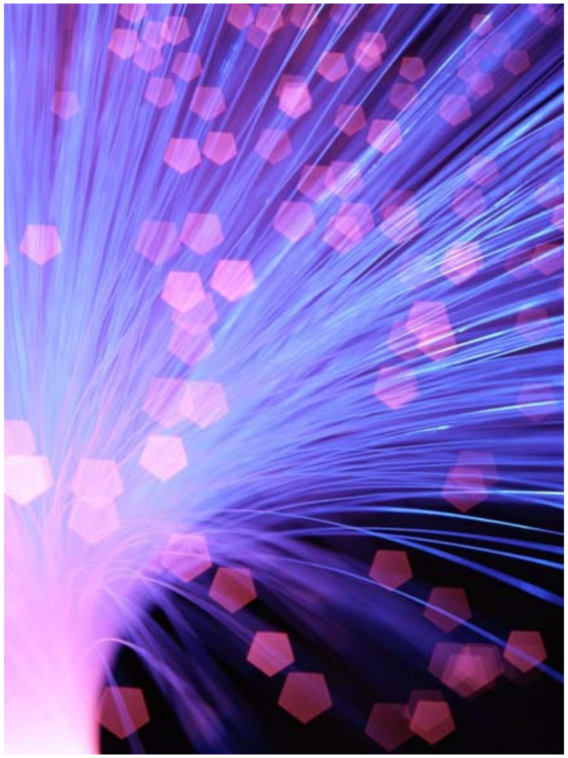
DWDM Primer



May 21, 2004

Trademarks and Copyrights

NETSMART is a registered trademark of
Fujitsu Network Communications Inc.

FLASHWAVE is a registered trademark of
Fujitsu Network Communications, Inc.

FLASH is a registered trademark of
Fujitsu Network Communications Inc.

FASTLANE is a registered trademark of
Fujitsu Network Communications Inc.

All other products or services mentioned in this document are identified by the trademarks, service marks, or product names as designated by the companies that market those products or services or own those marks. Inquiries concerning such products, services, or marks should be made directly to those companies

This document and its contents are provided by Fujitsu Network Communications, Inc. (FNC) for guidance purposes only. This document is provided "as is" with no warranties or representations whatsoever, either express or implied, including without limitation the implied warranties of merchantability and fitness for purpose. FNC does not warrant or represent that the contents of this document are error free.

Furthermore, the contents of this document are subject to update and change at any time without notice by FNC, since FNC reserves the right, without notice, to make changes in equipment design or components as progress in engineering methods may warrant. No part of the contents of this document may be copied, modified, or otherwise reproduced without the express written consent of FNC.

Lesson 1

Course Description

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

Course Description

Name

Dense Wavelength Division Multiplexing Primer

Purpose

The purpose of the DWDM Primer course is to provide an introduction to dense wavelength division multiplexing (DWDM). Additionally, this course will discuss why DWDM is an important innovation in optical networks and the benefits it can provide.

Prerequisite

While there are no formal prerequisites for this course, the following make the course more meaningful, as an in-depth analysis of these subjects is beyond the scope of DWDM Primer course:

- SONET knowledge and experience
- Ethernet knowledge and experience

Objectives

After completing this course, the student should be able to:

- Identify DWDM optical network elements
- Describe DWDM characteristics
- Identify DWDM optical network considerations
- Identify Fujitsu Network Communications, Inc. (FNC) products that offer network solutions

Scope

The DWDM Primer course is intended for network planners, and engineers who would like to familiarize themselves with DWDM technology. In addition, other personnel who wish to gain a general understanding of DWDM are encouraged to attend.

This student guide is intended as a tool for classroom use only.

Students interested in training on other aspects of FNC equipment and capabilities should investigate other courses offered by FNC, such as applicable turn-up & testing, maintenance, and engineering courses.

Reference Documents

The following documents were used to develop this course:

- *FNC-742-0031-120, System Description and Engineering (FLASHWAVE 7420)*
- *FNC-591-0013-120, System Description and Engineering (FLASHWAVE 7500)*
- *TRN-7500-TM-013, FLASHWAVE 7500 Turn-Up and Test*
- *TRN-7420-TM-031, FLASHWAVE 7420 Turn-Up and Test*
- *PMB-03-031 FLASHWAVE 7500 Product Management Bulletin (Release 1.3 Announcement)*
- *PMB-03-004 FLASHWAVE 7420 Product Management Bulletin (New Product Announcement)*

Figure 1-1: Support Organizations

Educational Services
Richardson, Texas Register for class 800-777-3278 ext. 4961 fax: 972-479-7117 e-mail ed.svcs@fnc.fujitsu.com
Technical Assistance Center (TAC)
Richardson, Texas 800-USE-FTAC (800-873-3822)
Repair and Return
Richardson, Texas (800-525-0303)
Sales
Richardson, Texas/Regional Offices 800-777-FAST (800-777-3278)
Technical Publications
Richardson, Texas 800-777-FAST (800-777-3278)

Support Organizations

FNC support organizations (see Figure 1-1) include:

- Educational Services—Provides training on all FNC products. Classes are conducted at Richardson, Texas as well as at customers' locations.
- Technical Assistance (Richardson, Texas)—Answers questions regarding FNC products. Service is provided via telephone.

  Call 800-USE-FTAC (800-873-3822) for questions regarding:

  - Technical Performance
  - Equipment Specifications

Note: *FTAC stands for Fujitsu Technical Assistance Center.*

- Repair and Return (Richardson, Texas)—Provides repair services for all FNC products.

  Call 800-525-0303

  Fujitsu Network Communications, Inc.
  2791 Telecom Parkway
  Richardson, Texas 75082-9983

- Sales (Richardson, Texas and regional offices)—Provides sales assistance for all FNC products.

  Call 800-777-FAST (800-777-3278) for information regarding:

  - Upgrades
  - Replacement Parts
  - Ordering Information
  - Local Sales Offices
  - Product Descriptions
  - Documentation

Note: *FAST stands for Fujitsu Assistance.*

- Technical Publications (Richardson, Texas)

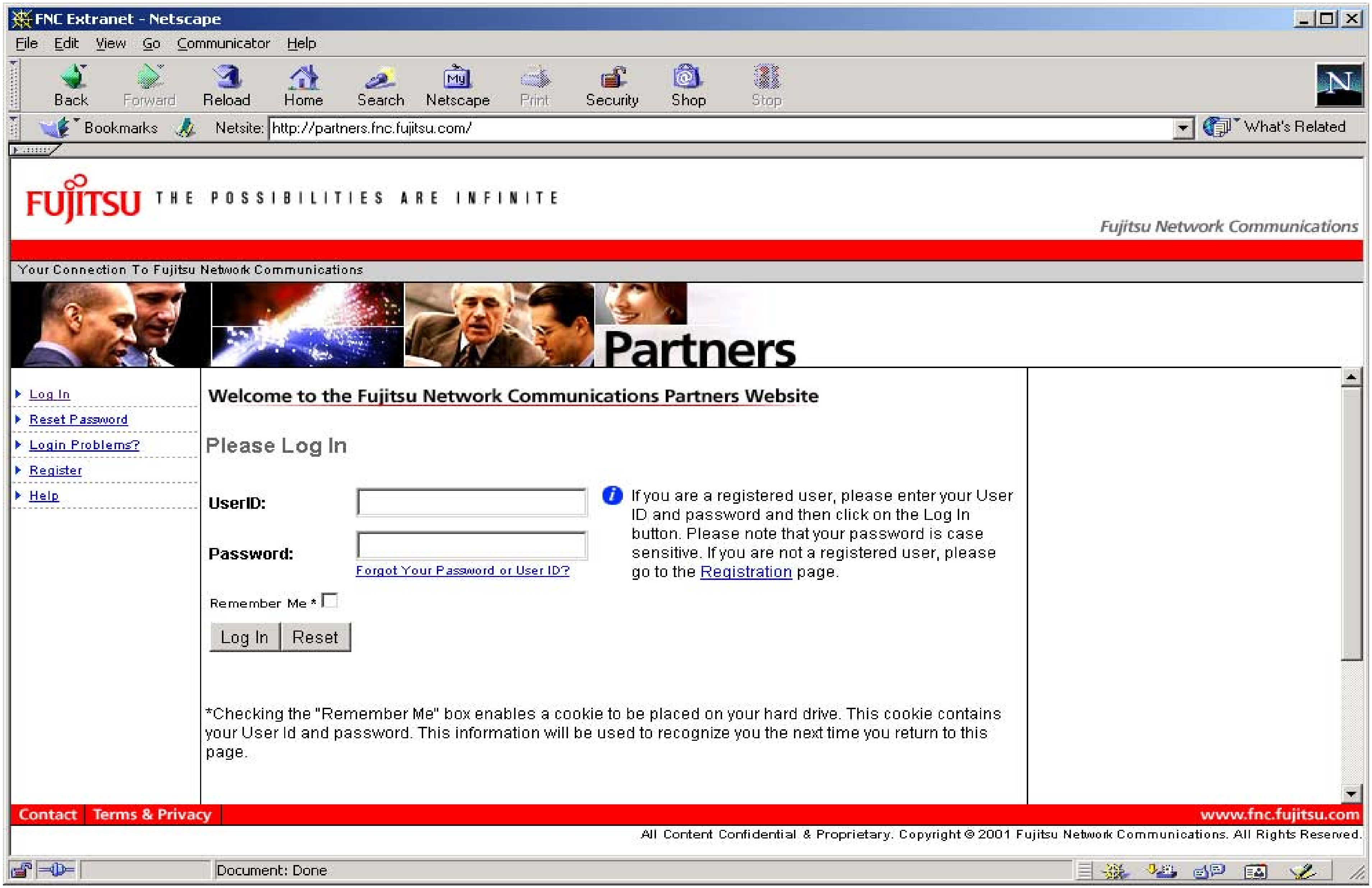
Additional information regarding FNC and any of the support organizations can be located at our Web site:

http://us.fujitsu.com/services/telecom

Note: *Online documentation is available to FNC customers on the FNC Web site by accessing Partners and FOCIS:*

https://partners.fnc.fujitsu.com

Figure 1-2: FOCIS



FOCIS

FOCIS is a Web based, customer accessible repository of Fujitsu technical documentation such as:

- Product change notices
- Information bulletins
- Manufacturer discontinued notices
- Manuals
- Software downloads and links
- Training information
- Document downloads

In addition, FOCIS has information on Technical Assistance Center (TAC) contacts, links to technical training courses and FLEXR registration.

- Access the FNC Web site at

  https://partners.fnc.fujitsu.com

- Select **Logon to FOCIS**

Note: *If you know your user name and password, log on. If not, go to the registration link and request a logon. Wait one business day for verification of access.*

- The Partners page is displayed (see Figure 1-2).
- Select **FOCIS**.
- Select Services—Various FNC services are listed for query.

Reference Documentation: Not applicable

Lesson 2

DWDM Primer Overview

Purpose

This lesson provides an overview of dense wavelength division multiplexing (DWDM).

Objectives

Upon completion of this lesson, the student should be able to:

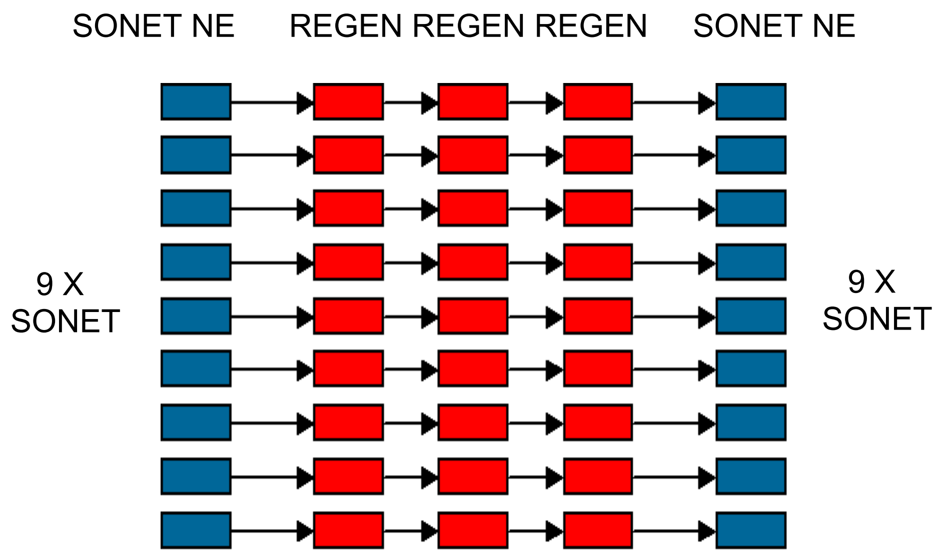
- Define DWDM
- Recognize the advantage that DWDM has over time division multiplexing (TDM)
- Define a wavelength

Reference Documents

The following documents were used in the development of this lesson:

- *TRN-7500-TM-013, FLASHWAVE 7500 Turn-Up and Test*
- *TRN-7420-TM-031, FLASHWAVE 7420 Turn-Up and Test*
- *PMB-03-031 FLASHWAVE 7500 Product Management Bulletin (Release 1.3 Announcement)*
- *PMB-03-004 FLASHWAVE 7420 Product Management Bulletin (New Product Announcement)*

Figure 2-1: Discrete Channels



Why DWDM?

Dense wavelength division multiplexing permits rapid network deployment and significant network cost reduction. Use of DWDM allows deployment of less fiber and hardware with more bandwidth being available relative to standard SONET networks.

DWDM Definition

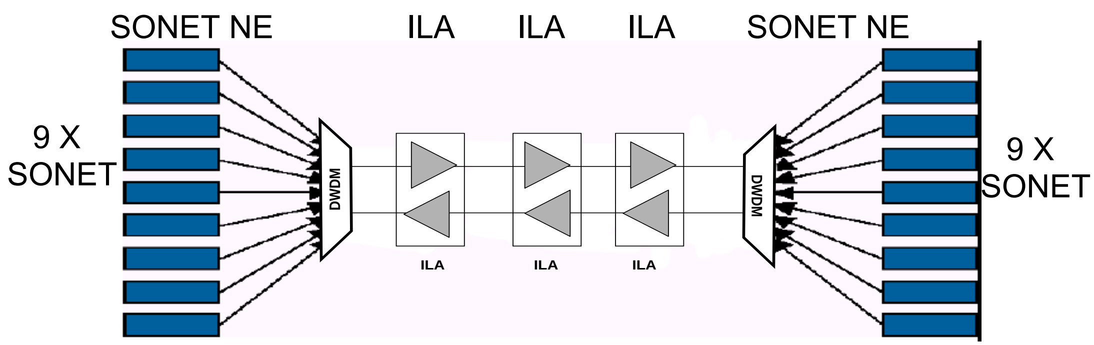
Dense wavelength division multiplexing is a fiber optic transmission technique that employs light wavelengths to transmit data (refer to "What is a Wavelength?" on page 9).

Discrete Transport Channels vs. DWDM Transport

Traditional SONET, TCP/IP, ATM, and voice over Internet Protocol (VoIP)[1] are transmitted over discrete channels, each requiring a fiber pair between the end points. Figure 2-1 shows nine channels, each at 10 Gb/s, using nine discrete fiber pairs. This traditional SONET method requires 3 regenerators to condition the signals across each fiber path between each of the nine nodes, a total of 27 regenerators.

1. VoIP is a method of digitizing voice to allow it to occupy less bandwidth and therefore allow more voice channels over a given bandwidth.

Figure 2-2: DWDM Transport



Dense wavelength division multiplexing systems allow many discrete transport channels to be carried over a single fiber pair. Nine discrete channels share the fiber pair with an aggregate bandwidth of 90 Gb/s in Figure 2-2.

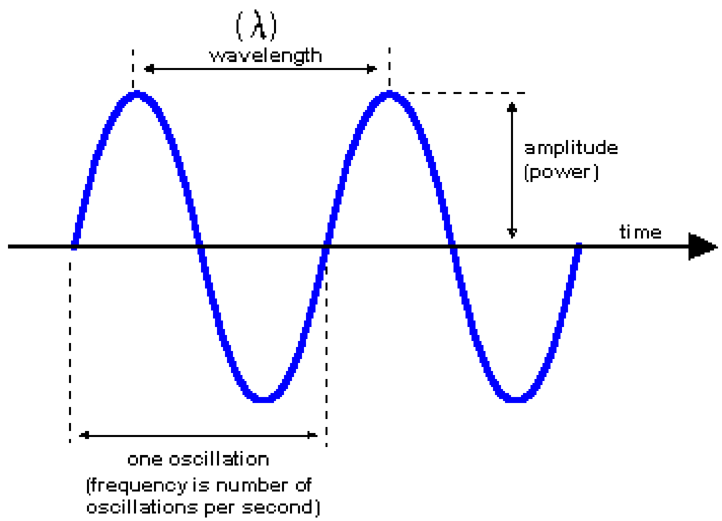
Service Provider Advantages

The service provider uses an existing installed fiber plant more effectively by incorporating DWDM systems. Comparing Figure 2-2 to Figure 2-1, the service provider recovers eight fiber pairs to expand its network for its investment in two 9-channel (wavelength) DWDM terminals and three in-line amplifiers (ILAs), as described below.

