Challenges in DWDM System Spectral Analysis

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Understanding the characteristics of DWDM transmission systems and analysis equipment to ensure its successful operation.

ABSTRACT

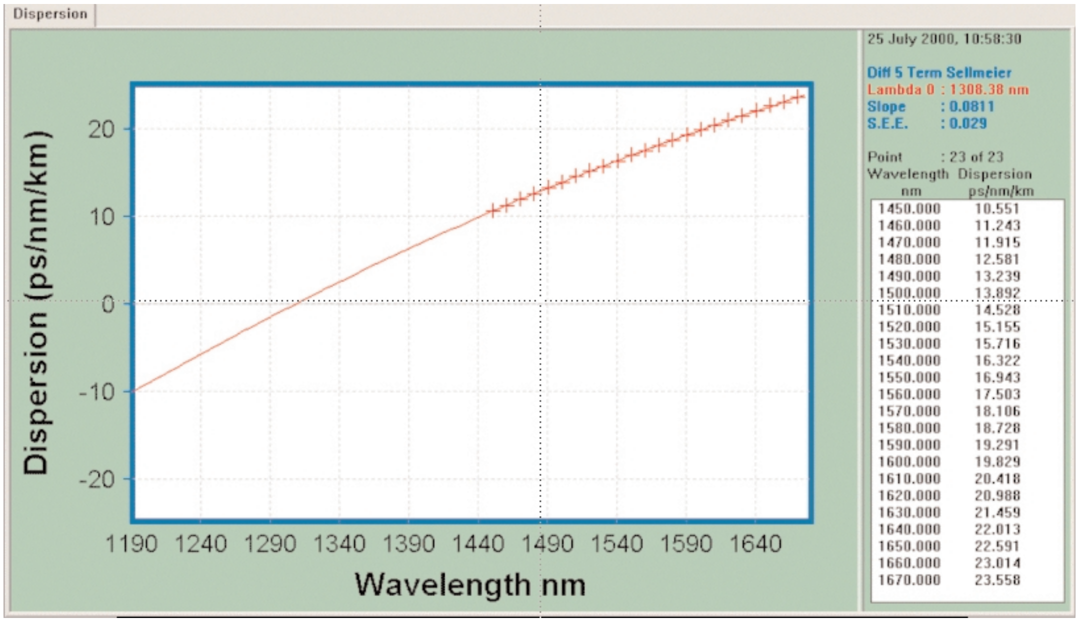
Wide-scale field deployment of DWDM systems with high count, closely spaced channels has led to the development of a new generation of optical spectrum analyzers. These new analyzers can be deployed either as portable test systems, embedded systems to be incorporated in the DWDM transmission systems or as bench-top instrumentation for DWDM system characterization. The advances in this field, current applications, and differentiation between platforms will be discussed.

1.0 Satisfying The Thirst For Bandwidth

The continued emergence of the Internet and the insatiable demand for real-time interaction with multimedia applications has continued to fuel the demand for increased bandwidth. To satisfy this need, telecommunication providers have continued to widely deploy high-speed DWDM systems. In some cases, these systems have surpassed the terabit/second threshold. DWDM system designers have focused on three areas for bandwidth increases: high channel count systems, high data rate systems, and increased spectrum utilization. Each one of these approaches has its advantages and disadvantages, but economics continues to be the primary reason for selecting a specific approach.

The prohibitive argument for deploying L-band systems is the additional cost of deploying L-band amplifiers in the transmission system, dispersion compensating devices and other associated optical components. In most cases, the response of the physical plant to L-band transmission has yet to be characterized. Both attenuation and chromatic dispersion are significantly higher for transmission in the L-band (Fig.1). Operating at data rates greater than 10 Gb/sec can also be challenging due to dispersion, non-linear effects (Four Wave Mixing, Cross Phase Modulation and Self Phase Modulation) and the additional cost of more complex electronics.

Recently several companies announced DWDM transmission systems operating at channel spacing of 12.5 GHz or less. At this channel spacing, the ability to qualify and measure the spectral characteristic of the channels becomes critical to successful system operation.



