



Dense Wavelength Division Multiplexed (DWDM) Testing

Definition

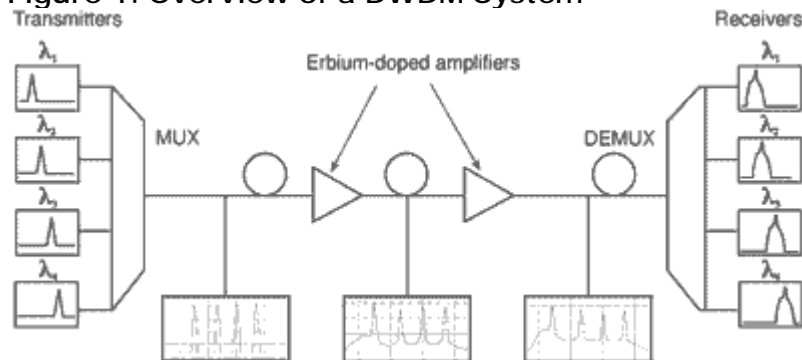
At its simplest, a dense wavelength division multiplexed (DWDM) system can be viewed as a parallel set of optical channels, each using a slightly different light wavelength, but all sharing a single transmission medium. This new technical solution can increase the capacity of existing networks without the need for expensive recabling and can significantly reduce the cost of network upgrades.

Overview

DWDM systems offer an attractive, cost-effective way for the telecommunications industry to expand network bandwidth. This new technology allows telecom operators to meet ever-growing requirements for new services and have greater flexibility in the provision of these services. By allowing fiber-optic links, both existing and new, to carry several channels simultaneously, DWDM makes optimum use of facilities, easily reaching transmission capabilities four to eight times those of traditional time division multiplexed (TDM) systems and offering even greater potential capacities.

The planning, installation, and maintenance of DWDM networks demand that much closer attention be paid to a number of limiting performance parameters than has been the case until now (see *Figure 1*). This tutorial discusses these parameters as well as other factors involved in field testing DWDM systems.

Figure 1. Overview of a DWDM System



Topics

1. The Need for New Testing Tools
2. Spectral Measurements
3. Parameters to be Measured in the Field
4. Optical Spectrum Analyzer
5. OSA Characteristics
6. Wavelength Meter
7. New Requirements for Traditional Fiber-Optic Test Instruments
8. Characterizing Fiber for DWDM Applications
9. Field Testing DWDM Systems
10. Conclusion
 - Self-Test
 - Correct Answers
 - Glossary

1. The Need for New Testing Tools

Although both designing and implementing DWDM systems calls for considerably more care than has been needed for conventional systems, by and large, the skill and capability necessary has increased to a degree: existing knowledge bases and facilities, with some additional training and upgraded instrumentation, will meet the challenges that the new technology presents. However, the same cannot be said for field testing. New parameters must be measured, and component characteristics once of interest only before installation must now be verified regularly. In addition, accuracy and stability requirements reach new levels, and an entirely new dimension—wavelength—must be considered. Field test equipment suitable for troubleshooting in single-wavelength systems cannot cope with these needs. New instrumentation is urgently required.

Testing and troubleshooting single-wavelength systems in the field can be accomplished by monitoring a few well-defined parameters. For example, optical power loss, or attenuation, has always been a key factor in the performance of fiber-optic links, and portable optical loss test sets have been developed to measure this loss in the field. Instruments with optical time domain reflectometric capabilities have been developed to locate faulty elements in a link. As system sophistication has grown, so has the significance of optical return loss, especially in the CATV field, where source-laser instability caused by reflected energy can have serious effects on signal quality. Field instrumentation has been

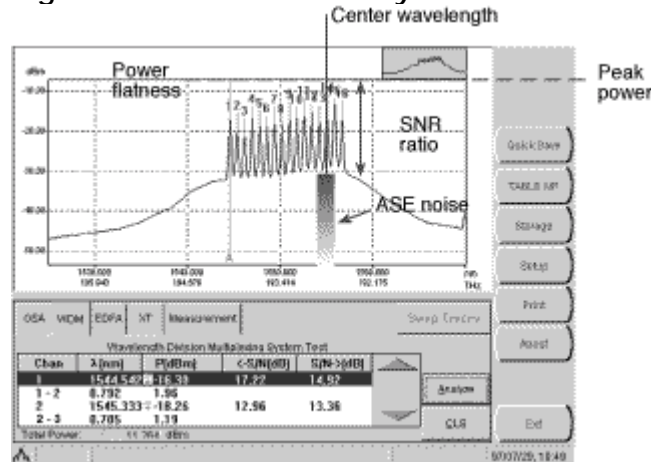
developed to monitor this parameter as well. All this test equipment is still required in the DWDM environment, but with characteristics adapted to the much more stringent needs of wavelength division systems.