Multiplexing reduces the cost per bit sent and received over the network. In Figure 2-1, the distances require three regenerator sites for traditional SONET traffic. In Figure 2-2, these 27 regenerators are removed and replaced by three ILAs. The cost of an ILA is typically 50 percent of the cost of a SONET regenerator and the single ILA carries all nine wavelengths.

Multiservice traffic of all types can now be carried over the DWDM infrastructure shown in Figure 2-2. Thereby enabling faster speed to market of multiservice traffic offerings at a lower cost for new services to be transported over the DWDM system.

Figure 2-3: Wavelength



What is a Wavelength?

A wavelength is the distance between the crests of a wave (Figure 2-3). The higher the frequency, the shorter the wavelength.

Lesson 3

Wavelength Division Multiplexing

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

Purpose

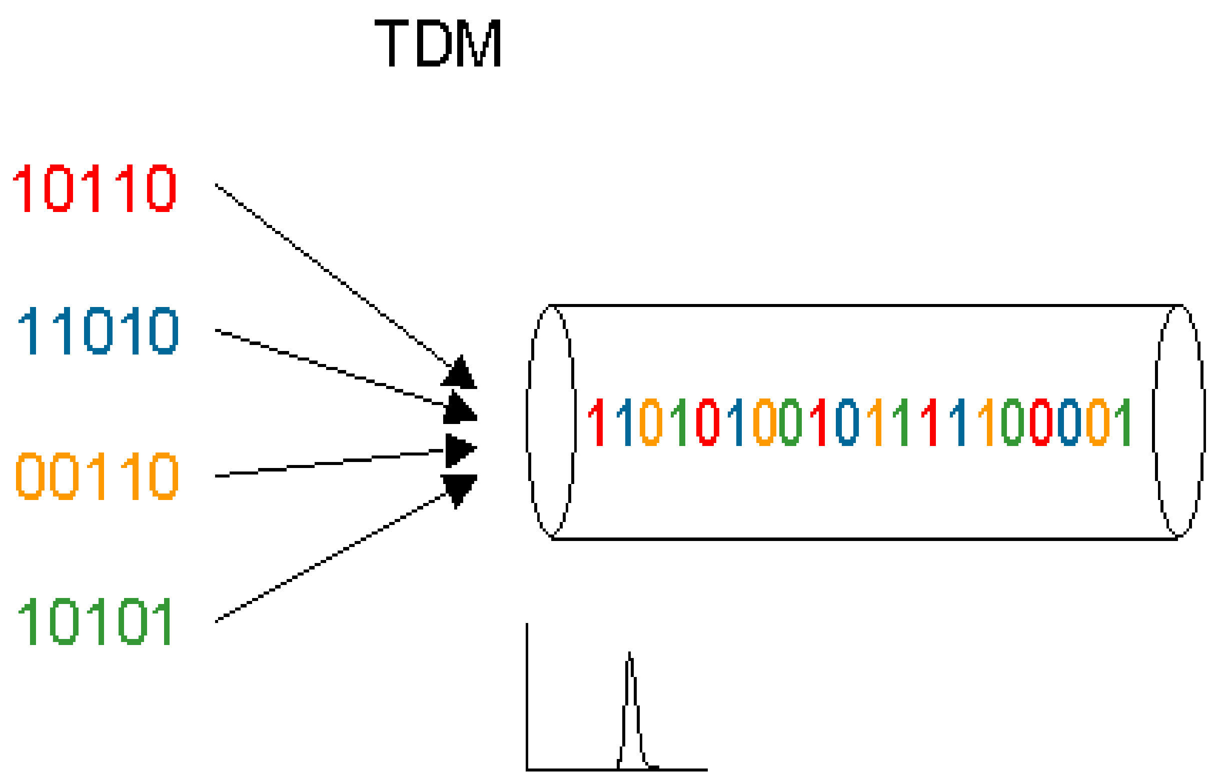
This lesson provides an overview of wavelength division multiplexing (WDM). Since DWDM systems are derived from wavelength division multiplexing (WDM) systems, WDM will be discussed and the relationship between WDM and DWDM systems will be examined.

Objectives

Upon completion of this lesson, the student should be able to:

- Understand basic WDM theory and operational concepts
- Describe the different WDM types

Figure 3-1: Time Division Multiplexing



Types of Multiplexing

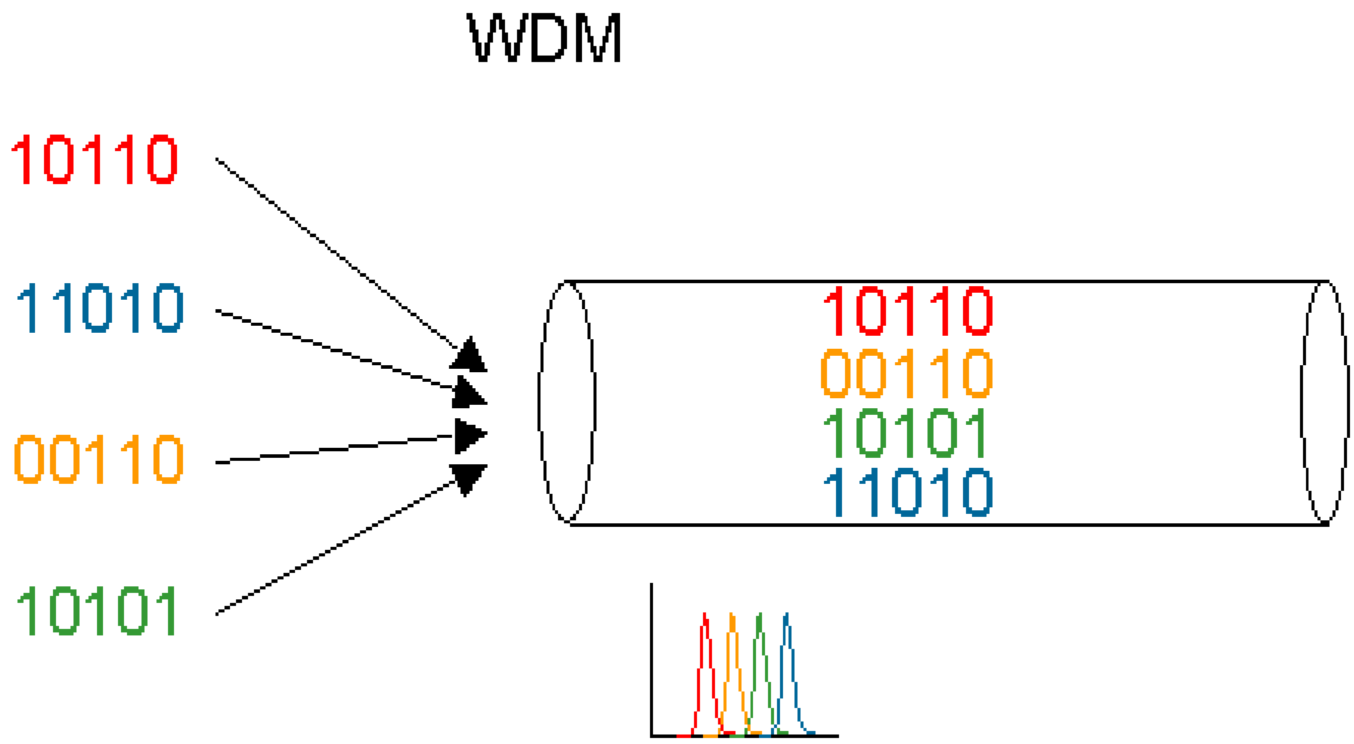
Multiplexing is sending multiple signals or streams of information through a circuit at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end. Basic types of multiplexing include frequency division multiplexing (FDM), time division multiplexing (TDM), and wavelength division multiplexing (WDM), with TDM and WDM being widely utilized by telephone and data service providers over optical circuits.

Time Division Multiplexing

TDM, as represented in Figure 3-1, is a method of combining multiple independent data streams into a single data stream by merging the signals according to a defined sequence. Each independent data stream is reassembled at the receiving end based on the sequence and timing.

Synchronous Optical Network (SONET), Asynchronous Transfer Mode (ATM) and Internet Protocol (IP) utilize TDM techniques. In modern telecommunications networks, TDM signals are converted from electrical to optical signals by the SONET network element, for transport over optical fiber.

Figure 3-2: Wavelength Division Multiplexing



Wavelength Division Multiplexing

WDM increases the carrying capacity of fiber by assigning incoming optical signals to specific frequencies of light (wavelengths, or lambdas) within a certain frequency band. This method allows for the combining of multiple optical TDM data streams onto one fiber through the use of multiple wavelengths of light (Figure 3-2). Each individual TDM data stream is sent over an individual laser transmitting a unique wavelength of light.

Varieties of WDM

Early WDM systems transported two or four wavelengths that were widely spaced. WDM and the follow-on technologies of coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM) have evolved well beyond this early limitation.

WDM

Traditional, passive WDM systems are wide-spread with 2, 4, 8, 12, and 16 channel counts being the normal deployments. This technique usually has a distance limitation of under 100 kilometers.

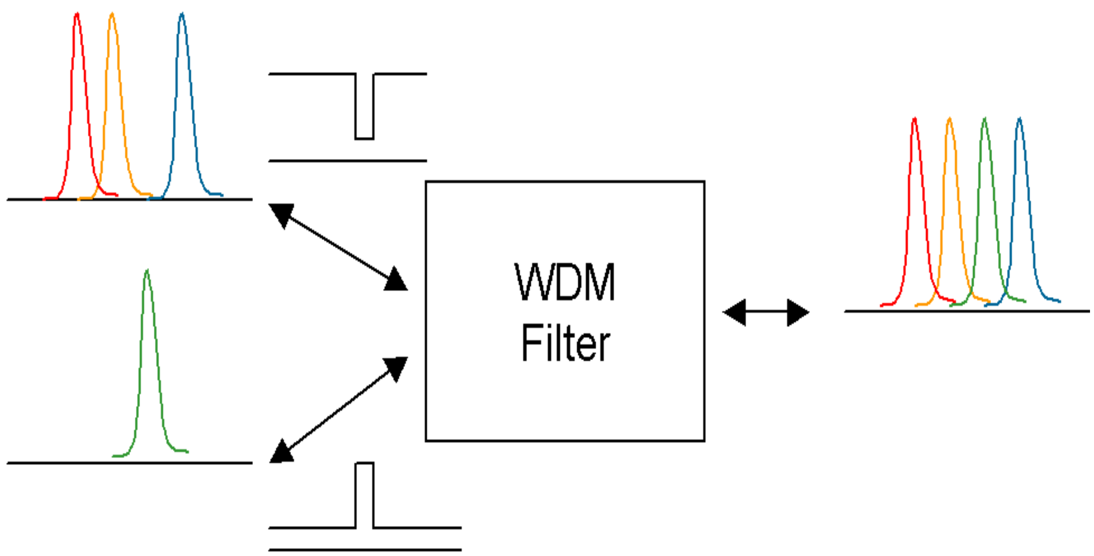
CWDM

Today, CWDM typically uses 20-nm spacing (3000 GHz) of up to 18 channels. The CWDM Recommendation ITU-T G.694.2 provides a grid of wavelengths for target distances up to about 50 kilometers on single mode fibers as specified in ITU-T Recommendations G.652, G.653 and G.655. The CWDM grid is made up of 18 wavelengths defined within the range 1270 nm to 1610 nm spaced by 20 nm.

DWDM

As with CWDM, the difference between WDM and DWDM is fundamentally one of degree. DWDM spaces the wavelengths more closely than does WDM. Therefore, DWDM has a greater overall capacity. DWDM common spacing may be 200, 100, 50, or 25 GHz with a channel count reaching up to 128 or more channels at distances of several thousand kilometers, with amplification and regeneration along such a route.

Figure 3-3: WDM Filters



Optical Multiplexing Technology

Optical multiplexing technologies, such as DWDM and WDM systems, have revolutionized the use of optical fiber networks. Different colors of light, called wavelengths, are combined into one optical signal and sent over a fiber-optic cable to a far-end optical multiplexing system.

Optical Multiplexing Filters

Figure 3-3 illustrates that a filter is a physical device that combines each wavelength with other wavelengths. Many technologies are used in multiplexing, including:

- Thin-film filters
- Bragg gratings
- Arrayed waveguide gratings (AWGs)
- Interleavers, periodic filters, and frequency slicers)

Lesson 4

Optical Networks

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

Purpose

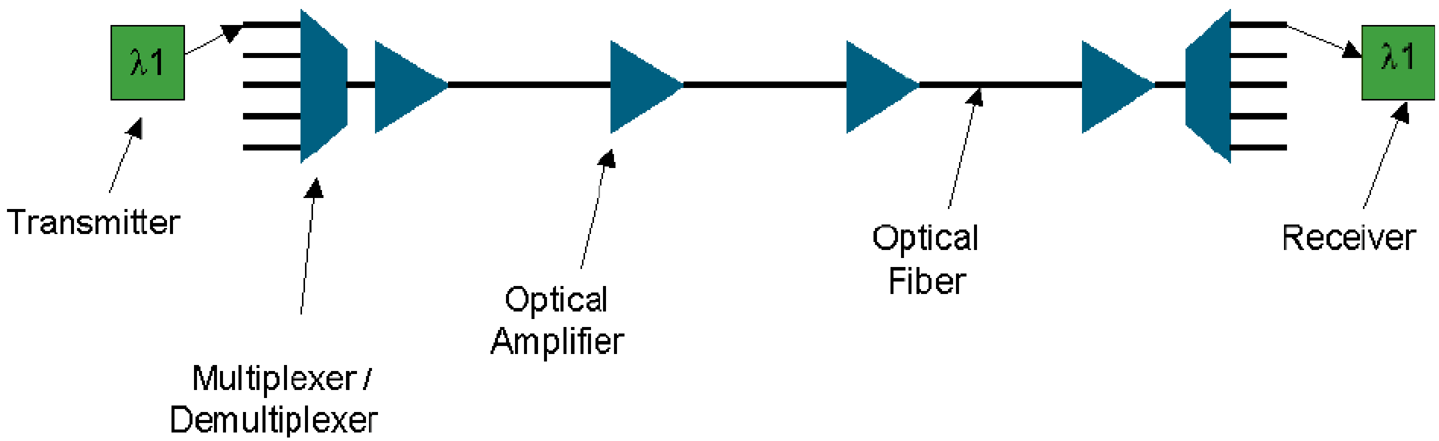
This lesson provides an overview of optical networks and the components that make up an optical network.