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Diff 5 Term Sellmeier
Lambda 0 : 1308.38 nm
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S.E.E. : 0.029

Point : 23 of 23

Wavelength nm	Dispersion ps/nm/km
1450.000	10.551
1460.000	11.243
1470.000	11.915
1480.000	12.581
1490.000	13.239
1500.000	13.892
1510.000	14.528
1520.000	15.155
1530.000	15.716
1540.000	16.322
1550.000	16.943
1560.000	17.503
1570.000	18.106
1580.000	18.728
1590.000	19.291
1600.000	19.829
1610.000	20.418
1620.000	20.988
1630.000	21.459
1640.000	22.013
1650.000	22.591
1660.000	23.014
1670.000	23.558

Figure 1. Chromatic Dispersion in the L-band

In most cases, a general guideline for limiting the maximum amount of dispersion to 1/10 the bit duration which would indicate that a network operating at 40 Gb/sec would only have an allowable dispersion limit of 2.5 ps. This would severely limit the number of possible installed fiber routes eligible for this improved transmission rate without some form of dispersion management or pre-distortion of the optical signal implemented. While dispersion-compensating devices for chromatic dispersion (CD) are widely available, the use of these devices incorporate added material and engineering cost into the system. On the other hand, Polarization Mode Dispersion compensation techniques have only recently become available.

2.0 The Solution, DWDM

Decreasing the channel spacing of the transmission system is an approach that circumvents the need for additional electronics, fiber characterization and new fiber plant infrastructure, while also allowing exploitation of the existing infrastructure. Recently, several companies announced DWDM transmission systems operating at channel spacing of 12.5 GHz or less. At this channel spacing the ability to qualify and measure the spectral characteristic of the channels become critical to successful system operation.

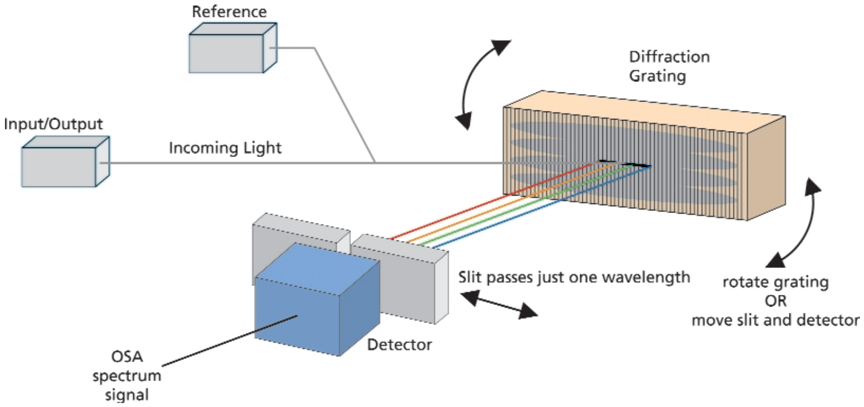

Figure 2. Simplified OSA Diagram

Today, the majority of deployed bench top and field portable spectrum analyzers consist of a mechanically scanned double-pass or four-pass grating monochromator, while embedded systems utilize a Fabry-Perot filter as tuning element.

The traditional method to characterize the spectral characteristics of a DWDM system has been with an optical spectrum analyzer. At the fundamental level, all optical spectrum analyzers consist of an input, wavelength filter element, detector and in some instances a wavelength reference (Fig. 2). The wavelength selective device typically consists of a monochromator or a Fabry-Perot filter. In some applications it is also possible to use a detector array with a fixed grating and no slit. Today, the majority of deployed bench-top and field-portable spectrum analyzers consist of a mechanically scanned double-pass or four-pass grating monochromator, while embedded systems utilize a Fabry-Perot filter as the tuning element (Fig 3). The decision between technologies is largely dependent upon customer size constraints and operating requirements. Another significant factor in the decision process is the required Mean Time Between Failure (MTBF) of the system. For most embedded applications, the MTBF goal is approximately 15 years. Scanning once per second, an embedded instrument would need to scan 1/2 billion times between failures. Most mechanical scanning systems will fail much earlier, as mechanical actuation components like ball screws have typical lifetimes ranging from 1 to 10 million cycles.

In determining the capability of these analyzers and their suitability for an application, several important characteristics of the device need to be understood; spectral resolution, wavelength accuracy, dynamic range, polarization sensitivity and channel selection characteristics.