In the fiber itself, both chromatic and polarization mode dispersion spread signal pulses and set limits on the transmission capacity, and their effects may be severe on the transmission signal integrity. New instrumentation capabilities may be needed to identify the sources of these disturbing influences and ensure that they do not adversely affect performance.

2. Spectral Measurements

The major new requirement in the test and monitoring of DWDM systems is the need to characterize components and link accurately as a function of wavelength. Instrumentation to do so already exists—the optical spectrum analyzer (OSA) has long been a fixture in network development and test laboratories. Now, however, similar capabilities must be provided in the field. Capabilities must be usable for maintenance personnel working in conditions that are very different from those in the stable, controlled laboratory environment. Major advances in instrumentation engineering are needed to take measurement capabilities that were once available only in a laboratory out into the field (see *Figure 2*).

Figure 2. DWDM Critical System Parameters



3. Parameters to Be Measured in the Field

The core measurement capabilities needed in the spectral domain include the following:

- **channel power**—One must be able to measure the optical power in each channel to verify the equal distribution of power over the

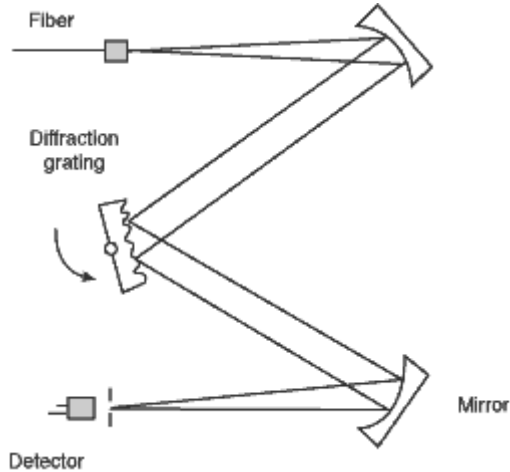
bandwidth of the optical amplifiers (EDFAs) that are used in the link (i.e., to measure the spectral uniformity of the optical power).

- **channel center wavelength and spacing**—The precise value of the center wavelength of each channel must be measured in order to detect unacceptable drifts in DFB laser sources.
- **signal-to-noise ratio**—This is one of the most important parameters to be measured for each channel in a DWDM system, as it is the best indicator of the overall performance of the channel. The noise measurement it incorporates must be based on measurements of the noise floor between channels.
- **crosstalk**—This parameter reveals the level of unwanted signal (noise plus contribution from other channels) in the passband of the tested channel. It is awkward to incorporate its measurement into field tests because it is a two-step operation, but it can be critical.
- **total optical power**—Because adverse effects of non-linear phenomena in the optical fiber depend on the total power carried, the parameter must be measured or calculated by summing the individual channel powers.

4. The Optical Spectrum Analyzer

Although by its very nature the laboratory-based optical spectrum analyzer meets the new testing requirement for measurements as a function of wavelength, present-day OSA versions are entirely unsuited to field use. Large and heavy, laboratory OSAs are not packaged for portability. The sophisticated optics they contain make them extremely vulnerable to shock and in frequent need of re-alignment and re-calibration. Their proper use requires a high degree of operator skill. All in all, laboratory OSAs are the antithesis of a good candidate for field use (see *Figure 3*).