Objectives

Upon completion of this lesson, the student should be able to:

- Identify the components of an optical network
- Describe functions of the major components that make up an optical network

Figure 4-1: Optical Network Drawing

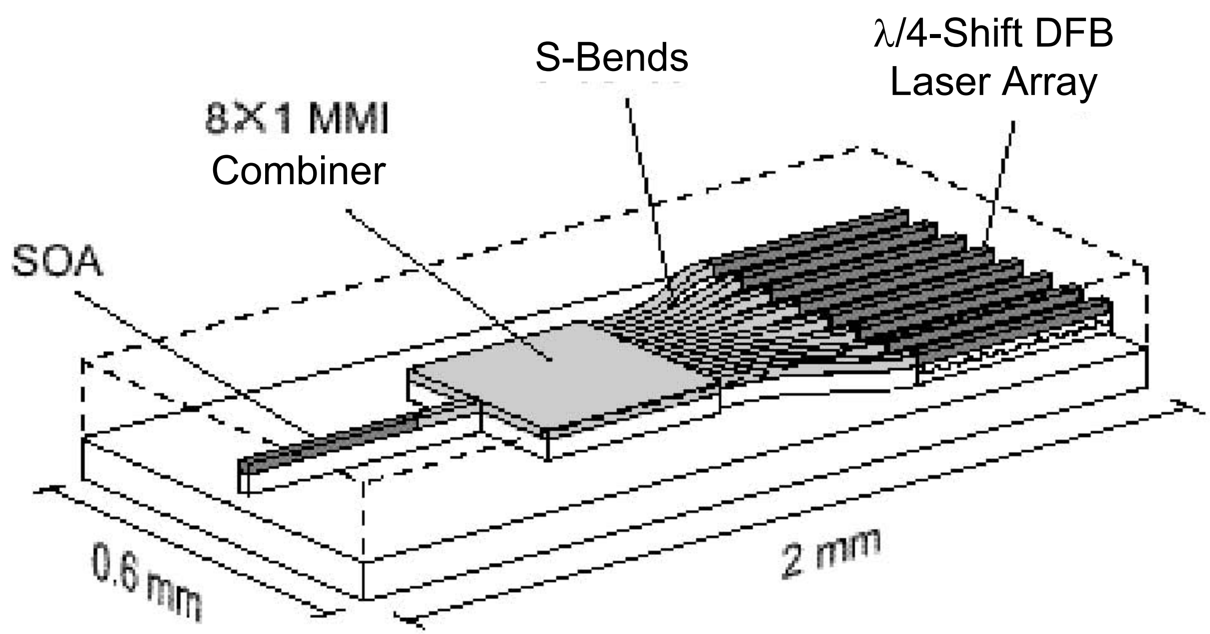


Optical Network

Figure 4-1 shows the five main components of a DWDM optical network. The components of a DWDM optical network are:

1. Transmitter (transmit transponder):
   - Changes electrical bits to optical pulses
   - Is frequency specific
   - Uses a narrowband laser to generate the optical pulse
2. Multiplexer/demultiplexer:
   - Combines/separates discrete wavelengths
3. Amplifier:
   - Preamplifier boosts signal pulses at the receive side
   - Postamplifier boosts signal pulses at the transmit side (postamplifier) and on the receive side (preamplifier)
   - In line amplifiers (ILA) are placed at different distances from the source to provide recovery of the signal before it is degraded by loss.
4. Optical fiber (media):
   - Transmission media to carry optical pulses
   - Many different kinds of fiber are used
   - Often deployed in sheaths of 144–256 fibers
5. Receiver (receive transponder):
   - Changes optical pulses back to electrical bits
   - Uses wideband laser to provide the optical pulse

Figure 4-2: Tunable Laser

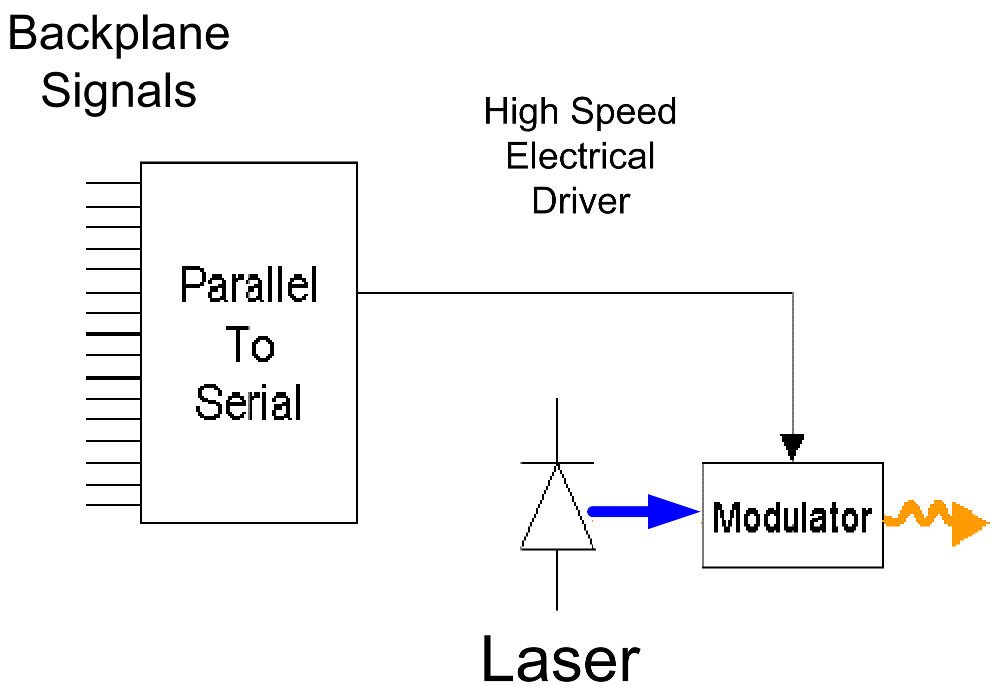


Tunable Laser

Figure 4-2 shows one method of transmission, the tunable laser.

Multiple individual lasers, eight in this example, are built into one piece of silicon. One selected laser is turned on and temperature tuned to the exact desired wavelength. A waveguide feeds the signal combiner that sums the input 1310 nm wavelength with the desired laser wavelength and then routes the signal from the laser to the silicon optical amplifier (SOA) that boosts the signal output. Configuration is controlled by the operating system software in use for the DWDM system.

Figure 4-3: Laser Signal Sources



Lasers as the Signal Source

Transmitters use lasers as the signal source shown in Figure 4-3. Optical fiber transmission is in the infrared band. Wavelengths in use in this band are longer than visible light. As a result, you cannot see the light used in fiber-optic transmission. The transmitter must be very tightly controlled to generate the correct wavelength.

Usually the manufacturer carefully adjusts the transmitter module at the factory and then the frequency is set to specific wavelengths for each transmitter that the customer needs. There are environmental parameters that the laser transmitter expects for proper on-wavelength operation as well as regulated sources of electrical power.

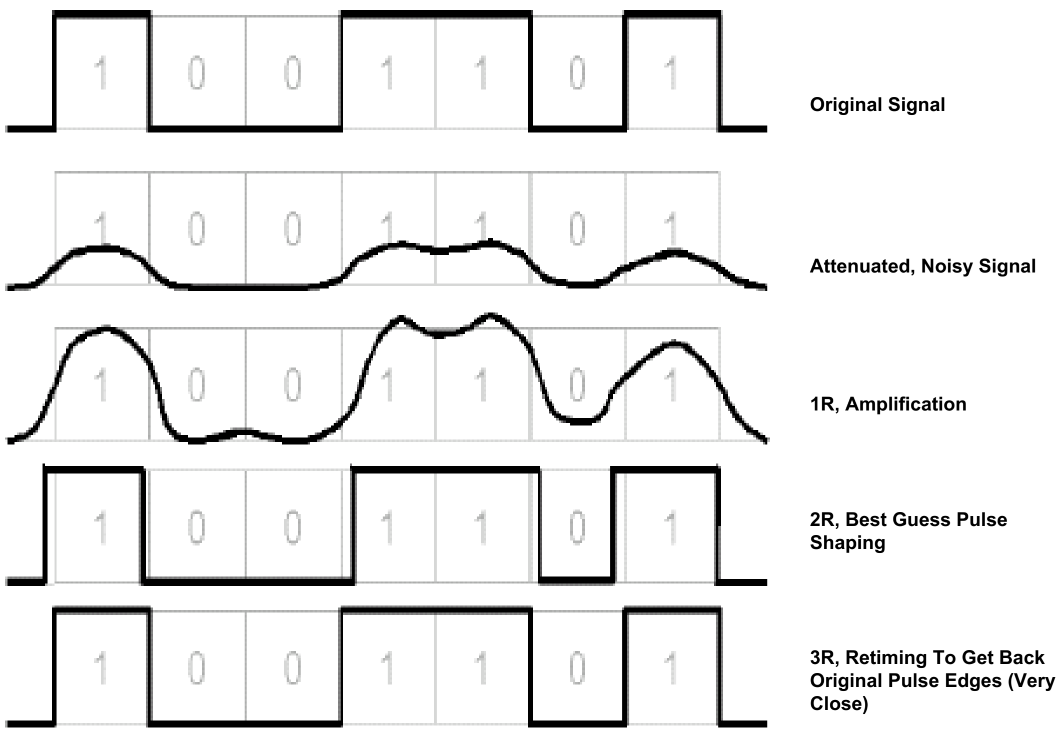
Safety Concerns

There is the risk of damage to the technician’s eyes by laser energy. DWDM lasers are usually Class I lasers and that means that enough light power is present to cause eye damage or blindness if the person exposed looks directly into a fiber end.

Modulator

The modulator changes the laser signal by either pulsing it off and on or by changing the phase of the signal so that it carries information. DWDM systems typically use phase modulation. Each variation represents a 1 or a 0.

Figure 4-4: Regeneration



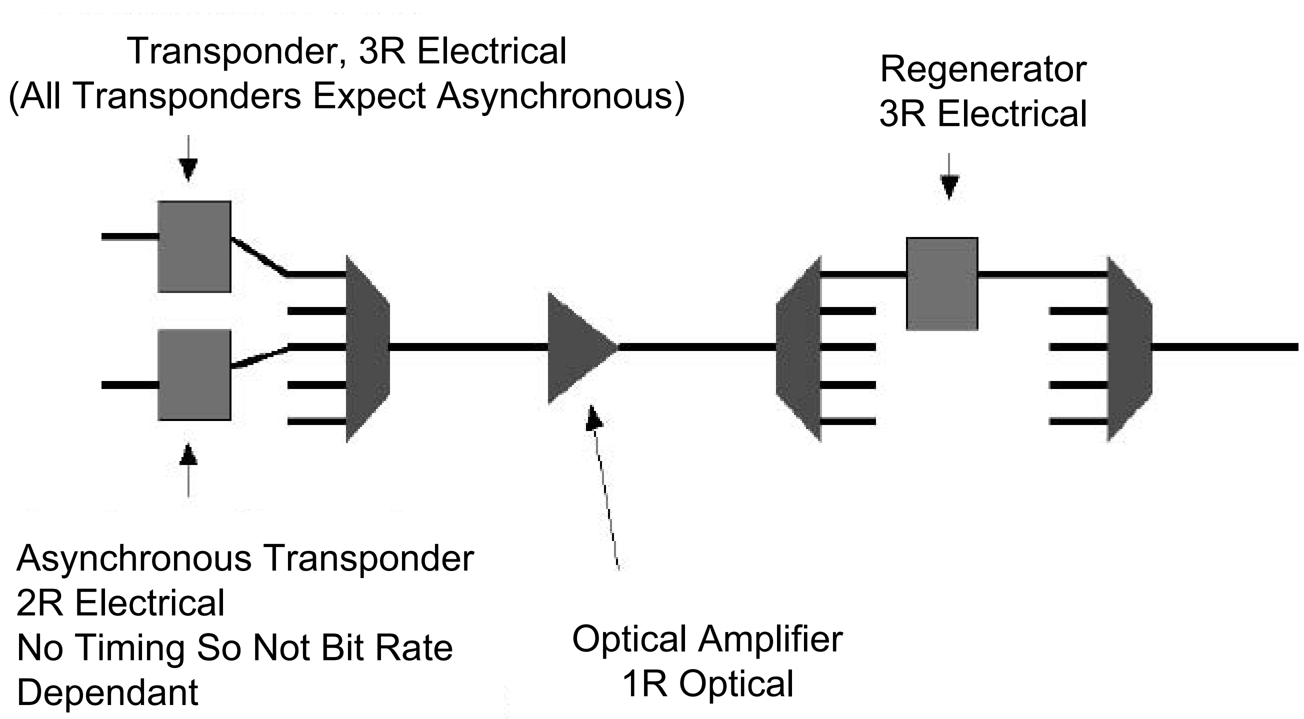
Amplifiers and Regeneration

Amplifiers are defined as type 1R, 2R, or 3R, which are described as follows:

- 1R—Reamplify
- 2R—Reamplify and reshape
- 3R—Reamplify, reshape, and retime

Figure 4-4 illustrates the effect on a degraded optical signal after it has been 1R, 2R, or 3R regenerated.

Figure 4-5: Network Regeneration



Network Routes and Regeneration

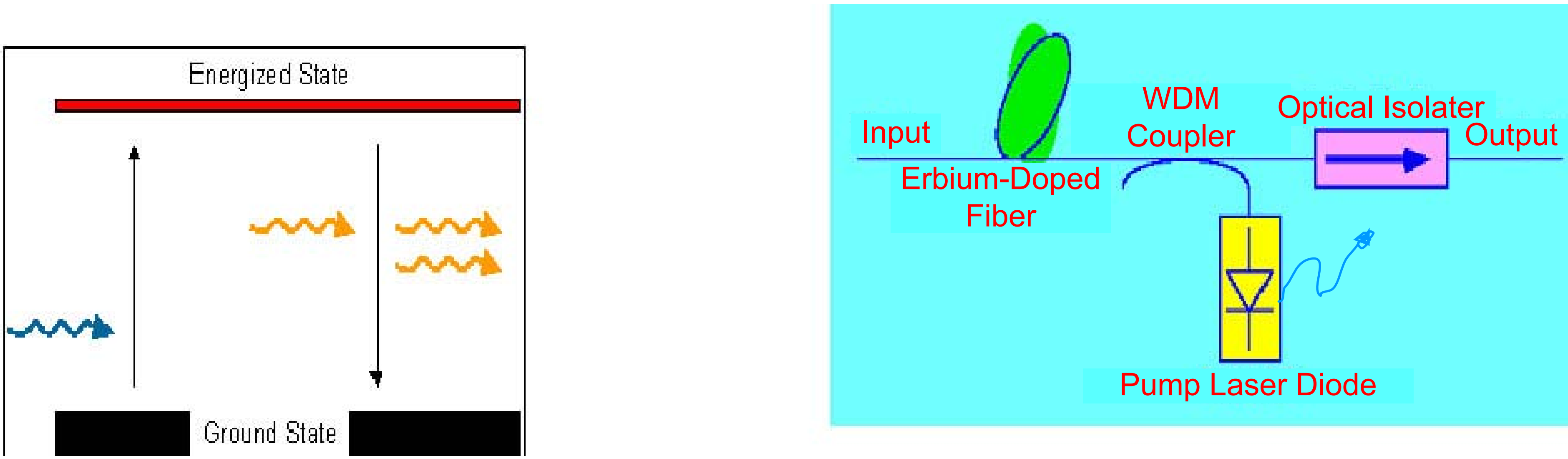
Figure 4-5 shows that optical networks can have 1R, 2R, and 3R devices.

The 1R device only amplifies the signal received. A 2R device provides amplification and reshaping of the waveform to provide some data recovery. The 3R device provides amplification and reshaping and requires a time source so that it can provide retiming for the transponder.

Asynchronous input transponders do not depend on timing and cannot be retimed. Such transponders commonly support non-SONET rates and have a SONET output that is internally clocked by the transponder.

By observation, you see that 3R devices include 1R and 2R as well as 3R functions.

Figure 4-6: EDFA Model

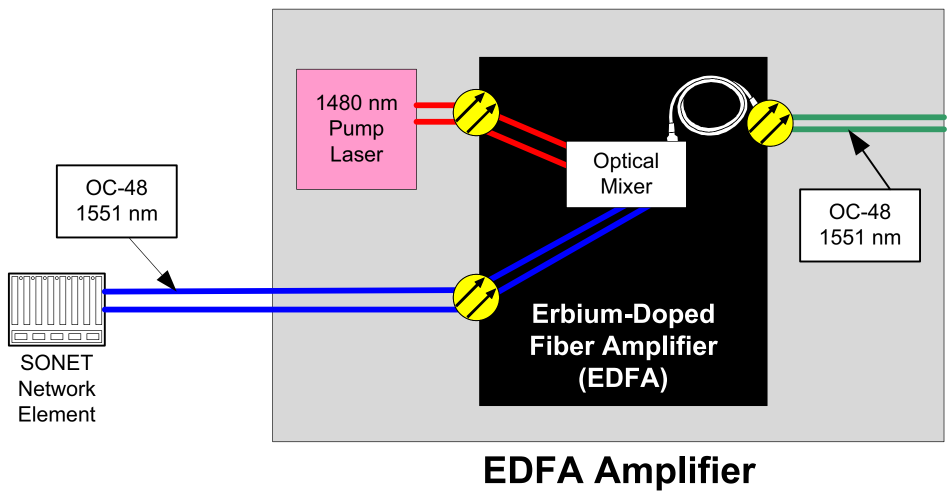


Erbium-Doped Fiber Amplifier Model

Erbium-doped fiber amplifiers (EDFAs) provide the gain mechanism for DWDM amplification, depicted in Figure 4-6. DWDM systems use erbium amplifiers because they work well and are very efficient as amplifiers in the 1500 nm range. Only a few parts per billion of erbium are needed.

Light is pumped in at around 1400 nm (pump laser diode) to excite the erbium ions, and then the incoming 1500-nm light signal from the source system is amplified.