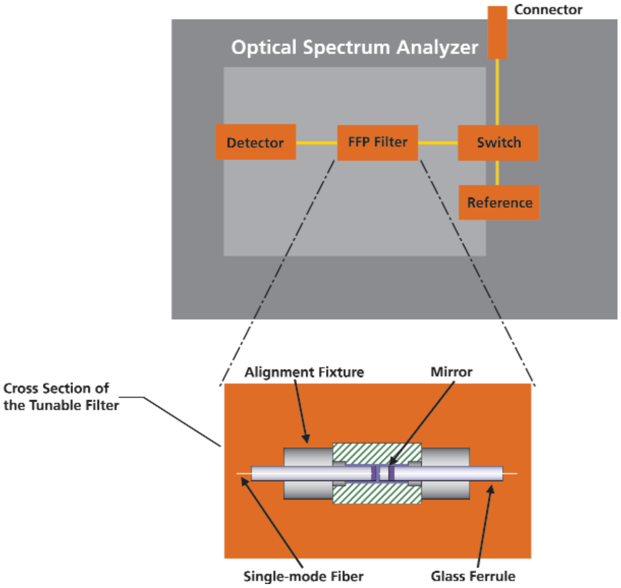

Figure 3. OSA based upon Fabry Perot Filter (courtesy Micron Optics)

The most important definition for optical resolution of a spectrum analyzer used for multi-channel measurements is the ability to resolve and characterize channels at a specified separation.

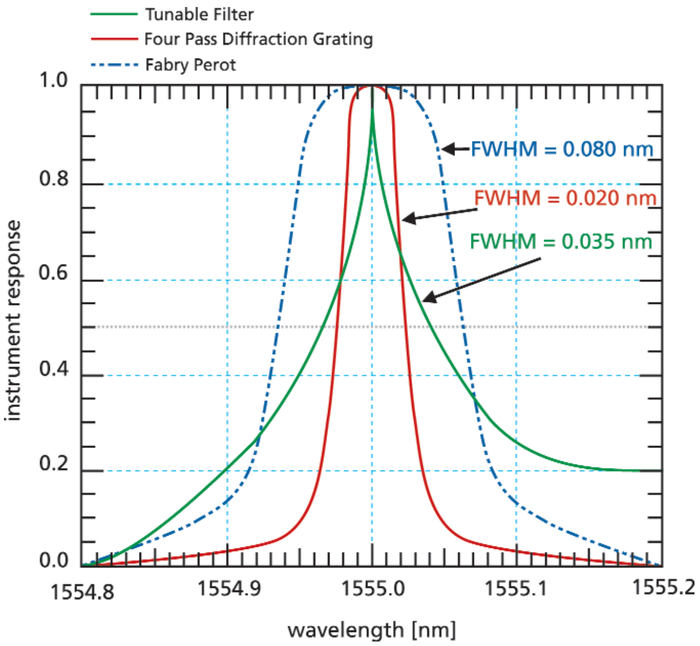

Figure 4. Spectral Response of Various Filter Techniques

3.0 Resolution

The optical resolution of a spectrum analyzer is one of the more commonly misunderstood terms in the Test and Measurement industry. There have been numerous definitions available ranging from data point spacing, channel resolution, to the 3 dB FWHM measurement of the optical filter element within the instrument. However, the most important definition for optical resolution of a spectrum analyzer used for multi-channel measurements is the ability to resolve and characterize channels at a specified separation. This ability is directly related to the bandwidth of the filter contained within the instrument and the sideband skirts of the filter. As an example, consider three different instruments: one based upon a double-pass monochromator, a second based on Fabry-Perot filter, and a third employing a 4-pass monochromator (Fig 4). The instrument based upon the double-pass monochromator would have excellent dynamic range performance but would be limited to channel resolution lower than the FWHM of the scanning element. The bandwidth of a monochromator based spectrum analyzer is a function of the grating rule and the input and exit aperture dimensions. An instrument based upon Fabry-Perot technology would be able to resolve channels that are closely spaced together due to the spectral response of the filter, but would be limited in dynamic range performance due to the sidebands of the filter element. Bandwidth and out-of-band rejection of the Fabry-Perot filter are a function of the Finesse (F) and Free Spectral Range (FSR) of the filter and are described by the following equations:

$BW=FSR/F$ $\qquad$ $FSR=c/(2nl)$

Cavity length=l
Speed of light=c
Index of refraction =n
Finesse=F

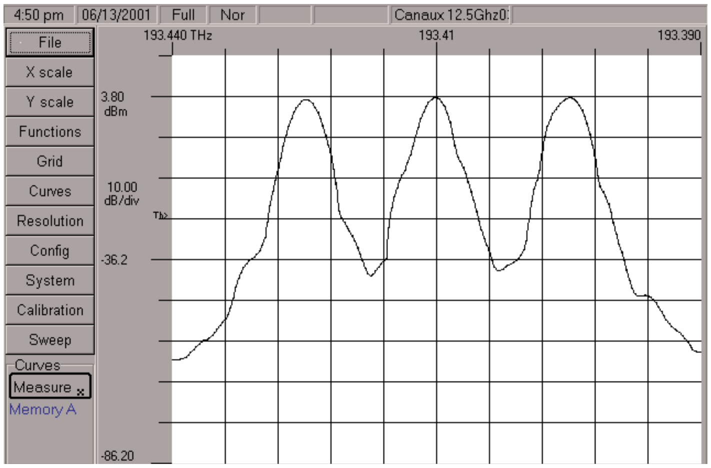

Figure 5a. 12.5GHz Channel Spacing

The ideal instrument for the measurement would be one that combines the characteristics of both techniques-sharp spectral response and high dynamic range.