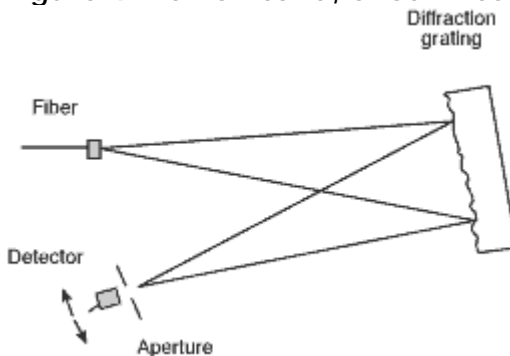
Figure 3. Traditional Optical Spectrum Analyzer Design, Single Pass Monochromator



Producing an OSA that is small, rugged, and reliable enough to be carried about in the field and to be operated by technicians lacking extensive experience with laboratory OSAs is a challenge whose resolution involves the following three steps:

1. eliminating the features and capabilities of laboratory instruments not required for the maintenance of DWDM networks (e.g., spectral measurement abilities outside the EDFA wavelength region)
2. selecting and developing an optical configuration that can withstand shock and operate without the delicate mechanical displacements used by conventional single-pass and double-pass monochromator designs (see *Figure 4*)

Figure 4. Narrowband, Shock-Resistant OSA Design



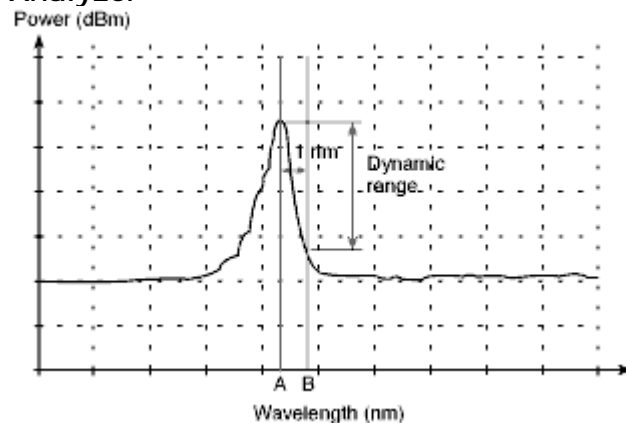
3. simplifying the traditional, complex, laboratory-oriented user interface to accommodate the needs of the field operator

5. OSA Characteristics

Characteristics essential to a field version of an OSA, while measuring the core parameters already identified, include the following:

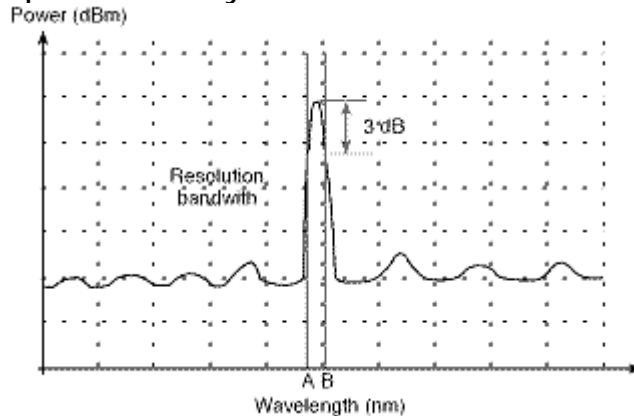
- **dynamic range**—An adequate dynamic range—the ability to measure weak signals in the presence of strong ones—is needed to measure the power in a strong, non-saturated signal and that of the adjacent noise floor (in a specified bandwidth). For example, in a system with 100 GHz (0.8 nm) channel spacing, an OSA must be able to measure an optical signal at a given wavelength and, just 0.4 nm away, an ASE noise level that may be 30 dB to 35 dB weaker (see *Figure 5*).

Figure 5. Dynamic Range Calculation for an Optical Spectrum Analyzer



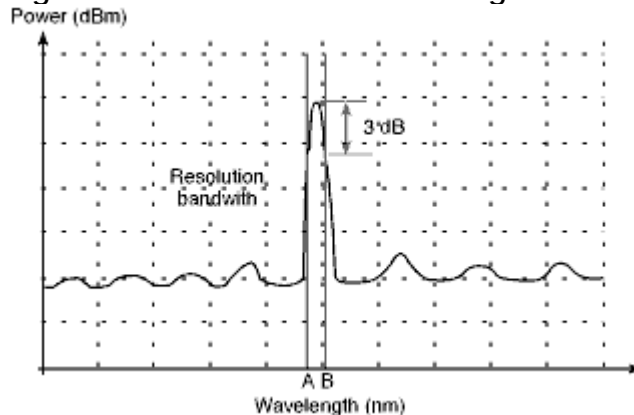
- **optical sensitivity**—The instrument sensitivity—the lowest signal level it can quantify—is generally determined by electronic considerations (the dark current of detectors, noise in detector preamplifiers, etc.). It must be low enough to permit the measurement of component insertion loss and assess the signal-to-noise ratio in all parts of a network.
- **resolution bandwidth**—The resolution bandwidth of an OSA determines its ability to deal with close optical channel spacing. It is measured as the width of the response curve at half peak power (i.e., 3 dB down) of the instrument to a monochromatic test signal. This specification is often called full-width half-maximum (FWHM) (see *Figure 6*).