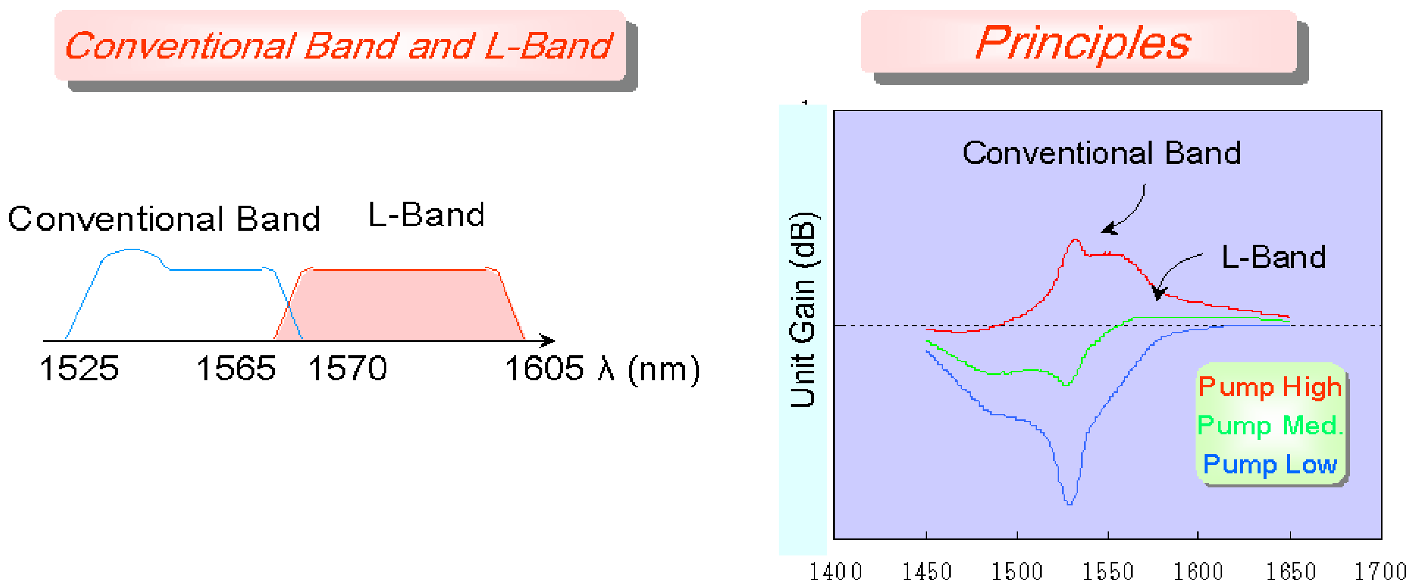
Figure 4-7: Erbuim-Doped Fiber Amplifier



The EDFA Amplifier

Figure 4-7 shows an erbium-doped fiber amplifier (EDFA) and is the last active component in the DWDM system on the transmit side (postamplifier). On the receive side, the preamplifier (a receive EDFA) is the first active component.

Figure 4-8: Fiber Bands and Amplifiers



Fiber Bands

Three optical frequency bands are used today for fiber-optic DWDM networks. Figure 4-8 highlights C-band and L-band, which are considered the most useful. The bands are:

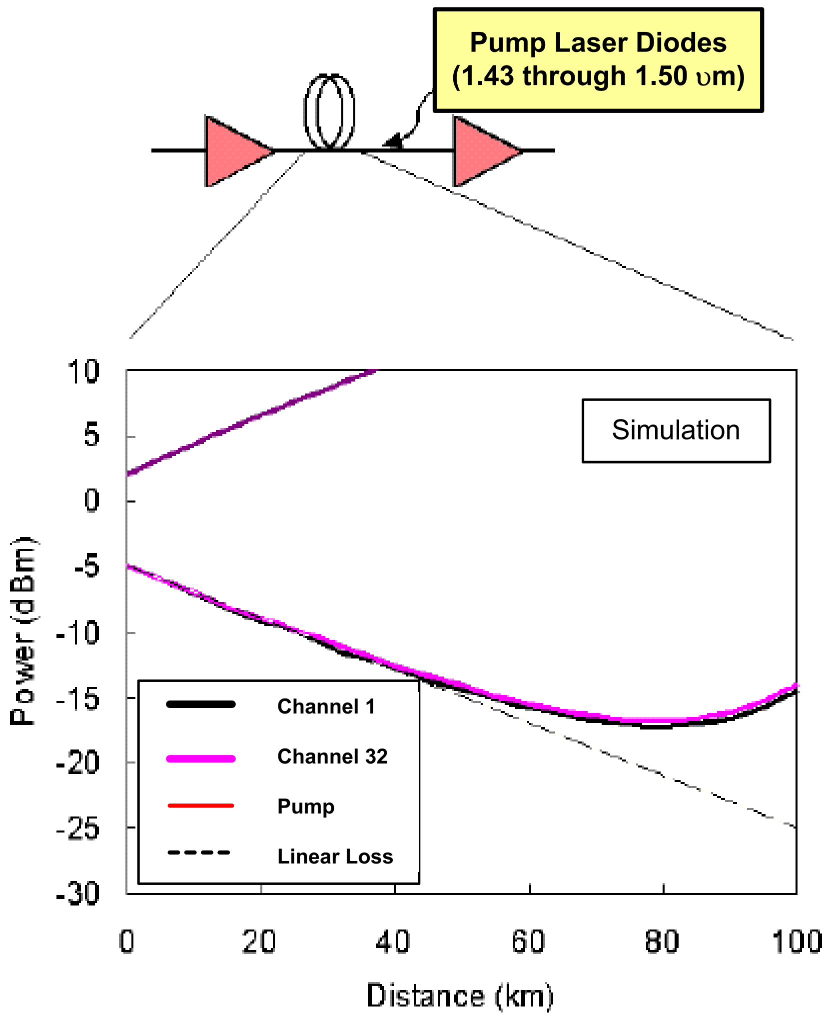
- C-band (conventional) has a range from 1530 nm to 1570 nm (most commonly used band in DWDM).
- L-band (long wavelength) has a range from 1570 to 1625 nm.
- S-band (short wavelength) has a range from 1450 to 1500 nm.

Amplifier Requirements

Different C-band and L-band amplifiers are required because EDFA must be optimized for either C-band or L-band amplification. The following applies:

- High pump power with short EDFA fiber is used for C-band amplifiers.
- Medium pump power with long EDFA fiber is used for L-band amplifiers.
- Thulium-doped fluoride-based fiber amplifier (TDFA) for 1450–1490 nm S-band is used in conjunction with Raman fiber amplifiers (RFA). The S-band has only recently come into DWDM system design.

Figure 4-9: Distributed Raman Amplifiers



Raman Amplification

Distributed Amplification In Transmission Fibers

Reduced Effective Span Loss

OSNR Improvement

Raman Amplifiers

Raman amplifiers (fiber amplifiers) are devices that amplifies an optical signal directly, without first converting the signal to an electrical signal, amplifying the signal electronically, and then reconverting it to an optical signal. Characteristics of Raman amplification include:

- Silicon fiber used as the gain mechanism
- Not as efficient as erbium; however, the lower efficiency is compensated for by the higher linear density of silicon in the fiber
- Amplifies over C-band, L-band, and S-band

Distributed Raman

Raman amplifiers, as shown in Figure 4-9, are coming into general use to accomplish operation over longer spans with fewer regeneration sites.

Raman amplification allows the transmission fiber to be used as an amplifier, resulting in the following benefits:

- Reduced effective span loss
- OSNR improvement

Lesson 5

Optical Network Considerations

Purpose

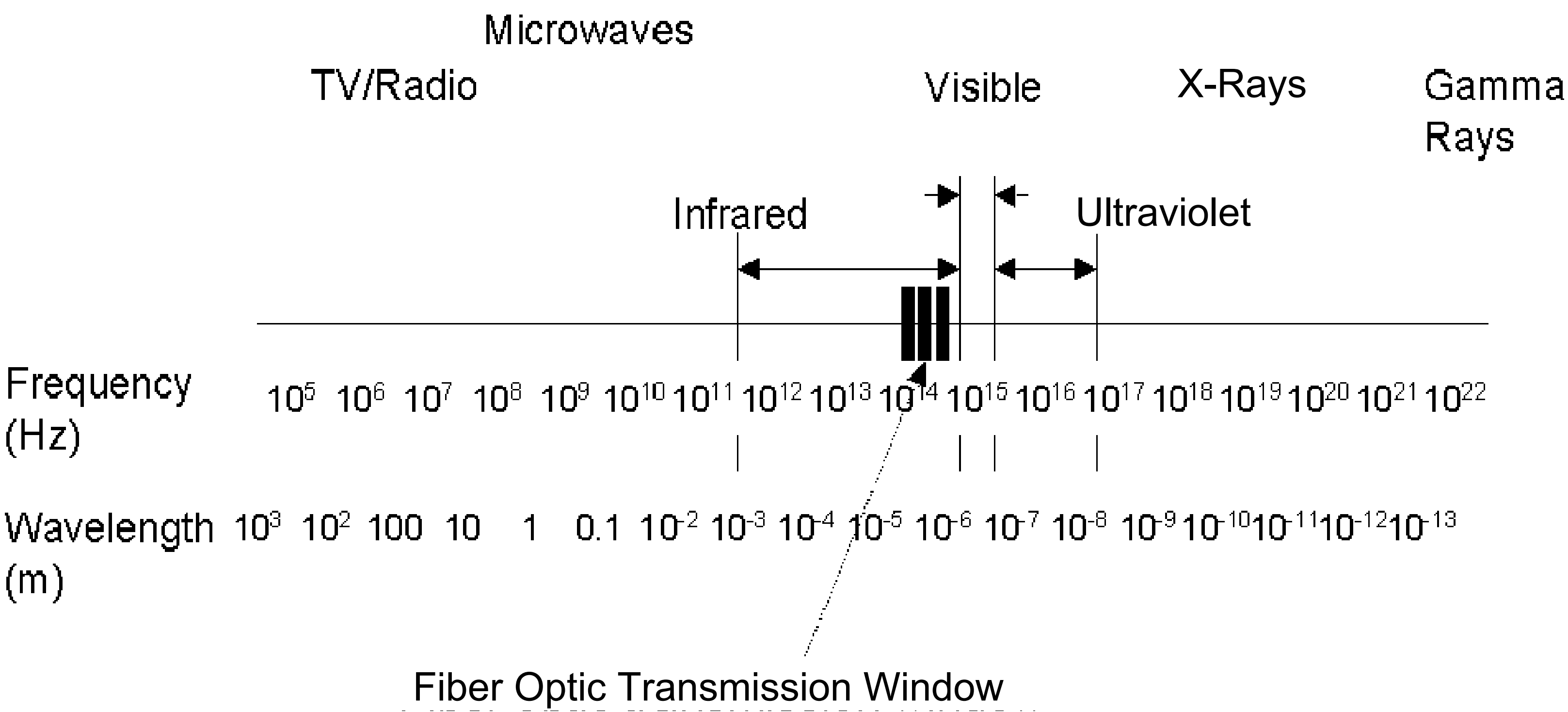
This lesson provides an overview of considerations that must be taken into account when designing an optical network.

Objectives

Upon completion of this lesson, the student should be able to:

- Identify the bandwidth range used in DWDM
- Identify common impairments to DWDM transmissions
- Describe how forward error correction (FEC) is a solution for bit error rate (BER)
- Identify the types of dispersion

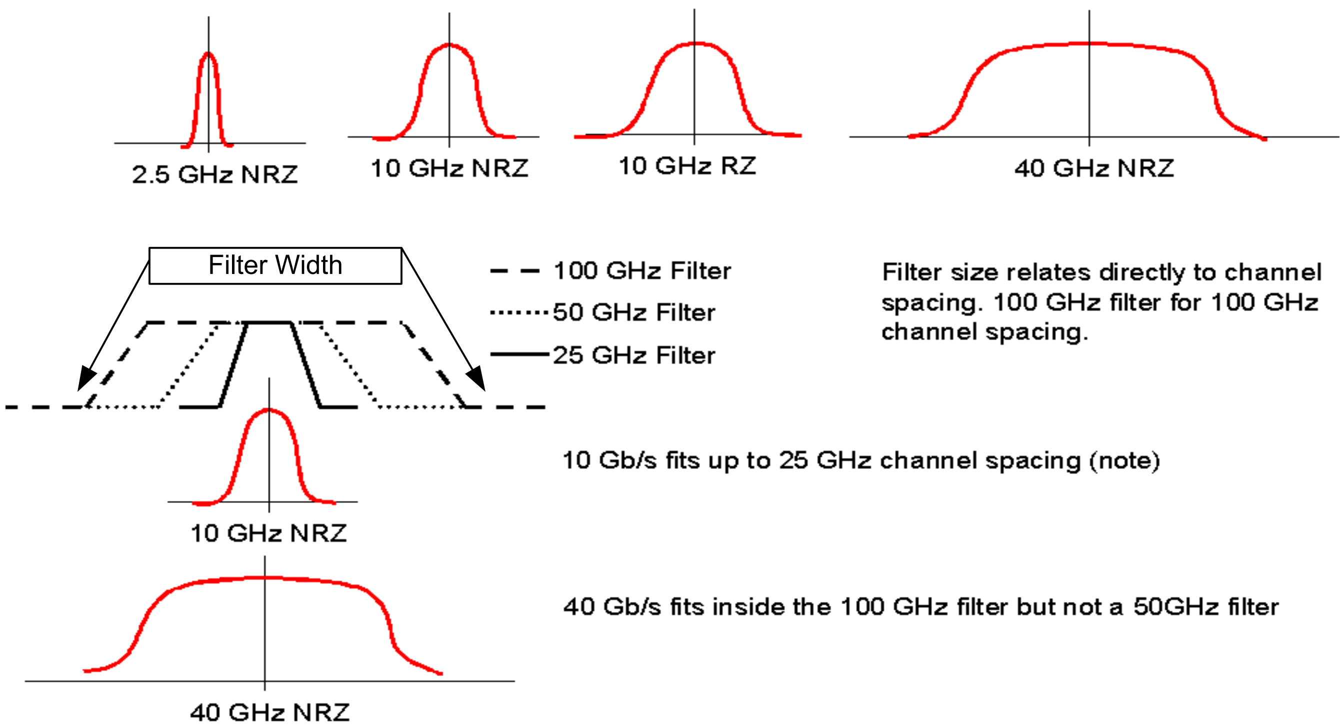
Figure 5-1: Optical Network Spectrum



Optical Network Considerations

Optical fiber transmission using DWDM typically occurs at 1500 nm wavelengths. The DWDM system transmission shown in Figure 5-1 operates in the 1500 nm range due to performance effect, component cost, and the availability of optical amplifiers.

Figure 5-2: Signal Bandwidth



Signal Bandwidth and Filtering

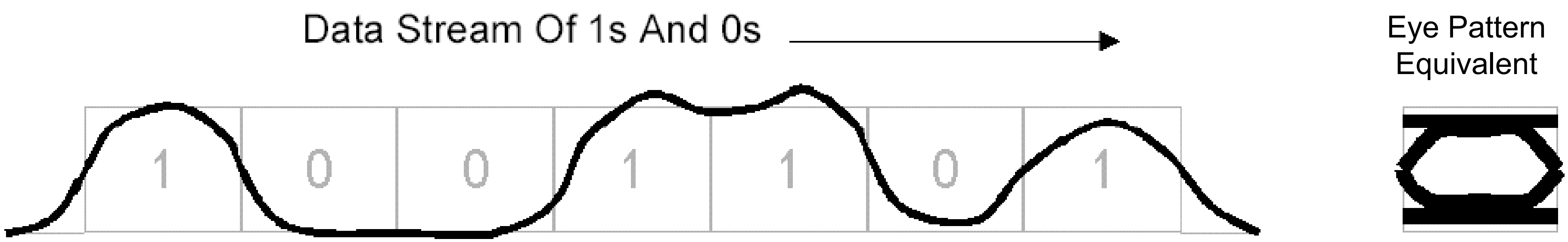
Figure 5-2 shows how signal bandwidth requirements change with data rate. Figure 5-2 indicates that a significant amount of bandwidth is normally consumed by the optical signal. The general rules of physics say that for each GHz of signal, 2 GHz are required for the signal. Typically an additional 10 percent for guard band is used.

ITU-T Grid

The International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) established a set of standards for telecommunications that drives all optical DWDM systems today.

Systems are based on an absolute reference to 193.10 THz that corresponds to a wavelength 1552.52 nm with individual wavelengths spaced in steps of 50 GHz or a wavelength step of 0.41 nm from the reference. All land-based DWDM systems follow this standard.

Figure 5-3: Eye Pattern vs. Data Stream



Impairments to DWDM Transmission

There are different kinds of impairments to error-free transmission over DWDM. Some techniques of detection and correction are discussed below.