The ideal instrument for the measurement would be one that combines the characteristics of both techniques-sharp spectral response and high dynamic range. In this case an instrument based upon a 4-pass monochromator would allow dense channel measurement while still preserving the dynamic range capability of the instrument. In this optical layout each pass of the light on the grating increases dispersion therefore improving resolution. This technique could be combined with a double-monochromator design to achieve a higher dynamic range and a clean-cut spectral response (Fig 5). At a channel spacing of 12.5 GHz an instrument with this optical layout achieves in excess of 40 dB of dynamic range (Fig. 5a)!

With most spectrum analyzers, it is fairly common to measure bandwidth by using an external single laser line as the stimulus. This method of measurement gives a fairly accurate representation of the profile of the filter within the spectrum analyzer; however, it does not give an indication of the laser profile, as the laser linewidth is typically in the MHz range, far below the bandwidth of the spectrum analyzer.

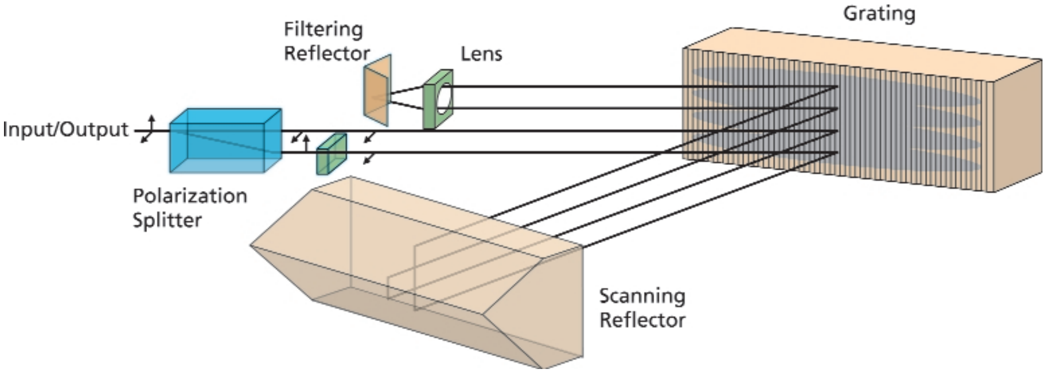

Figure 5. Quadruple-Pass Polarization Balanced Double Monochromator Configuration

4.0 Wavelength Accuracy

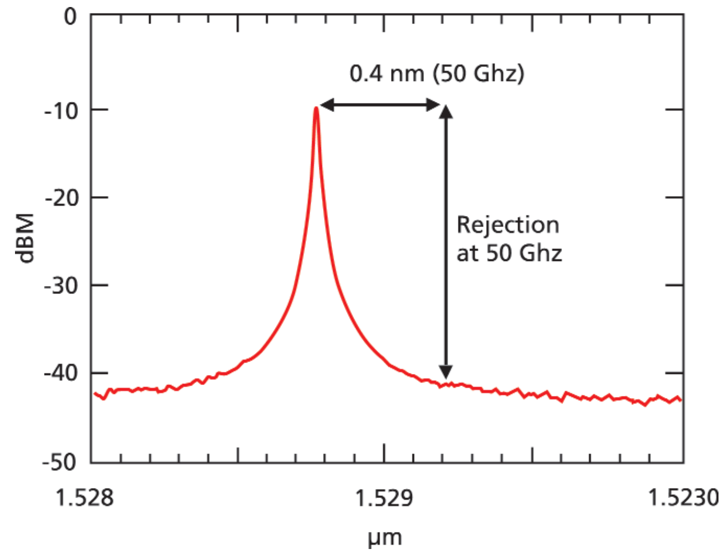

Figure 6. Optical Rejection Ratio

For DWDM systems with channel spacings approaching 80 pm, wavelength accuracy and the accurate measurement of, becomes increasingly important. Most commercially available spectrum analyzers have wavelength accuracies ranging from 15 pm to 50 pm, usually specified at a specific operating condition over a wavelength range. For most customers deploying systems incorporating channel spacings below 25 GHz (200 pm), a wavelength accuracy better than 30 pm is required across the wavelength range of interest and over the operating temperature range.

