Results

In-Band Results

Avg Loss (dB):	4.31
Ripple (dB):	0.01
Slope (dB/nm):	-0.0638

Out-Band Side 1 Results

Avg Loss (dB):	58.58
Ripple (dB):	6.19
CrossTalk (dB):	53.73
RollOff@3.00dB (dB/nm):	127.962
$RollOff_{max}$ (dB/nm):	872.629
$λ@RollOff_{max}$ (nm):	1554.4510
Transition Band (nm):	0.1070

Pass Band Test Results (Continued)

Out-Band Side 2 Results

Avg Loss (dB):	58.34
Ripple (dB):	3.12
CrossTalk (dB):	54.34
RollOff@3.00dB (dB/nm):	-100.701
$RollOff_{max}$ (dB/nm):	-736.111
$λ@RollOff_{max}$ (nm):	1555.2283
Transition Band (nm):	0.1150

Spectral Width 1 Results

$λ_{peak}$ (nm):	1554.6750
$Level_{peak}$ (dB):	-4.23
$λ_{mean}$ (nm):	1554.8391
$Level_{mean}$ (dB):	-4.31
Δλ@3.00dB (nm):	0.5645

Spectral Width 2 Results

$λ_{mean}$ (nm):	1554.8388
$Level_{mean}$ (dB):	-4.31
Δλ@1.00dB (nm):	0.5078

Spectral Width 3 Results

$λ_{mean}$ (nm):	1554.8388
$Level_{mean}$ (dB):	-4.31
Δλ@20.00dB (nm):	0.6938

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Mar 11, 2019

Figure 8. IL measurement of a WSS using the CTP10 component tester. The maximum slope measured for one particular channel was 872.6 and 736.1 dB/nm (left and right slopes).

> In the case of ranged optical detectors, the detector’s ability to accurately measure fast power variations usually depends on the selected range.

Due to their reconfigurable nature, WSSs must be characterized in various configurations and therefore require multiple measurements. The ability to measure components quickly and reliably is therefore particularly critical to eliminate bottlenecks in R&D and manufacturing.

Adding to the complexity of slope measurement, the ability of optical detectors to measure fast power variations is not uniformly specified in the industry and can sometimes be expressed in dB/nm for a given sweep speed, in dB/µs or as a cutoff frequency in kHz. The values expressed in dB/µs and dB/nm can be easily related using the laser sweep speed:

$$\mathit{Specification}_{[dB/\mu s]} \cdot 10^{6} = \mathit{Specification}_{[dB/nm]} \cdot \mathit{Laser\ sweep\ speed}_{[nm/s]}$$

A cutoff frequency (usually given at 3 dB) is a lot more difficult to interpret because the exact spectral response of the detector is unknown, making it difficult to estimate the degree of trace distortion. Any signal at the specified 3 dB cutoff frequency will by definition be attenuated by 50 %, but signal distortion builds up gradually below the cutoff frequency, making it challenging to estimate beforehand how the detector will perform.

The most straightforward way is to provide a value expressed in dB/nm (or dB/pm) and the corresponding laser sweep speed for which this value is valid. For instance, a value of 0.5 dB/pm at 10 nm/s is equivalent to 500 dB/nm (at 10 nm/s) and may already be limiting for the latest generation of optical components (e.g., WSS). Using the same detector at 100 nm/s would result in a tenfold decrease in measurable slope, achieving only 50 dB/nm, clearly insufficient for most optical filters.

In the case of power-range-dependent optical detectors, the detector’s ability to accurately measure fast power variations usually depends on the selected range. Electronic circuits with a higher amplification gain (corresponding to lower range settings) tend to have slower time constants and are therefore less accurate at measuring fast power variations. The figure below shows the same filter measured at 5 nm/s and 200 nm/s using the 0 and -30 dBm power ranges. At 5 nm/s, a good agreement is observed between the 0 and -30 dBm ranges, and both traces are superimposed. However, the traces acquired at 200 nm/s show a noticeable offset resulting from the slower time response of the -30 dBm range, creating an artificial wavelength shift towards longer wavelengths. This offset, as well as any slope discontinuity, will make trace stitching challenging and raise some questions regarding metrological concerns and measurement uncertainties.

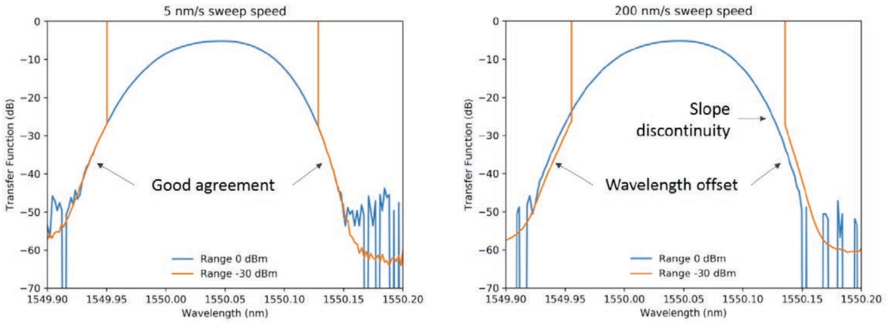

Figure 9. Narrow-band filter measured using a power-range-dependent optical detector at 5 nm/s (left) and 200 nm/s (right) with the 0 dBm and -30 dBm range settings.

In addition to requiring several successive sweeps, care must be taken to ensure that the range is compatible with the expected slope to be measured. If not, the laser sweep speed must be adjusted accordingly, further reducing the overall measurement speed.