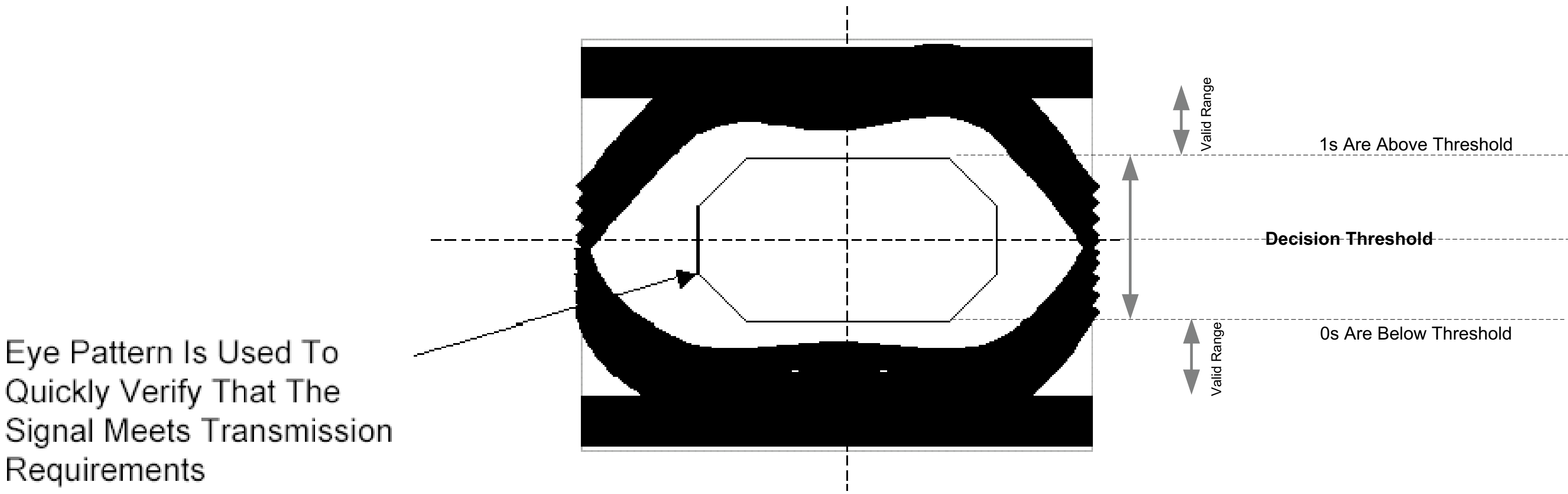
Bit Error Rate

The bit error rate (BER) is a ratio of error bits to total transmitted bits. Typical values are 10^{-12} BER for SONET and 10^{-15} for next generation long-haul transport equipment. The value 10^{-15} is one error bit in 10^{15} bits, which equates to one error in 11.6 days for a 10-Gb/s signal.

Eye Pattern

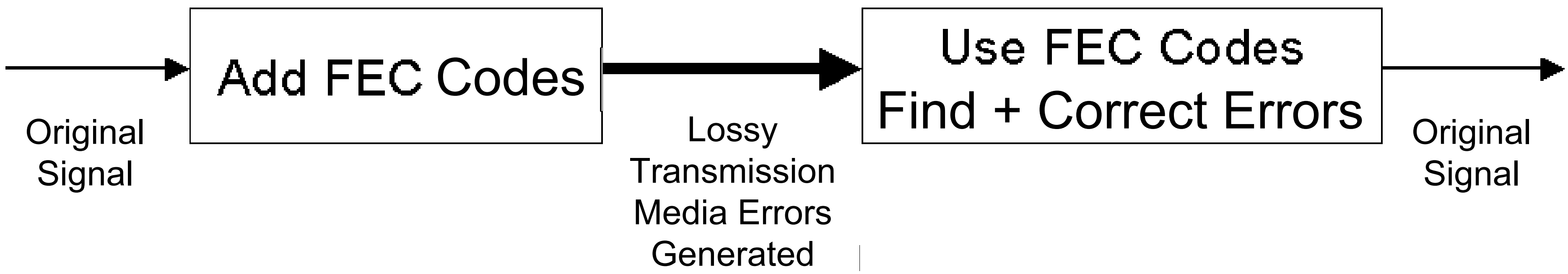
The eye pattern in Figure 5-3 is a visual depiction of the waveform being transmitted to look for impairments. It consists of the waveform for each wavelength overlaid on one screen.

Figure 5-4: Eye Pattern Display



The eye pattern display in Figure 5-4 allows quick verification of signals that meet performance specifications. In the display, the 1 signals are above the center point and the 0 signals are below the center point. An eye pattern is an oscilloscope display in which a pseudorandom optical data signal from a optical receiver is repetitively sampled and applied to the vertical input, while the optical signalling rate is used to trigger the horizontal sweep. System performance information can be derived by analyzing the display. An open eye pattern corresponds to minimal signal distortion. A closure of the eye pattern is a result of distortion of the signal waveform due to inter-symbol interference.

Figure 5-5: Forward Error Correction



Forward Error Correction—Solution to BER

Forward error correction (FEC) is used to support higher capacity and longer transmission distances by improving the bit error rate (BER). FEC makes the system more robust in respect to errors (Figure 5-5). The FEC code bytes are used at the end of a transmitted frame by the receiving system to find and correct errors.

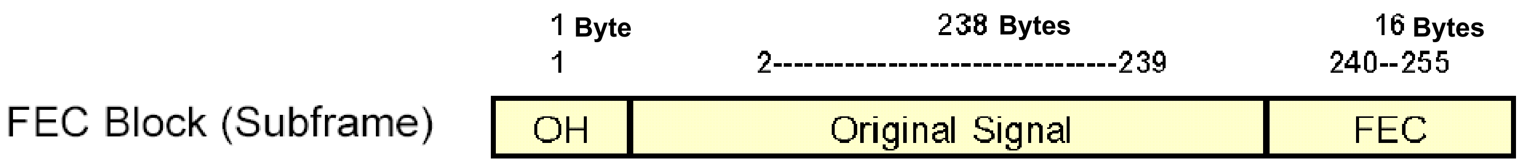
Types of FEC

The two main kinds of FEC used in optical transmission are in-band and out-of-band. In-band is sometimes called simple FEC.

In-Band FEC

In-band forward error correction (FEC) is the most common method used in SONET Network Elements. FEC bytes are carried as part of the SONET overhead. The simple FEC shown in Figure 5-5 is representative of in-band FEC.

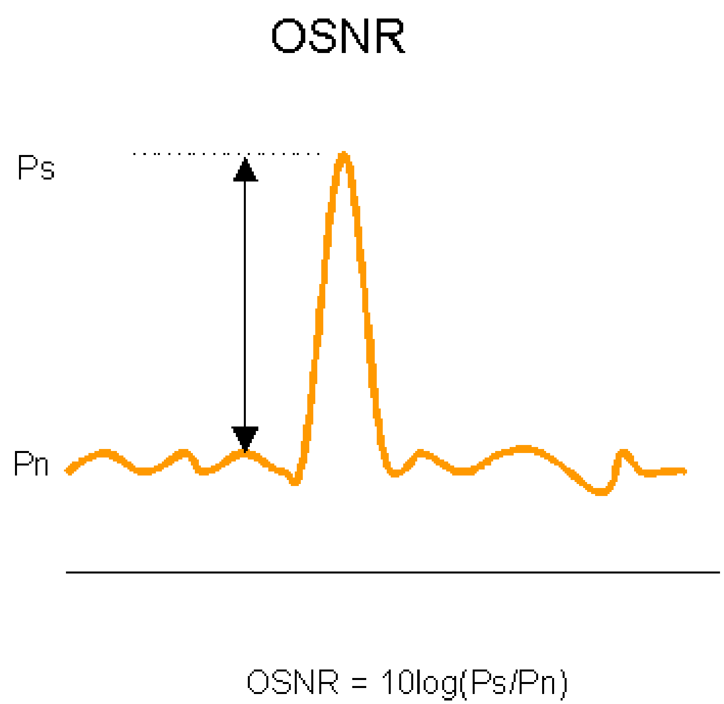
Figure 5-6: OOB-FEC Example



Out-of-Band FEC

Out-of-band forward error correction (OOB-FEC) is the type used for DWDM systems. FEC bytes are added on top of the signal to be carried (Figure 5-6). For example, adding OOB-FEC changes the signal from 9.958 Gb/s to 10.7 Gb/s for 10 Gb/s SONET transport, resulting in 6 percent overhead added outside the normal signal envelope. The effect of approximately 6-dB optical system gain, depending on OSNR and other impairments on the DWDM route, can be achieved. The 6-dB gain is not an actual power gain, but an improvement in the OSNR. It permits greater distance between ILA sites on the optical span.

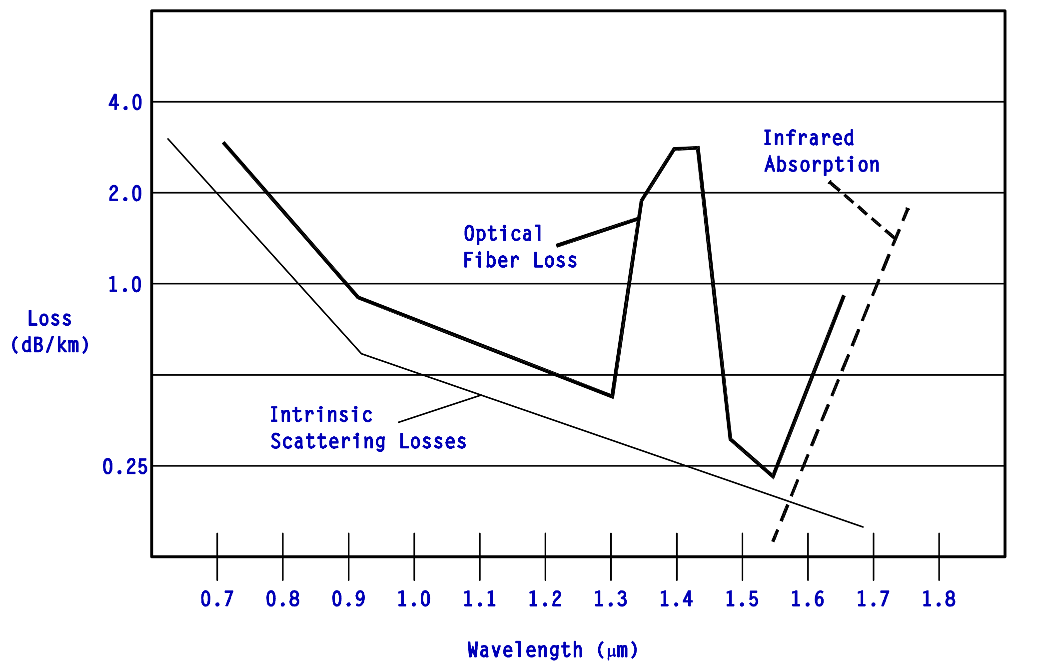
Figure 5-7: OSNR



Optical Signal-to-Noise Ratio

Figure 5-7, optical signal-to-noise ratio (OSNR), shows the ratio of power in the signal to the noise that is with the signal. Better OSNR is indicated by high numbers. In most cases, a OSNR of 10 dB or better is needed for error-free operation. P_n is the power level of the noise and P_s is the power level of the signal ($OSNR = 10\log_{10}(P_s/P_n)$).

Figure 5-8: Fiber Attenuation



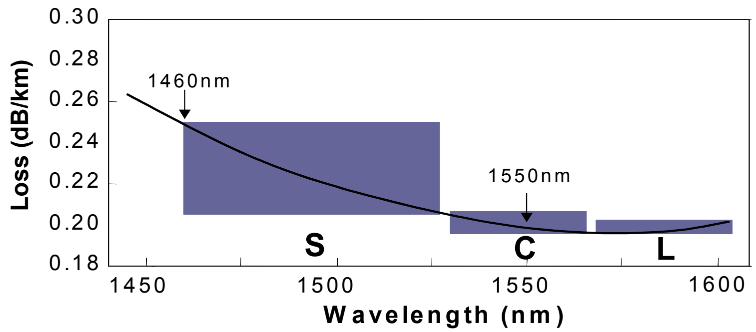
- For silica-based fiber, 1.55 μm is optional wavelength for minimum loss.
- Fibers at 1.3 μm are typically used.

Fiber Attenuation

All transmission fiber suffers from the losses brought about by attenuation, as shown in Figure 5-8. The characteristics of the common fibers have the following in common:

- The 1550-nm window has the lowest attenuation.
- The large spike is due to absorption by water molecules. This problem has been greatly reduced on fibers manufactured today, allowing almost optimum minimum attenuation.

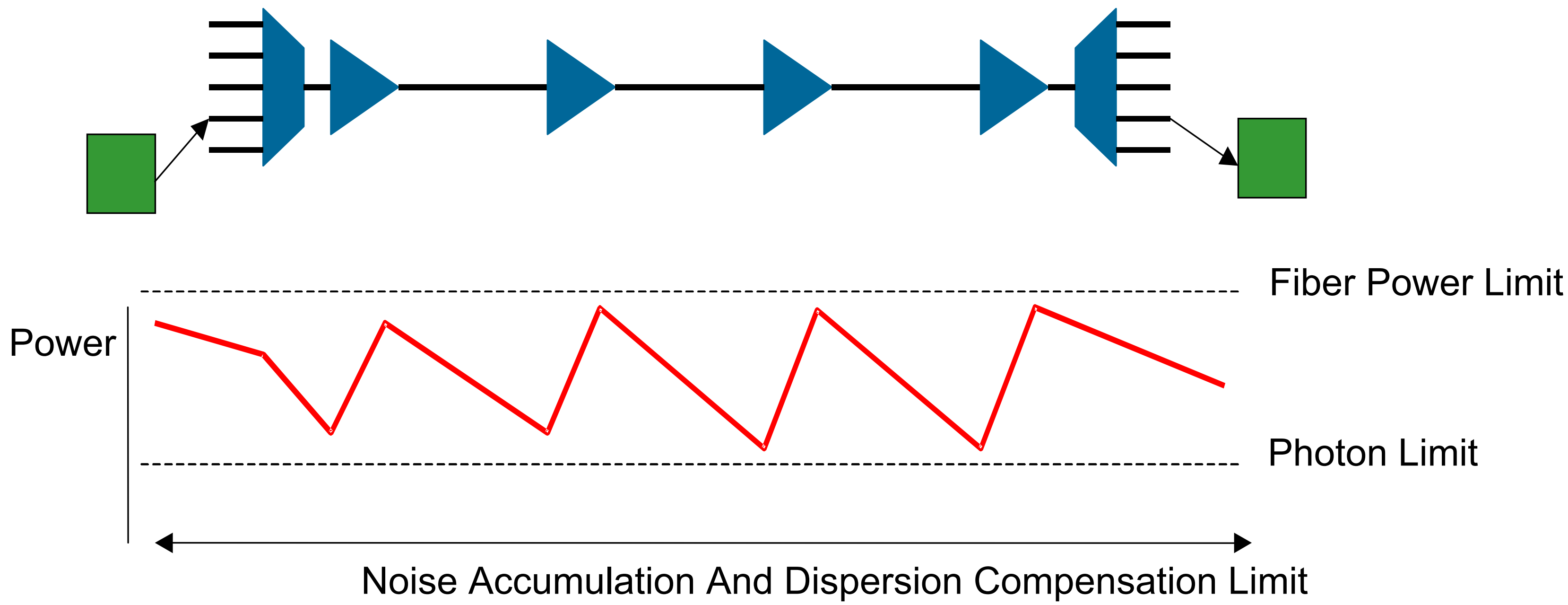
Figure 5-9: Fiber Signal Loss in S-Band, C-Band, and L-Band



Attenuation Loss in S-Band, C-Band, and L-Band

The S-band has the greatest attenuation, and is seldom used in DWDM design. The C-band and L-band have the most even rates of loss, as shown in Figure 5-9, and this is the portion of optical fiber that is most useful.

Figure 5-10: Power Levels



Attenuation of Optical Signal

Amplification is needed in an optical network because photons leak out or are absorbed by the fiber.

Fiber nonlinearity limits the allowable launch power into a fiber. These include a variety of effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), and four-wave mixing (FWM).

Light is limited to power increments of photons, so there is a lower limit to the amount of power/number of photons a receiver needs to correctly detect 1s and 0s.