Figure 6. Resolution Bandwidth Calculation for an Optical Spectrum Analyzer



- **wavelength accuracy**—This is without doubt the shortcoming of the optical spectrum analyzer. Good absolute wavelength accuracy requires the perfect positioning of the grating, which is difficult to do with rotational mechanisms. However, the precision of OSAs gives them the ability to detect unacceptable relative drifts in DFB laser sources. Outboard calibration options such as acetylene absorption cells can be used to improve absolute accuracy to a level acceptable for many other DWDM test applications (see *Figure 7*).

Figure 7. OSA Absolute Wavelength Accuracy



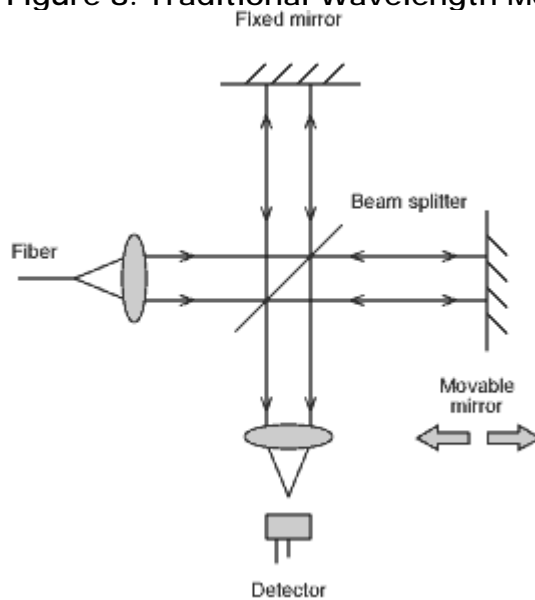
Although complete redesign of the traditional OSA is needed before its capabilities can be offered to field personnel faced with the difficult task of maintaining and troubleshooting DWDM networks, its potential advantages in measuring appropriate parameters make the OSA the leading candidate to dominate the DWDM test field. The OSA offers, in a single package, virtually all the test capabilities needed, but many steps must be taken to simplify the hardware and make it rugged, as well as to provide the one-button test procedures, auto-diagnostic functions, and easy-to-follow approaches needed to

take its undisputed advantages smoothly to the field, where they are badly needed.

6. The Wavelength Meter

The interferometer-based wavelength meter is used in the laboratory to make accurate, repeatable measurements of source wavelengths. Such measurements are often needed in DWDM systems, in particular to check the center wavelengths and the drift characteristics of each of the transmitted optical channels. Although the intrinsic accuracy of about 0.001 nm that such instruments attain in the laboratory is entirely adequate to characterize DWDM components, providing comparable capabilities in field instruments—including such features as internal wavelength-reference sources and fast-fourier transform (FFT) processing for deconvolution—is a design and engineering challenge of considerable magnitude (see *Figure 8*).

Figure 8. Traditional Wavelength Meter Design



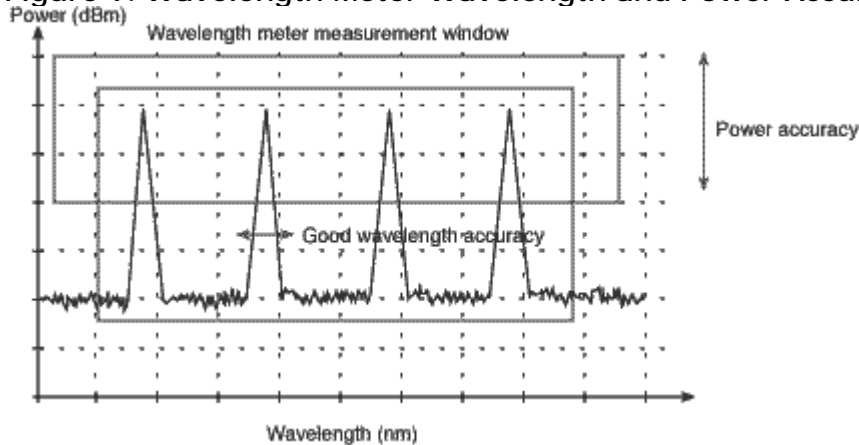
Nevertheless, the wavelength meter is expected to be the instrument of choice for such DWDM tasks as accurately measuring the center wavelengths of distributed feedback lasers and monitoring how they change with time (both short-term and long-term), temperature, and other environmental conditions. Among the characteristics that are particularly important in a field version of a wavelength meter are the following:

- **absolute wavelength accuracy**—The ability to accurately measure the absolute wavelength of a channel is the strongest attribute of this type of instrument. With the help of an interferometer, which is usually both precise and accurate in wavelength, the absolute accuracy of the

wavelength meter should be better than about 0.005 nm, adequate to locate individual DWDM channel wavelengths.

- **absolute power accuracy**—The ability to measure the exact power in each DWDM channel is important to verify the power flatness throughout the link. Using a wavemeter, the actual power in each channel can be determined through use of the FFT calculation to an accuracy that is limited by the approximations inherent in that calculation. The resulting absolute power accuracy will usually be a little lower than that of the OSA (see *Figure 9*).

Figure 9. Wavelength Meter Wavelength and Power Accuracy



- **dynamic range**—The ability to measure weak signals in the presence of strong ones, dynamic range is required—as it is in the OSA—to measure the noise floor in a multichannel transmission system. The wavelength meter can attain a dynamic range of 20 dB to 25 dB for characterization of DWDM channels.
- **number of channels**—The number of channels the instrument can extract depends on the mechanical precision of the interferometer and on the extraction capacity of the FFT algorithm used. Forty to a hundred channels should be attainable, enough to characterize DWDM systems properly.

The wavelength meter's strength in absolute wavelength measurement enhances the OSA and is an excellent complementary instrument for the complete characterization of DWDM systems. Furthermore, certain field operations—determining DFB center wavelengths and troubleshooting lasers, in particular—require the accuracy that the wavelength meter provides.

Once again, the challenge is to modify present wavelength meters, which are intended for use in the laboratory, to make them suitable for the demanding DWDM field environment. The new field wavelength meter will have to be rugged

and portable and will have to offer simple and—to as great a degree as possible—automatic test procedures.

7. New Requirements for Traditional Fiber Optic Test Instruments

In addition to instrumentation specifically designed for the maintenance of DWDM systems (i.e., the new OSAs and wavelength meters whose characteristics have been outlined elsewhere in this tutorial), conventional field installation and test equipment must also be considered because of the strong influence that some of the properties of fiber-optic links have on DWDM transmission. Although many of the basic attributes of these links are independent of the transmission mode used (TDM or WDM) and can thus be measured using conventional instruments, a few parameters are critical to proper DWDM operation, and special care must be taken in selecting field instruments to measure them.

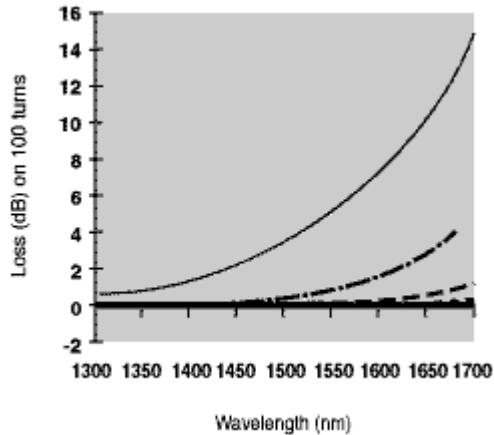
Optical Loss Test Sets (OLTS)

Because of the use of several channels at different, precisely defined wavelengths, dedicated WDM power meters must be calibrated at specified wavelengths in the 1530 nm to 1565 nm band, in order to measure the power in individual channels at the output of demultiplexers. Optical loss test sets will also be used at the wavelengths used for optical supervisory channels (OSC)—1480 nm, 1510 nm, and 1625 nm, depending on the system design. Dedicated DFB light sources will be needed to verify the loss budget when the fiber is installed. The longest OSC wavelength, 1625 nm, requires particular attention since this wavelength lies outside the range in which the fiber or cable manufacturer guarantees the performance of its product. Optical loss test sets specifically intended for this wavelength can be expected to reach the market soon.