EXFO's range-free series of component testers are built around specially designed electronics capable of measuring steep filter slopes in a single sweep. The CTP10 component tester can measure components with slopes up to 10,000 dB/nm at 100 nm/s (equivalent to 1 dB/µs), well beyond the steepest components commercially available today.

EXFO's range-free series of component testers are built around specially designed electronics capable of measuring steep filter slopes in a single sweep.

Triggering method

The triggering method describes how the wavelength and power readings are synchronized during the laser sweep. Two triggering methods are possible:

- Electrical triggering
- Optical triggering

The triggering method is also strongly related to the wavelength measurement. With the electrical triggering method, the wavelength measurement is taken within the tunable laser, whereas with the optical triggering method the wavelength is measured externally.

Electrical triggering

The electrical triggering method relies on an electrical trigger sent from the tunable laser to the optical detector using an external BNC cable.

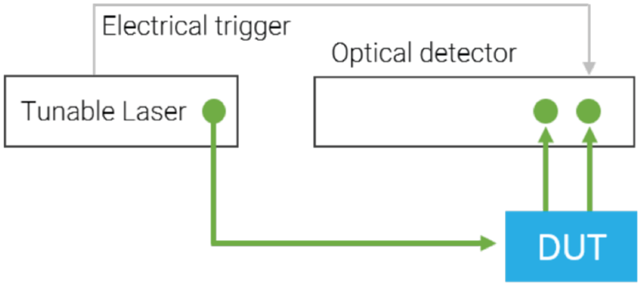

Figure 10. Measurement configuration using the electrical triggering method. Power acquisition on the optical detector is triggered by the tunable laser.

Electrical triggers are issued by the tunable laser during the laser sweep to trigger a power measurement on the optical detector. At the end of the laser sweep, the wavelength and power arrays can be retrieved from the tunable laser and optical detectors respectively and combined to plot the transmission spectrum of each channel.

In this configuration, the wavelength accuracy and sampling resolution are solely determined by the tunable laser. This triggering method therefore puts stringent requirements on the laser, which cannot always maintain best performance at the fastest sweep speed. This may for example affect the sampling resolution of the electrical triggers or the wavelength accuracy, preventing fast measurements with the best sampling resolution and/or accuracy. In addition, the buffer used to store wavelength data points within the tunable laser is usually limited to a range of 50K to 100K points. Although tunable lasers nowadays have a wavelength range between 100 nm and 200 nm, the internal buffer prevents the use of such lasers for picometer resolution measurements over the full range.

Swept measurements offer undisputable advantages over the step-by-step approach, providing picometer resolution over a wide wavelength range within seconds.

Optical triggering

The optical triggering method relies on optical measurement of the laser wavelength during the laser sweep. Optical triggering is typically used in integrated solutions where the function can be embedded in the system and trigger the power acquisition seamlessly without an external cable. This integrated solution, generically referred to as a component tester, serves as an interface between the tunable laser and the DUT.

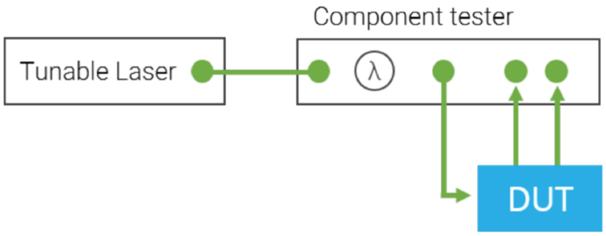

Figure 11. Measurement configuration using the optical triggering method embedded in a component tester. A small portion of the light is tapped within the component tester for optical triggering.

Within the component tester, a small portion of the incoming light is tapped for optical triggering. In addition to optical triggering, component testers usually also integrate a power monitoring photodetector to measure and compensate for power variations from the tunable laser. In the case of optical triggering, the sampling resolution and wavelength accuracy are determined by the component tester rather than by the laser. That way, you can use a less expensive laser, which is even more advantageous when several lasers are required, for example to cover a wider wavelength range.

Typically, a sampling resolution of 1 pm can be achieved together with a wavelength accuracy below ±5 pm at full speed (100 nm/s or above). In this regard, component testers are a very effective solution to simultaneously achieve the best sampling resolution, accuracy and measurement speed.

Conclusion

Swept measurements offer undisputable advantages over the step-by-step approach, providing picometer resolution over a wide wavelength range within seconds. This measurement method is already widely used in R&D and manufacturing to test optical components and will help maintain high throughput, resolution, speed and accuracy when next-generation optical components are tested.

This application note addressed three notions that play an indirect role in determining the final specifications of a system. The table below summarizes the most common specifications and what needs to be verified with test equipment manufacturers to ensure that the final specifications meet the requirements.

	Tunable laser + optical detectors	Tunable laser + component tester
Triggering method	Electrical	Optical
Sampling resolution	Check if affected by - laser sweep speed - laser model	1 pm typ. at full speed
Wavelength accuracy	Check if affected by - laser sweep speed - laser model	Independent of laser sweep speed
Slope measurement	Check the detector's specifications	
Measurement speed	Check if the detectors use power ranges	

EXFO's swept test solutions include sweeping tunable lasers and the CT440 and CTP10 component testers. The CT440 and CTP10 use optical triggering and range-free optical detectors to provide single-sweep solutions with picometer resolution and maximum wavelength accuracy at full speed, offering a future-proof solution to characterize current and next-generation optical components.

Figure 12. T500S-Swept tunable laser / CTP10-Component test platform / CT440-Component tester

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