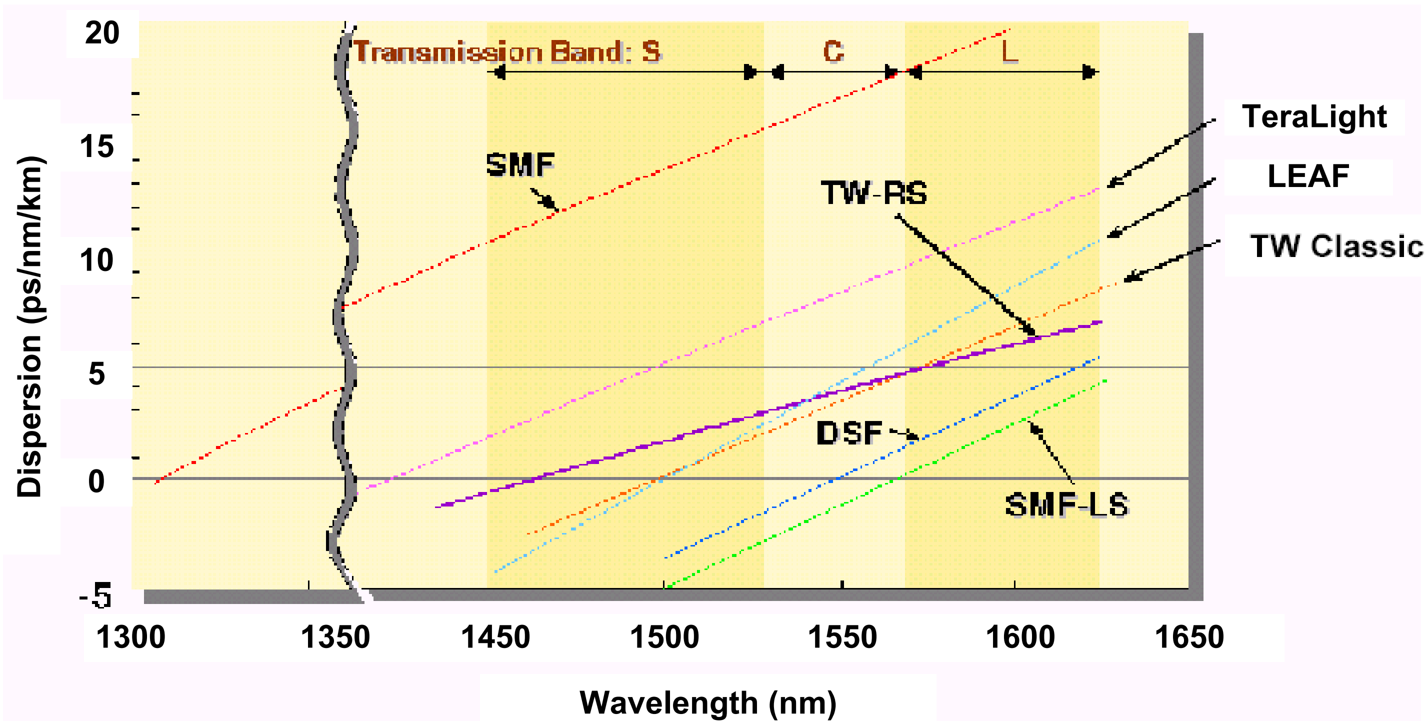
Signal Amplification

An optical power budget is maintained throughout the network. Distributed amplification overcomes the power limits of transmission over fiber as shown in Figure 5-10. Additional amplification considerations are:

- Amplifiers amplify noise to the desired signal as well as amplification.
- The number of amplifications that are possible before a signal must be terminated is limited by the effects of noise.
- Some amplifier cross talk and inter-symbol interference restricts the transmission distance.

Note: *In a digital transmission system, distortion of the received signal, which distortion is manifested in the temporal spreading and consequent overlap of individual pulses to the degree that the receiver cannot reliably distinguish between changes of state, that is, between individual signal elements. At a certain threshold, inter-symbol interference will compromise the integrity of the received data. Inter-symbol interference attributable to the statistical nature of quantum mechanisms sets the fundamental limit to receiver sensitivity. Inter-symbol interference may be measured by eye patterns.*

Figure 5-11: Dispersion and WDM



Cross Talk in DWDM Systems

Compensating for Cross Talk in DWDM Systems

Some dispersion is required in WDM networks, as shown in Figure 5-11, because it keeps down cross talk by minimizing stimulated Brillouin scattering.

Some early fibers (DSF) sought to eliminate dispersion but had the following disadvantages:

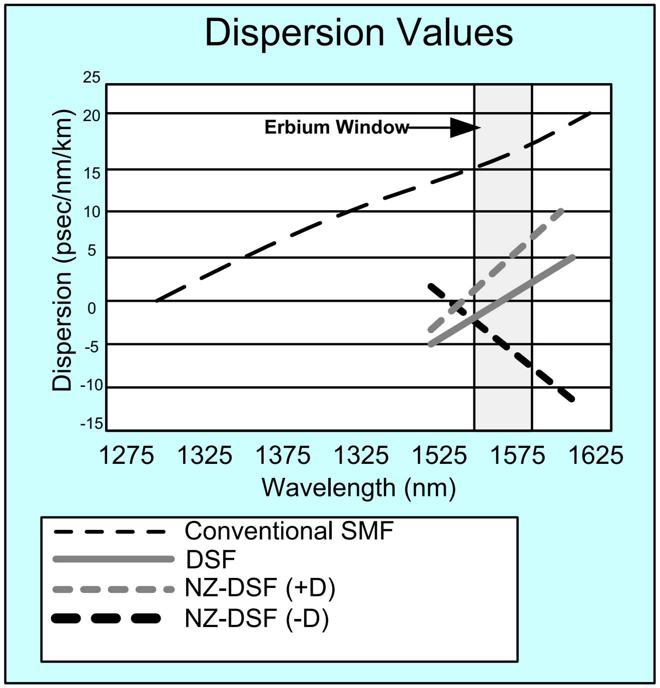
- Not very good for WDM; too much cross talk
- Limited power levels in the system; greatly reduced span budgets

Newer fibers have just enough dispersion to eliminate cross talk; however, they do not present enough dispersion to make dispersion compensation difficult.

Fiber Dispersion

There are two kinds of dispersion, the most common is called chromatic dispersion and is routinely compensated for by DWDM systems for proper operation. The effects of polarization mode dispersion (PMD) are much more insidious and difficult to make compensation for in deployed networks.

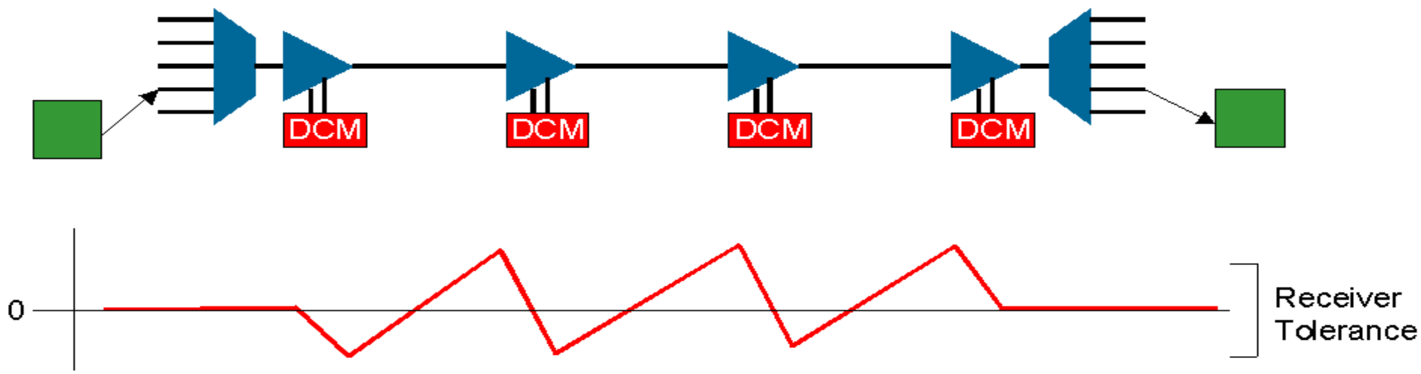
Figure 5-12: Chromatic Dispersion



Chromatic Dispersion

Chromatic dispersion is a measure of fiber delay for different wavelengths. Different wavelengths travel at different velocities through fiber. The difference in velocity is called delay or chromatic dispersion of the signal. Figure 5-12 illustrates the common fiber type delay profiles. The erbium window represents the minimum slope of chromatic dispersion.

Figure 5-13: Compensation Modules



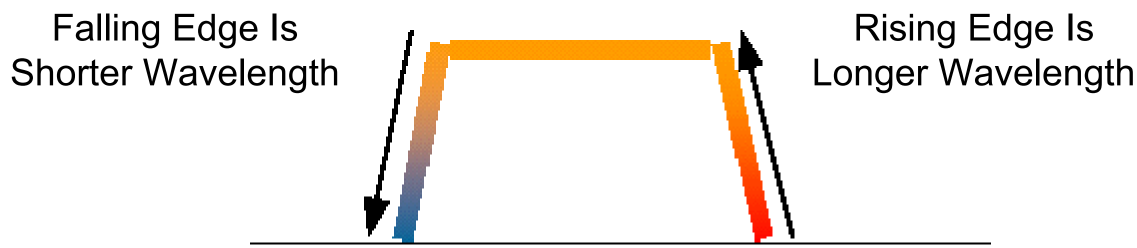
The DWDM system must compensate for dispersion to support 10-Gb/s transmission using methods like those shown in Figure 5-13.

Dispersion Compensators

A compensator is a device that has the opposite chromatic dispersion effect as the transmission fiber. Various technologies are available that can compensate for all wavelengths in a band or for each wavelength. Compensating for all wavelengths greatly reduces the cost of compensation. Per-band compensation is used in some DWDM products. The various methods include:

- Dispersion compensation module (DCM)
  - A type of single-mode fiber
  - Used extensively in FNC products
- Fiber Bragg gratings
- High order mode devices
- Virtual image phase array (VIPA), a free-space dispersion device

Figure 5-14: Chirp



An Example Of Negative Chirp

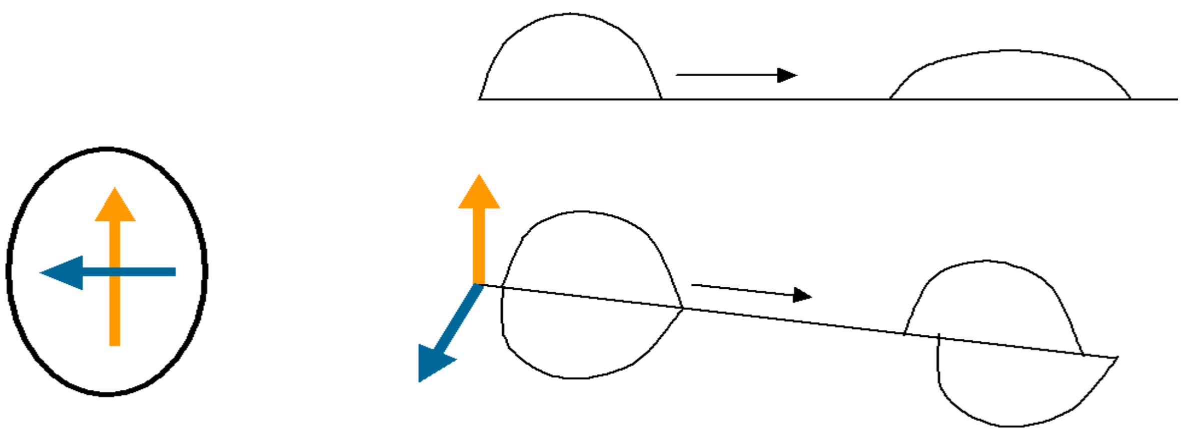
Chirp

Chirp is an abrupt change of the center wavelength of a laser, caused by laser instability. When the modulator pulses the laser, a difference in the refractive index of the laser output occurs that can cause chirp in a DWDM system. Chirp is the phenomenon of the rising edge of a pulse having a slightly different frequency than the falling edge (shown in Figure 5-14). It is a common effect in devices that generate optical pulses (optical modulators). Additionally, chirp interacts with fiber dispersion potentially providing more or less dispersion tolerance.

Chirp usually occurs with a value of +1 GHz to –1 GHz. Each laser transmits coherent light at a different center frequency for each λ. Chirp can be provisioned to match the system input requirements on many DWDM systems. On systems that allow changes, the technician may adjust the chirp value to support the network requirement, commonly the technician can only report the presence and degree of chirp.

Chromatic dispersion near the tolerance limit for DWDM receivers may be worse due to the chirp effect, and may require dispersion compensation or closer spacing of ILA systems.

Figure 5-15: Polarization Mode Dispersion



Polarization Mode Dispersion

Polarization is used to describe the orientation of a lightwave around its axis of propagation (Figure 5-15).

Polarization mode dispersion (PMD) describes the variation in velocity of light waves as a result of traveling different polarization paths.

As light is refracted within the fiber, slight changes in the polarization of the light may occur. Light which takes different paths within the fiber will have polarization differences resulting in dispersion.

PMD Effect

Although known, polarization mode dispersion (PMD) was not considered in early fiber manufacturing because of the limited impairments that PMD represented at the lower data rates prevalent at that time. Later, as faster data transmission rates became practical, various manufacturers began to provide fibers that helped manage the PMD effects, for example:

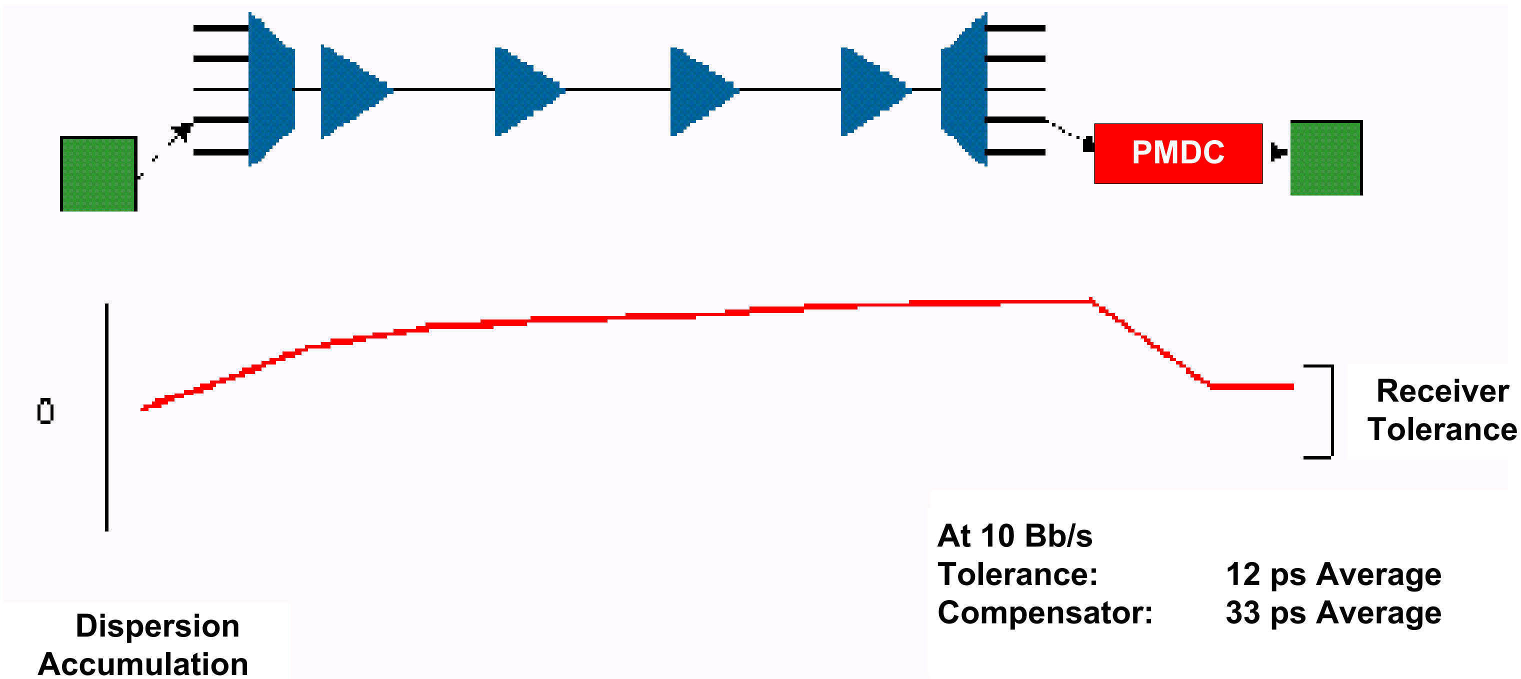
- Low PMD fibers produced by outside vapor deposition method (Corning).
- High PMD fibers produced by inside vapor deposition method (Lucent).