Optical Time Domain Reflectometer

A clear tendency is emerging in the OTDR world to offer capabilities in the fourth window spectral 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 DWDM transmission continues uninterrupted in the EDFA spectral region. 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—places where the performance of the fiber is acceptable at the time of installation but could degrade over time (see *Figure 10*).

Figure 10. Bending Loss Comparison at 1310 nm, 1550 nm, and 1625 nm

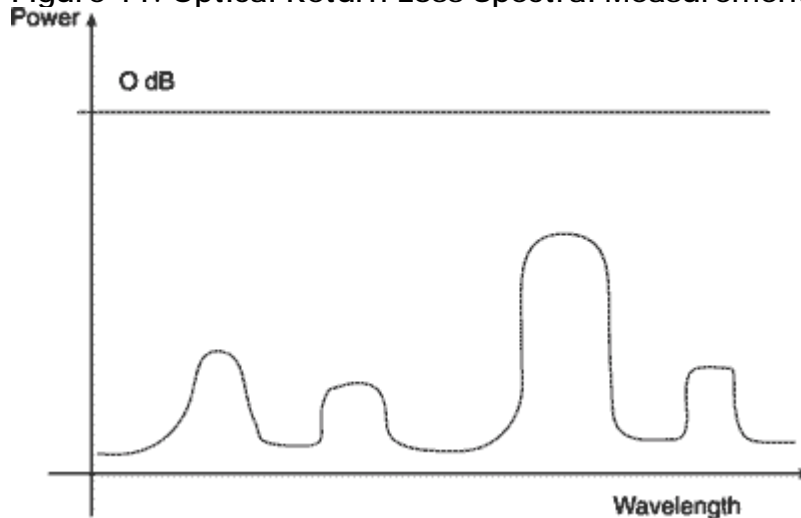


Back Reflection Meter

In a conventional (non-WDM) network, the optical return loss (ORL) can be determined with a single measurement using a back reflection meter at the operating wavelength. In DWDM systems 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 ORL variation with wavelength may be caused by defective Bragg gratings or, more often, from bad connectors at the output port of a multiplexer or demultiplexer. Excessive back reflection can cause instability in DFB source lasers, thereby affecting the overall system performance. As a result, an 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. The value of the ORL as a function of wavelength is often a more useful parameter intrinsically, and its determination may be essential if the simpler aggregate test should fail on a particular link. It is measured using a high-power broadband source, usually an erbium-amplified spontaneous emission (ASE) source. High power is needed to provide enough power in each measurement band, which may be as little as 0.1 nm wide, to give an adequate signal-to-noise ratio at the detector for the lowest ORL of interest. The detector is an optical spectrum analyzer of adequate resolution and sensitivity. The result, of course, is an individual ORL reading—often just the information needed to guide a troubleshooting session—for each DWDM channel (see *Figure 11*).

Figure 11. Optical Return Loss Spectral Measurement



8. Characterizing Fiber for DWDM

Theory predicts—and field experience confirms—that the characteristics of the fiber itself can have significant impact on the performance of DWDM networks and that the particular characteristics which are most important are not necessarily those of greatest concern in conventional single-wavelength links.

Chromatic Dispersion

Chromatic dispersion, the variation of the index of refraction of the fiber with wavelength, can be a critical determinant of system performance in DWDM systems, especially those that use a judiciously selected amount of dispersion to minimize certain undesirable nonlinear effects in the fiber itself. Its value is determined during fiber manufacture, however, and few situations have arisen in which it is necessary to verify this value in the field.

As DWDM systems are operated ever closer to their limits, however, a need is likely to emerge to verify that this parameter is adequately controlled at every point in the optical path. The eventual development of field instrumentation to measure chromatic dispersion is likely, especially if the management of chromatic dispersion on installed fiber turns out to be more complex than expected.