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If the instrument is being used in an embedded application for system monitoring and gain equalization, a wavelength accuracy of 20 pm would be desired. It is feasible that embedded spectrum analyzers will one day be used for wavelength locking functions within a DWDM system. For this application, the wavelength accuracy of the instrument would have to be enhanced to 10 pm or better. Manufacturers attempting to meet these accuracy requirements for both portable and embedded applications will include some form of precision wavelength reference internal to the instrumentation. Thermally controlled Bragg gratings or acetylene cells are two examples of wavelength references commonly used and in order to achieve a higher accuracy over a wider spectral range multi-point references may be used.

5.0 Dynamic Range

Similar to spectral resolution, there are several definitions of dynamic range, from input power dynamic range and optical rejection ratio to the measurement of the noise floor at a specified distance away from the center wavelength of the channel under test. In the case of the input power dynamic range measurement of a spectrum analyzer, it is the difference between the maximum input power range and the minimum detectable power level of the instrument. For example, an instrument with a detectable power range extending from +10 dBm to -70 dBm would have an input power dynamic range of 80 dB. Although this definition is useful if the primary goal of the instrument is to measure the power of a single laser line, it is not very applicable to multi-channel systems. Further complicating this definition is whether or not the term is specific to total input composite power or power per channel.

A commonly used definition of dynamic range is to identify the response of the scanning element a pre-defined distance away from the center of the channel (Fig 6). Referred to as Optical Rejection Ratio, this term can be specified at either 0.5 nm or 1.0 nm away from the center of the channel. For DWDM systems, it is common to specify this term at a distance of one-half the wavelength spacing of the next adjacent channel. In practical use, this definition neglects any effect of crosstalk between channels that may occur due to the spectral shape of the filter. In high channel count, narrowly spaced DWDM systems it would be more useful to specify the dynamic range of the instrument two ways: in the form of a maximum achievable OSNR at a specified channel spacing and input power dynamic range per channel.

6.0 Polarization Sensitivity

The polarization sensitivity an optical spectrum analyzer is a measurement of the power response change due to the input signal state of polarization. In most cases, this value is specified not to exceed 0.25 dB. In instances where the instrument is intended to be used within a system or to characterize the polarization effects on optical components, the required polarization sensitivity may be reduced to 0.1 dB.

For a spectrum analyzer based upon a diffraction grating the polarization sensitivity is mainly caused by the grating element; however, low sensitivity can be achieved with the use of a polarization-balanced configuration. See for example the instrument demonstrated in figure 5: With a polarization splitter and a half-wave plate, the 2 orthogonal polarizations have identical opposite paths. For most instruments based upon Fabry Perot technology, the polarization sensitivity arises from the sensitivity of the filter element and all other components within the optical path prior to detection.

7.0 Channel Selection

The deployment of DWDM systems has also presented system engineers and maintenance personnel with the added challenge of how to selectively choose one channel among many and analyze its performance. Manufacturers of Optical Spectrum Analyzers have responded with the capability within the instrumentation to stop the scanning mechanism at a particular position and route the channel of interest to another piece of test instrumentation.

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The main challenge is to ensure that the bandwidth of the filter does not degrade the integrity of the channel under test. In the case of a 10 Gb/sec modulated signal, depending on the modulation technique, the bandwidth of the filter within the spectrum analyzer may need to be in excess of 20 GHz. For practical use, it is desirable that the bandwidth of the filter be large enough to accommodate center wavelength drift of both the channel under test and the measuring device, as well as the sidebands of the modulated signal. For a 40 Gb/sec system the bandwidth of the device may need to exceed 80 GHz. At this point, due to the required bandwidth of the filter, the instrument would have limited applications in the measurement of high channel count, closely spaced DWDM systems.

It is also worth noting that the application of the channel drop capability and subsequent analysis by a BER tester is limited to points in the network where there is sufficient input power available for the BER tester.

The continued deployment of high channel, count ultra-dense DWDM systems continue to present significant measurement challenges to Test and Measurement companies targeting field, laboratory and embedded applications. The evolution of DWDM systems toward 12.5 GHz spacing is a recent example of evolving measurement challenges. There are multiple choices available for Optical Spectrum Analyzer technology and new techniques are underway. It is only through a detailed understanding of the measurement application and technical capabilities of the instrument that one can ensure that the right instrument has been chosen for the application.

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