Polarization mode dispersion became an issue in the early 1980s. Manufacturing methods were improved and now fibers can be manufactured that have low PMD. The PMD standard, Standard Reference Materials (SRM) 2518, published by the National Institute of Standards and Technology (NIST), states 0.5 ps of PMD per the square root of the fiber length in kilometers as the proven PMD management interface, that is:

$$0.5\ ps/km^{-1/2}$$

The new fiber types have less than 0.5 PMD. For example, 10-Gb/s signals with 10 ps of PMD tolerance, derived from the formula above, would exhibit a range of about 400 kilometers; 40 Gb/s with 2.5 ps tolerance has an effective range of 25 kilometers (PMD compensation required). Research is underway to make even lower PMD fibers. New LEAF fiber, with 0.1 ps/kilometers, allows distances of up to 10,000 kilometers of 10 Gb/s or 625 kilometers of 40 Gb/s.

Figure 5-16: PMD Compensation



Polarization Mode Dispersion Compensation

A PMD compensator (PMDC) compensates for polarization mode dispersion. The PMDC device has tunable PMD (Figure 5-16) and is new to optical networking.

The compensator applies the opposite amount of PMD as that produced by the physical attributes of the fiber network itself. Current technology compensates for PMD at the receiver. This requires a PMDC for each wavelength.

Effective Polarization Mode Dispersion Compensation

Polarization Mode Dispersion Compensators (PMDC) must consider the following conditions in their dynamic PMDC operation:

- Signal rate
- Noise accumulation limit of amplifiers
- Chromatic dispersion compensation limit
- PMD compensation limit

Lesson 6

DWDM Network Solutions

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

Purpose

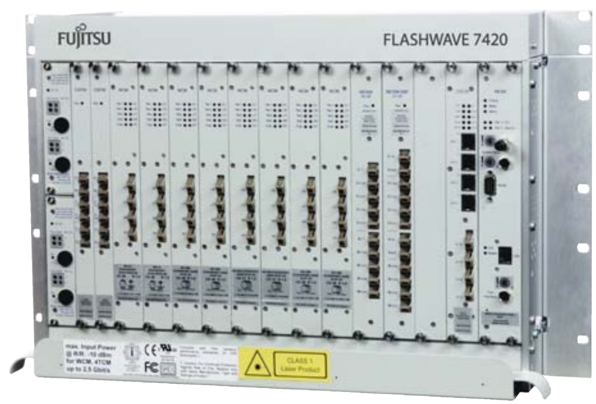
This lesson provides an introductory overview of two Fujitsu products that provide DWDM solutions for Metro congestion and fiber strain.

Reference Documents

The following documents were used in the development of this lesson:

- *TRN-7500-TM-013, FLASHWAVE 7500 Turn-Up and Test*
- *TRN-7420-TM-031, FLASHWAVE 7420 Turn-Up and Test*
- *PMB-03-031 FLASHWAVE 7500 Product Management Bulletin (Release 1.3 Announcement)*
- *PMB-03-004 FLASHWAVE 7420 Product Management Bulletin (New Product Announcement)*

Figure 6-1: FLASHWAVE 7420



FLASHWAVE 7420: The Ideal Metro Access WDM Transport

The FLASHWAVE 7420 DWDM transport system (Figure 6-1) is designed for use in enterprise and metropolitan networks. The FLASHWAVE 7420 DWDM can be configured as an optical terminal multiplexer, or add-drop multiplexer. The FLASHWAVE 7420 supports various topologies, such as two and four fiber point-to-point, and linear add-drop, as well as two-fiber rings.

System Description

The FLASHWAVE 7420, shown in Figure 6-1, is a DWDM networking system for transporting optical signals in multiple channels on a single fiber pair. The FLASHWAVE 7420 has been designed for use in metropolitan networks for both carrier and enterprise access. The system provides a high level of flexibility through protocol-transparent interfaces. It can interface easily with all types of fiber and transmission equipment, such as:

- SONET (OC-3/STM-1, OC-12/STM-4, OC-48/STM-16, and OC-192/STM-64)
- Fast Ethernet (100Base-TX)
- Gigabit Ethernet (1000Base-SX) (GigE)
- 10 Gigabit Ethernet (10GigE) at 10.3 Gb/s
- Fibre Connection (FICON) (1062 Mb/s)
- Fibre Channel (FC) (1062 Mb/s)
- ATM (OC-3, OC-12, and OC-48)
- Enterprise network connection (ESCON) (200 Mb/s)

System Objectives

The FLASHWAVE 7420 is an optical add/drop multiplexer (OADM) designed to provide two basic connections/links:

- Protected and monitored connections between nodes of an optical metropolitan network
- Unprotected or protected links between customer premises equipment and the optical metropolitan network of the carrier

Topologies

Signal transport is available in three different topologies:

- Point-to-point
- Linear add/drop
- Ring

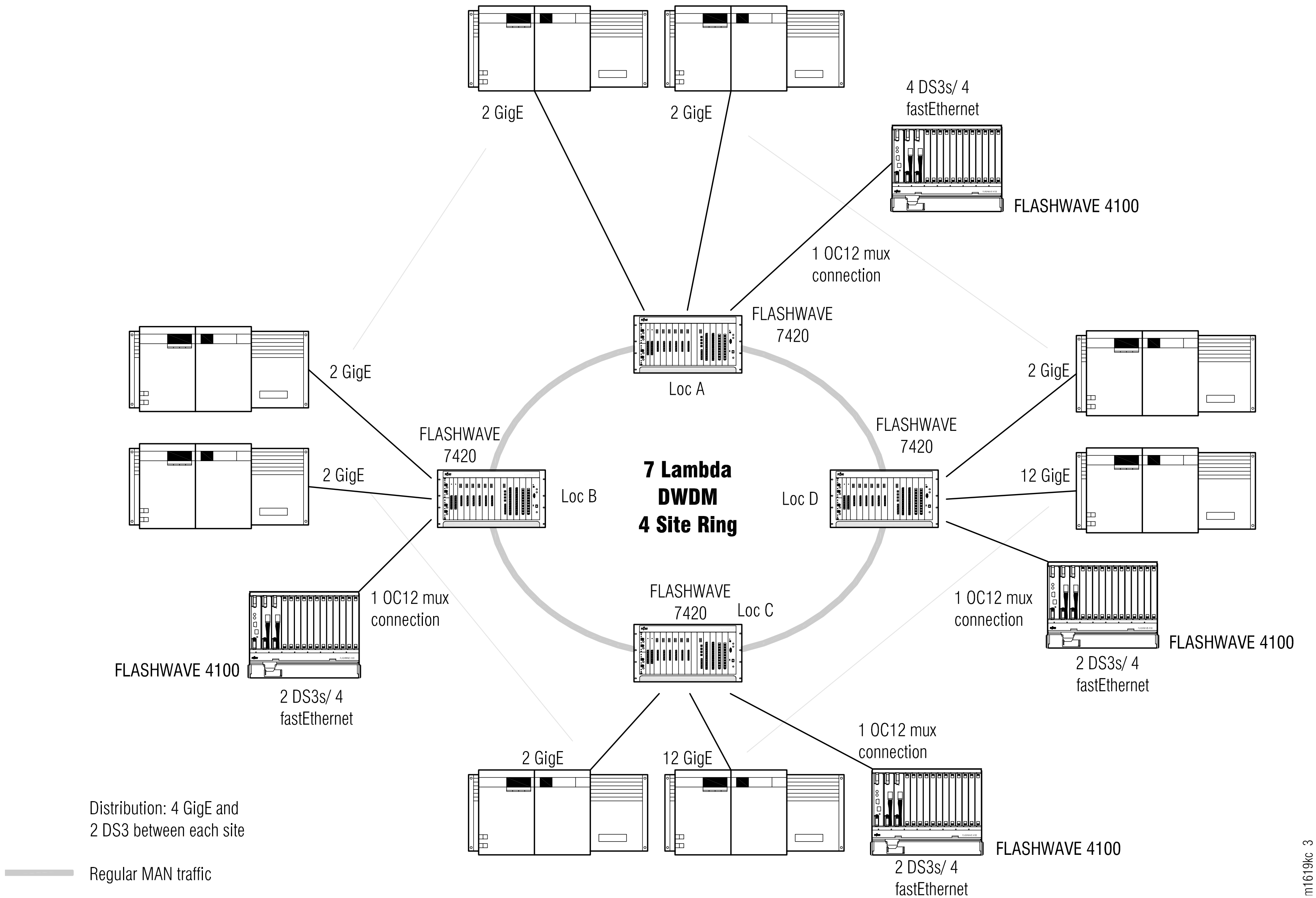
Protection

The FLASHWAVE 7420 system can be configured to provide both line protection and path protection, thus providing full channel protection. The NEs provide a range of protection abilities against individual component and other failures.

Technology

The FLASHWAVE 7420 uses DWDM technology with 32 channels conforming to ITU-T G.692 (200-GHz channel spacing) for signal transport. An optical supervisory channel (OSC) enables supervisory information exchange between all NEs. The OSC allows managing the complete network from a single point by access to any one of the nodes of a FLASHWAVE 7420 topology.

Figure 6-2: FLASHWAVE 7420 Ring

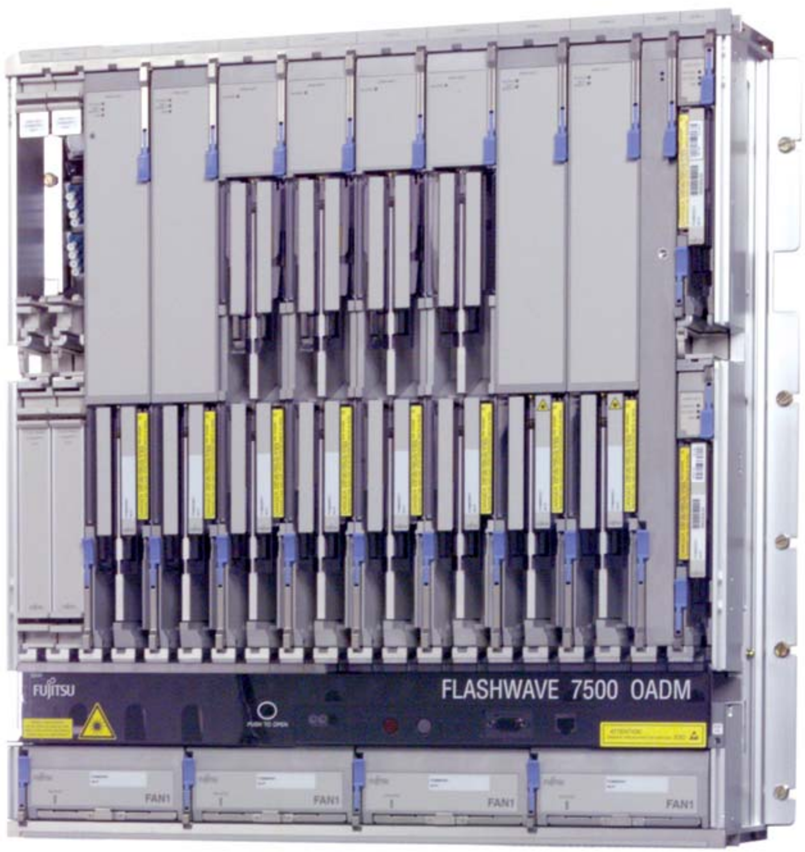


Applications

While the FLASHWAVE 7420 is ideally suited as an access transport for metro core equipment because of its application driven interface types, it is versatile enough to serve as a metro core in small cities. An example of its versatility is illustrated in Figure 6-2.

Figure 6-3: FLASHWAVE 7500

FLASHWAVE 7500 OADM Shelf



r0322.fh10_1

FLASHWAVE 7500 OLC Shelf

r0323.fh10_1

FLASHWAVE 7500: The Metro Core Solution

The all-optical FLASHWAVE 7500 DWDM system (Figure 6-3) provides a Reconfigurable Optical Add Drop Multiplexer (ROADM) core for use in metropolitan and Inter-Office Facility (IOF) networks. This next-generation ROADM platform is optimized for high capacity and evolving metro core networks. A variety of network configurations and traffic patterns are supported, including point-to-point, ring, and mesh network architectures. The FLASHWAVE 7500 offers 400 Gb/s of bandwidth that is scalable per wavelength.

System Description

The FLASHWAVE 7500 platform is a next-generation wavelength system that significantly drives down the cost of delivering wavelength services. The FLASHWAVE 7500 platform supports all metro applications with up to 10 nodes in a 400-km ring. The FLASHWAVE 7500 network only needs to be engineered once. Any wavelength can be added/dropped between any two nodes without manual attenuation adjustments, banding restrictions or reengineering. All traffic patterns hubbed, distributed and meshed are supported without stranding bandwidth in pre-planned bands.

Multi-rate line cards provide bit rate and protocol independence and deliver full interoperability with:

- SONET
- Next generation MSPP
- Gigabit Ethernet (100 megabit to 10 gigabit)
- Fiber Channel services

The FLASHWAVE 7500 is a reconfigurable OADM that at every site customers can add and drop any traffic as needed to meet current or future bandwidth requirements, leaving no stranded bandwidth.

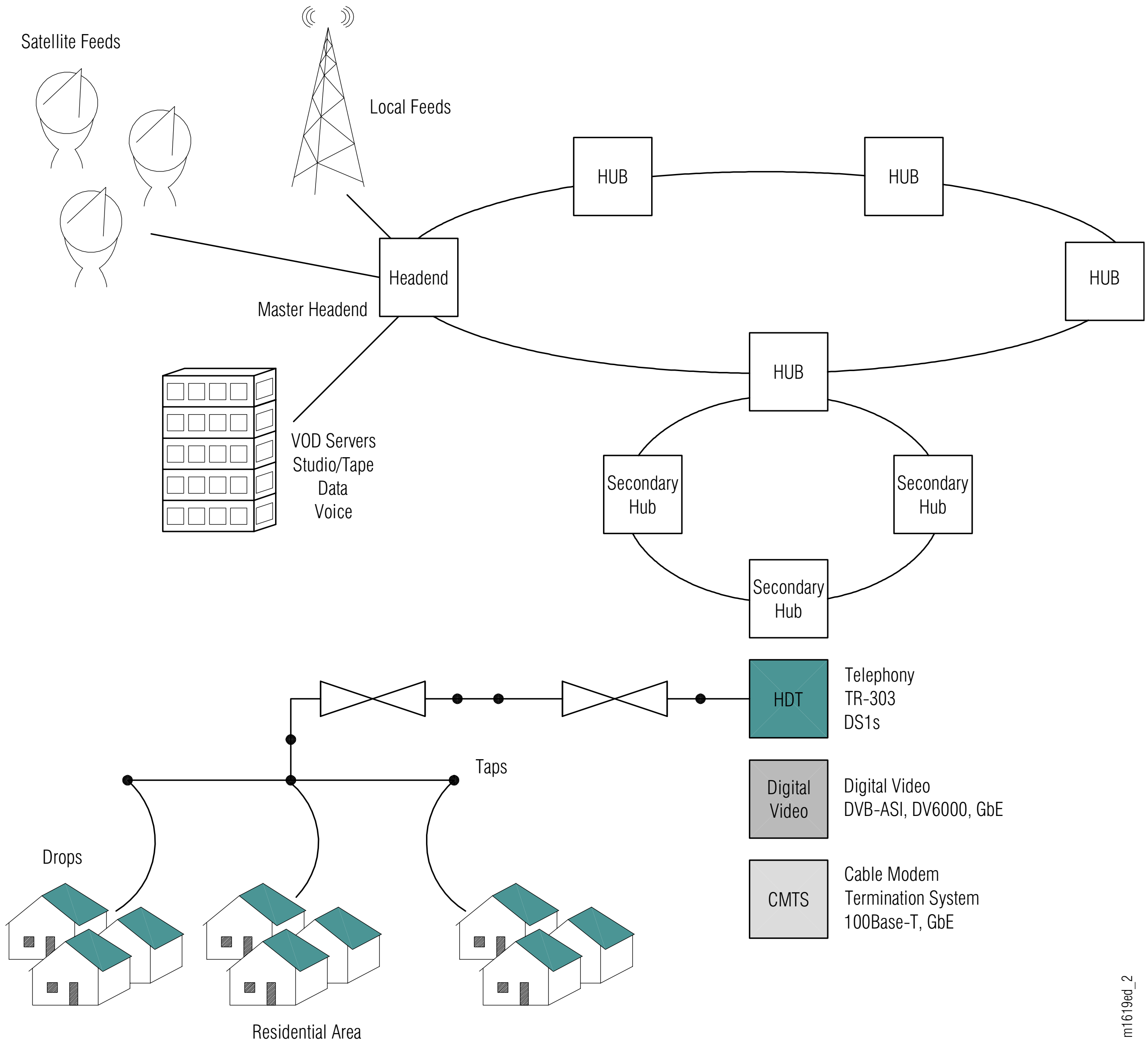
The system consists of an Optical Add/Drop Multiplexer (OADM) or core shelf, which houses the management units of the system, and the Optical Line Card (OLC) or tributary shelves for service offering units. Each OLC shelf can support up to a maximum of sixteen Low Speed OLC units or eight High Speed OLC units or a mixture of both. Up to ten OLC shelves can be managed with one OADM shelf. An optional Lambda Access Shelf (LAS) is available for ease of fiber management between switch fabric and OLC units.