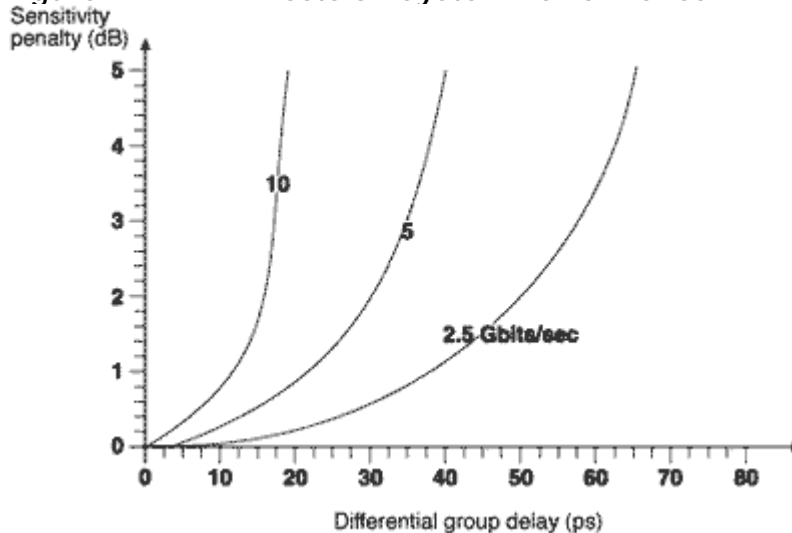
Polarization Mode Dispersion

Polarization mode dispersion (PMD), in which various polarization states of the optical signal propagate at different velocities, is especially difficult to deal with. Its effects prevent many present-day optical systems from using high-bandwidth

transmission equipment meeting 10-Gbps OC-192 specifications. Since current state-of-the-art DWDM technology offers eight such OC-192 channels, where the fiber can support the rate, PMD can be a serious limitation to system performance and to prospects for upgrading that performance.

PMD affects the transmission quality by spreading signal pulses and, therefore, raising the bit error rate (BER) of the system. It arises in the first place because of asymmetries in the fiber itself, so the primary remedy must be applied at the manufacturing level. But the damage does not necessarily end there. During installation, the fiber can be crushed, kinked, or otherwise overstressed. Environmental and climatic changes can also affect its circular geometry and thus worsen its PMD characteristics. Post-installation testing may be needed to ensure that a network does not overly suffer from PMD and that the installed facilities can be upgraded to support tomorrow's higher bit rates (see *Figure 12*).

Figure 12. PMD Effects on System Performance



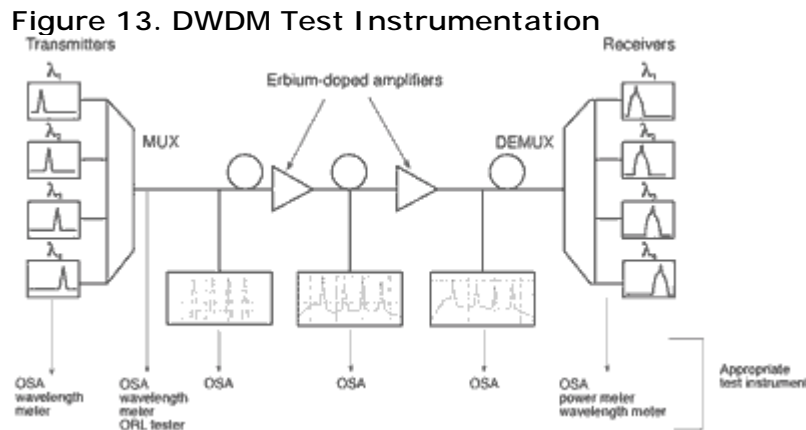
Second-order PMD, the variation of polarization mode dispersion with wavelength, is considered to have a negligible effect on network performance. However, it acts as a completely random contribution to the network's chromatic dispersion, possibly negating deliberate steps taken in network design to provide the exact amount of this dispersion to reduce nonlinear disturbances in signal propagation. Although this parameter bears watching, its long-term importance cannot yet be predicted.

9. Field Testing DWDM Systems

As previously indicated, the implementation of DWDM transmission systems in the field on a large scale will have a major impact on each level of installation and system verification. New skills will have to be developed to face these new

challenges, and existing test instrumentation will require adaptation. Nevertheless, one instrument emerges as the apparent reference DWDM system characterization tool—the optical spectrum analyzer.