Topologies

Signal transport is available in the following topologies:

- Point-to-point
- Linear add/drop (open ring)
- OUPSR
- Mesh network architectures

Figure 6-4: Multiservice Operations Applications



Multiservice Operations

Multiservice Operations (MSO), shown in Figure 6-4, provide varied services to residential customers. These services include:

- Video
- Voice
- Data
- Other Services

Video

Their networks provide many kinds of broadcast video delivery systems. The transport of video is very important to MSO operators and is the priority business of the network. The most common digital video transport techniques are:

- DVB-ASI Compressed Video at 270 Mb/s
- Digital Video (SMPTE 259M) at 270 Mb/s
- Video over GbE at 1.250 Gb/s
- DV6000® at 2.380 Gb/s

MSO Video applications are described in the following paragraphs.

Broadcast TV Programming

A combination of off-the-air broadcasts and satellite delivered broadcasts that are assembled at the MSO head-end facility and then transported to nodes for delivery to residences.

Video on Demand

Video on Demand (VOD) is a for-fee service that allows a wide selection of features that are chosen by the residential subscriber:

- The user has to ability to select and control (fast forward, pause, and start) content. Content examples are movies or other special programs.
- Bandwidth (BW) requirements are bursty, since BW is only required when a user requests content.

Near Video on Demand

Near Video on Demand (NVOD) is a for-fee delivery service that is provided at intervals and cannot be controlled after delivery begins by the residential subscriber:

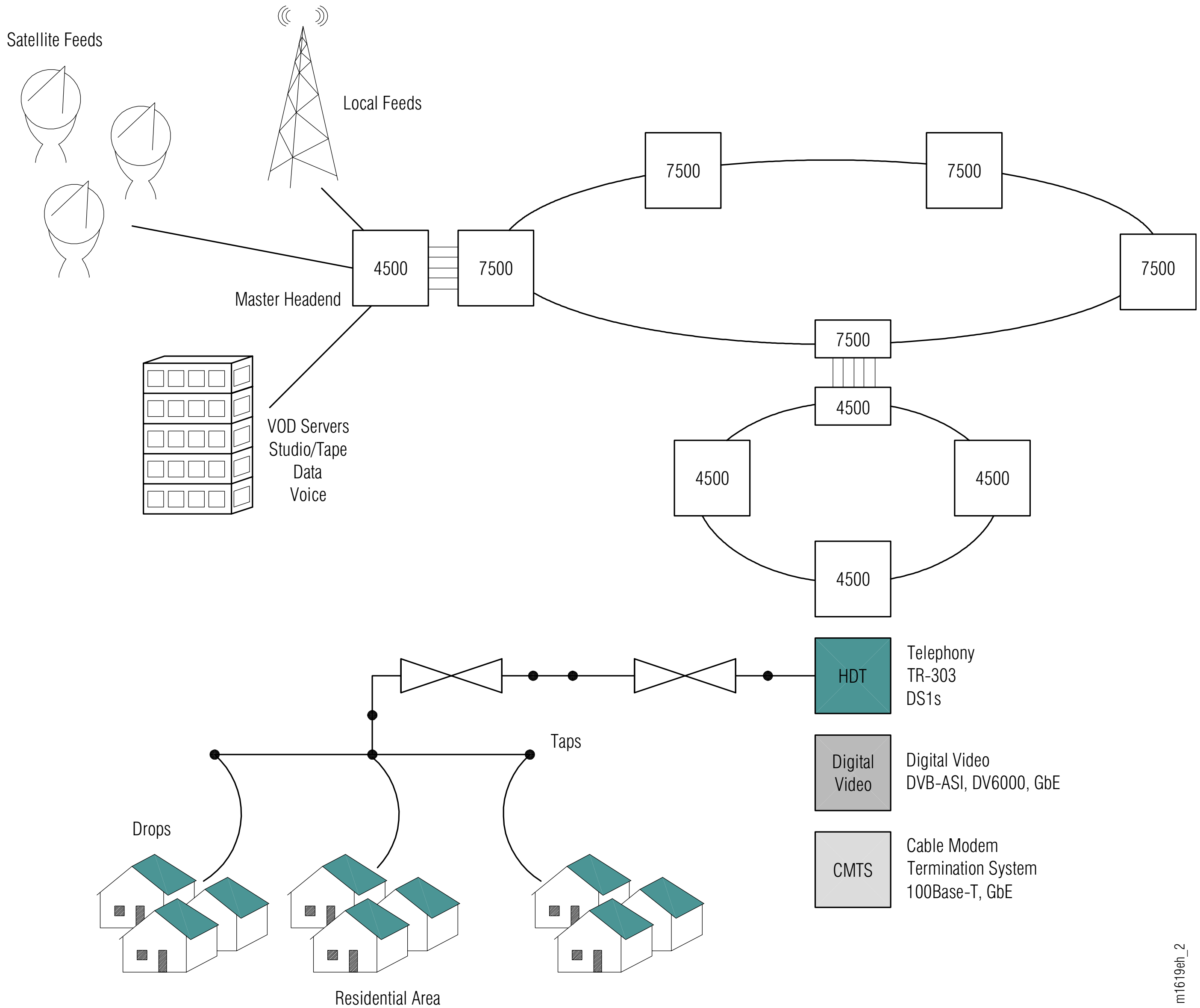
- The operator will broadcast popular movies in close intervals on multiple channels. The user has no control over the pausing or reviewing of the movie. Since the movies are broadcast on different channels in 30 minute intervals the user will only have to wait 30 minutes before they can begin viewing.
- Bandwidth requirements will be consistent since all movies are broadcast at the same time.

Subscription Video on Demand

Subscription Video on Demand (SVOD) programs are selected in advance by the residential subscriber, on an event basis. Typically SVOD is:

- Similar to VOD, the user selects specialty programming to view, for example, concerts, sporting events, or other special interest programs.
- Bandwidth requirements will be bursty, because BW is only required when a user requests content.

Figure 6-5: MSO Network Solution



Voice

The MSO seeks to deliver voice services to the residential subscriber in competition with the Local Exchange Carrier (LEC). The two techniques in use are described in the following paragraphs.

Switched Telephony

Sometimes called Plain Old Telephone Service (POTS), switched telephony is the traditional copper-based public switched telephone network (PSTN). Devices are employed that convert the DS0 voice signals to data and transport these signals as conventional PSTN signals to the LEC for transport throughout the PSTN.

Voice Over IP Services

Voice over Internet Protocol (VoIP) provides economical delivery of many voice channels over SONET devices, such as the FLASHWAVE 4500 as subtending network devices at each residential node, with the FLASHWAVE 7500 providing transport of the FLASHWAVE 4500 network links to conserve fiber bandwidth requirements. At the MSO head end the operator provides interface equipment that converts the VoIP signals back to switched telephony for delivery to the LEC for PSTN transport.

In some cases, the VoIP can be used to bypass the LEC for long-distance dial (LDD) services, providing a cost-savings to the residential subscriber that optimizes the value-add to that subscriber for using MSO services.

Data

Internet services have become a significant business for the MSO. Transport of residential subscriber Internet and other public communications data requirements is provided by use of routers placed in the subscriber nodes, that communicate to the headend over FLASHWAVE 7500 and/or FLASHWAVE 4500 facilities.

Other Services

In addition to residential subscribers, many MSO operators have facilities that pass by businesses. This feature makes the MSO an ideal solution for reduced cost communications facilities for business customers. Some typical applications include:

- Voice—Provision of services at a lower cost than the RBOC, especially for circuits that go to a second business facility on the MSO network
- Video Conference—Services for transport of conference-style video for employee training
- Data—All data services may be provided by the MSO

FLASHWAVE 7500 Solution

The network layout for the MSO network solution shown in Figure 6-5, provides a sample application that utilizes the FLASHWAVE 7500 and FLASHWAVE 4500 in the MSO environment.

Lesson 7

DWDM Acronyms

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

Table 1: DWDM Acronyms

Acronym	Description/Explanation
1R	regenerator that reamplifies optical signal
2R	regenerator that reamplify and reshape
3R	regenerator that reamplify, reshape, and retime
4WM	four-wave mixing (also called FWM) (impairment)
APD	avalanche photodiodes
ATM	Asynchronous Transfer Mode
AWG	arrayed waveguide
BER	bit error rate
BG	Bragg grating
C-band	optical band from 1530 to 1570 nanometers long
CS-RZ	carrier suppressed-return to zero
CWDM	course wavelength division multiplex/multiplexing
dB	decibel (a unit for expressing the ratio of two amounts of electric or acoustic signal power equal to 10 times the common logarithm of this ratio)
dBm	decibel per milliwatt (power ratio referenced to 1 milliwatt)
DCF	dispersion compensation fiber
DCM	dispersion compensation module (lumped dispersion)
DCN	data communications network
DS	dispersion shifted

Table 1: DWDM Acronyms (Continued)

Acronym	Description/Explanation
DSF	dispersion-shifted fiber
DWDM	dense wavelength division multiplex/multiplexing
EDFA	erbium-doped fiber amplifier
EDTFA	tellurite-based EDFA (Tellurium is the source rare-earth element.)
ELEAF	Corning Expanded Large Effective Area Fiber (NZ-DSF)
ESD	electrostatic discharge
FEC	forward error correction
FNC	Fujitsu Network Communications, Inc.
FWM	four-wave mixing (also called 4WM) (impairment)
Gb/s	gigabits per second
GHz	gigahertz
GW	symbol for gigawatt (one billion watts)
GS-EDFA	gain-shifted erbium-doped fiber amplifier
GUI	graphical user interface
ILA	intermediate line amplifier
IP	Internet Protocol
ISO	International Organization of Standards
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
LAN	local area network

Table 1: DWDM Acronyms (Continued)

Acronym	Description/Explanation
L-band	Optical band from 1570 to 1625 nanometers long
LEAF	Corning Large Effective Area Fiber (NZ-DSF)
LS	Corning NZ-DSF
MAC	media access control
MB/s	megabits per second
MMF	multimode fiber
mW	symbol for milliwatt power measurement
NDSF	non–dispersion-sifted fiber
NE	network element
NF	noise figure
nm	nanometer (unit of wavelength)
NRZ	non–return to zero coding
NVM	nonvolatile memory
NZ-DSF	non–zero dispersion-shifted fiber (offset from zero point)
OADM	optical add/drop multiplexer
OC	optical channel
OOB-FEC	out-of-band forward error control
OSI	Open Systems Interconnection (standard set of protocols)
OSNR	optical signal-to-noise ratio
OXC	optical cross-connect
PIN	simple photodiode

Table 1: DWDM Acronyms (Continued)

Acronym	Description/Explanation
PMD	polarization mode dispersion
PMDC	polarization mode dispersion compensator
ps	picosecond(s)
ps/nm	picosecond(s) per nanometer
Q-factor	measure of noise in a pulse
RAM	random access memory
RFA	Raman fiber amplifier
ROM	read-only memory
RZ	return-to-zero (coding)
S-band	optical band from 1450 to 1500 nanometers
SBS	Stimulated Brillouin scattering (impairment)
SDCC	section data communications channel
SMF	single-mode fiber
SMF-28	Corning SMF
SNR	signal-to-noise ratio
SOA	silicon optical amplifier
SONET	Synchronous Optical Network
SPM	self-phase modulation (impairment)
SRS	stimulated Raman scattering (impairment)
SSMF	standard SMF
Tb/s	terabits per second

Table 1: DWDM Acronyms (Continued)

Acronym	Description/Explanation
TCP	Transmission Control Protocol
TDFA	thallium-doped fluoride-based amplifier
TDM	time-division multiplex/multiplexing/multiplexer
TeraLight	Alcatel NZ-DSF
TFF	thin-film filter
TIB	Technical Information Bulletin
TrueWave Classic	Lucent non–zero dispersion-shifted fiber with offset
TrueWave Plus	Lucent non–zero dispersion-shifted fiber with offset
TrueWave RS	Lucent non–zero dispersion-shifted fiber with reduced slope
VIPA	virtual IP address (routers)
VIPA	virtual image phase array (compensator for dispersion)
VoIP	Voice-over-Internet Protocol
W	watt (symbol for watt power measurement)
WDM	wavelength division multiplex/multiplexing/multiplexer
XPM	cross-phase/modulation (impairment)

Lesson 8

DWDM Terms

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

Table 1: DWDM Terms

Term	Description/Explanation
chirp	Range of +1GHz to –1GHz that a laser frequency/wavelength when keyed or the rise/fall time delta of the laser pulse shifts
duobinary	Method of coding with three states
electron	Negatively charged sub-atomic particle
in-band FEC	Forward error correction carried in SONET overhead bits
lambda	Symbol for wavelength of optical signal
photon	Massless particle of light
power budget	Power needed to travel a specified distance
preemphasis	Technique to compensate for fiber or transmission impairments
Raman	Optical scattering that occurs in silicon atoms
Raman amp	Amplifier that capitalizes on Raman scattering to gain distance
velocity factor	The propagation delay in an optical fiber is based on the velocity factor of 67% of the speed of light.

Lesson 9

End of Course Evaluation

FLASHWAVE™

FUJITSU

THE POSSIBILITIES ARE INFINITE

End of Course Evaluation

If you complete the DWDM Self Evaluation and get fewer than 12 answers are correct, you should review and retake the Self-Evaluation until you do reach 12 or more right answers. The answers to the Self-Evaluation follow the questions, and contain links to the material in your self-study Tutorial.

DWDM Self-Evaluation

Circle the letter of your choice and then compare your answers on the "Self-Evaluation Sheet (Electronic)" on page 41.

1. Which statement is true?

   (A) DWDM systems cost more than installing more fibers.

   (B) DWDM systems cannot carry multiservice traffic.

   (C) DWDM systems are not used in SONET environments.

   (D) DWDM systems cost a fraction of added fibers.

2. The five components of a DWDM network include transmitter, receiver, optical amplifier, ___________________.

   (A) multiplexer/demultiplexer and optical fiber

   (B) SONET, voice-over-Internet Protocol, and dispersion

   (C) All of the above

   (D) None of the above

3. The terms retime, reamplify, and reshape describe ____ regenerators.

   (A) 1R

   (B) 2R

   (C) 3R

   (D) None of the above

4. You ________ see the light used in fiber-optic transmission.
   (A) can always
   (B) cannot
   (C) look through 3-D glasses to
   (D) none of the above

5. Signal bandwidth for 10-Gb/s signals is _____ gigahertz (GHz).
   (A) 20
   (B) 40
   (C) 10
   (D) 5

6. ____ FEC provides approximately _________ system gain.
   (A) In-band, 9 dB
   (B) Out-of-band, 6 dB
   (C) All of the above
   (D) None of the above

7. Laser chirp is ________________________________.
   (A) not allowed in FNC equipment
   (B) typically occurs between –1 GHz and +1 GHz
   (C) offered by different companies
   (D) none of the above

8. OSNR stands for optical ________.
   (A) signal–no return
   (B) signal-to-noise ratio
   (C) system–network ready
   (D) signal–network ready

9 Conventional DWDM usually uses the ____.

(A) C-band

(B) X-band

(C) L-band

(D) S-band

10 RAMAN amplifiers are ________________ than EDFA.

(A) more efficient

(B) less efficient

(C) more expensive

(D) less expensive

11 ____________ dispersion causes _____________.

(A) Polarization mode, signal failure

(B) Chromatic, flattening and widening of the signal

(C) Chromatic, polarization mode

(D) None of the above

12 ______________ is caused by looking at the invisible laser light coming out of a fiber.

(A) Eye damage

(B) Blindness

(C) Impotence/infertility

(D) All of the above

Self-Evaluation Sheet (Electronic)

If you get fewer than 8 correct, FNC recommends that you review using the hyperlinks in the Lookup Answer column. If you are using this tutorial on paper, go to the Lookup Answer page to find the information.

Table 1: Answers

Question	Correct Answer	Look Up Answer
1	D	See “Service Provider Advantages” on page 7.
2	A	See “Optical Network” on page 5.
3	C	See “Amplifiers and Regeneration” on page 11.
4	B	See “” on page 2.
5	A	See “Signal Bandwidth and Filtering” on page 7.
6	B	See “Out-of-Band FEC” on page 15.
7	B	See “Chirp” on page 30.
8	B	See “Optical Signal-to-Noise Ratio” on page 17.
9	A	See “Fiber Bands” on page 19.
10	B	See “Raman Amplifiers” on page 21.
11	D	See “Fiber Dispersion” on page 25.
12	A	See “Lasers as the Signal Source” on page 9.