The optical spectrum analyzer is eminently suited to almost all the field testing needed in DWDM systems: measurements of signal levels, signal-to-noise ratio, crosstalk as well as channel spacing and stability. The graphic presentation of modern OSA instruments, clearly showing how the parameter of interest varies with wavelength, gives an excellent overview of many of the phenomena crucial to the proper operation of DWDM networks and valuable clues for the subsequent investigation of any problems that the measurement might reveal. Nevertheless, in many contexts it offers too much information and often not the specific information the field maintainer or troubleshooter needs. Operating and readout procedures and tools must be greatly simplified from those appropriate to laboratory OSAs if the instrument is to be cost-effective in the field (see *Figure 13*).



However, to complement OSA testing in the field, center wavelengths must be accurately measured. This parameter can be important, especially if the system under study is part of a larger one whose standards must be respected. Other instrumentation offering more accurate wavelength calibration—a wavelength meter, most likely—is also needed for such operations as the measurement of DFB characteristics.

10. Conclusion

Any telecommunications service provider who operates or installs DWDM systems must meet testing requirements well beyond those needed for older-generation equipment and must be prepared to perform sophisticated testing in the field on existing lines and equipment. In particular, the spectral dimension, once of interest only to development laboratories, now must be considered

throughout the life cycle of a network, from planning through installation to routine maintenance.

These new requirements will inevitably lead to the development of new field test instruments tailored for use in DWDM systems. The core of this new instrumentation suite—the reference test instrument—is likely to be the optical spectrum analyzer because of its ability to perform most of the measurements needed for system characterization, maintenance, and troubleshooting.

The mini optical time domain reflectometer, or mini-OTDR, which brought sophisticated time domain reflectometry capabilities to field maintainers of fiber-optic systems, was developed over several years with very close, continual attention to the real needs of field users. The development of a field-ready mini-OSA should follow a similar path.

Self-Test

1. The introduction of DWDM technology is attractive because _____.
 - a. it is a cost-effective way to increase the transmission system bandwidth
 - b. it will one day replace TDM technology
2. New testing tools are required for DWDM testing because _____.
 - a. transmission rates are too high for actual testing instruments
 - b. DWDM transmission brings a new spectral dimension into play
3. Channel center wavelength is an important parameter because _____.
 - a. DWDM systems are precisely tuned for defined and dedicated wavelengths
 - b. it will have a major impact on the loss budget
4. Optical signal-to-noise ratio is _____.
 - a. a good indication of the power loss in the system
 - b. the best indicator of a channel's overall performance
5. The dynamic range of an optical spectrum analyzer is _____.
 - a. the ability to measure a weak signal in the presence of or next to a strong one

- b. the indication of the optical spectrum analyzer's distance range
6. The redesigned field optical spectrum analyzer is _____.
- a. the leading candidate for DWDM transmission field testing
 - b. a new instrument that is similar to the lab optical spectrum analyzer
7. The strength of the multiwavelength meter is _____.
- a. its capacity to measure optical signal-to-noise ratio
 - b. its ability to measure a wavelength with very good absolute accuracy
8. An optical time domain reflectometer will _____.
- a. no longer be used to test DWDM transmission systems
 - b. have to be adapted to the new DWDM reality
9. Chromatic dispersion has a major affect on DWDM system performance because _____.
- a. it impacts the loss budget of the system
 - b. it can have an impact on the four-wave mixing phenomenon
10. Polarization mode dispersion is _____.
- a. no longer a problem in DWDM systems
 - b. a phenomenon that may impact DWDM system performances at high bit rates

Correct Answers

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a. no longer a problem in DWDM systems

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Glossary

AFR

absolute frequency reference

ASE

amplified spontaneous emission

BER

bit error ratio

DFB

distributed feedback

EDFA

erbium doped fiber amplifier

FWM

four wave mixing

MPI

multiple path interference

MPI-R

main path interface at the receiver

MPI-S

main path interface at the transmitter

MWM

multiwavelength meter

NF

noise figure

OA

optical amplifier

OD

optical demultiplexer

OEO

optical electrical optical converter

OM

optical multiplexer

OSC

optical supervisory channel

OSNR

optical signal-to-noise ratio

PMD

polarization mode dispersion

RX

optical receiver

SDH

synchronous digital hierarchy

SNR

signal-to-noise ratio

SPM

self phase modulation

SBS

stimulated brillouin scattering

STM-*N*

synchronous transport module Level *N*

TDM

time division multiplexing

TX

optical transmitter

WDM

wavelength division multiplexing

XPM

cross-phase modulation