Prerequisite Training

November 15, 2002

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Purpose

This tutorial provides prerequisite information about dense wavelength division multiplexing (DWDM) systems. Since DWDM systems are derived from wavelength division multiplexing (WDM) systems, and recently the introduction of coarse wavelength division multiplexing (CWDM) systems each of these similar technologies will be discussed and inter related to DWDM. This material is applicable to all DWDM courses offered by Fujitsu Network Communications, Inc. (FNC). A list of acronyms used in this tutorial is in Table 2, and Table 3 provides DWDM terminology.

Objectives

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

- Understand basic DWDM theory and operational concepts
- Describe functions of the major components used in DWDM
- Describe DWDM limitations

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.

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 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.

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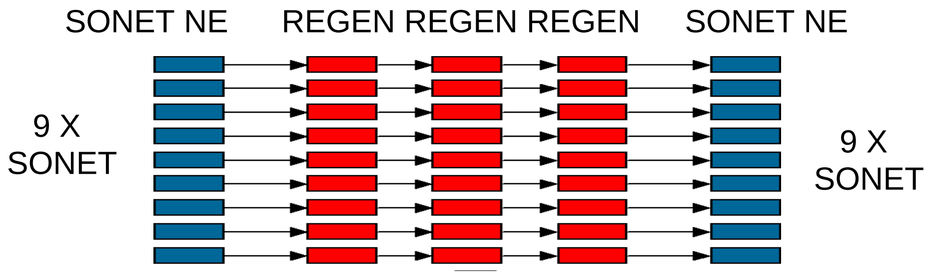

Figure 1: Discrete Channels

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.

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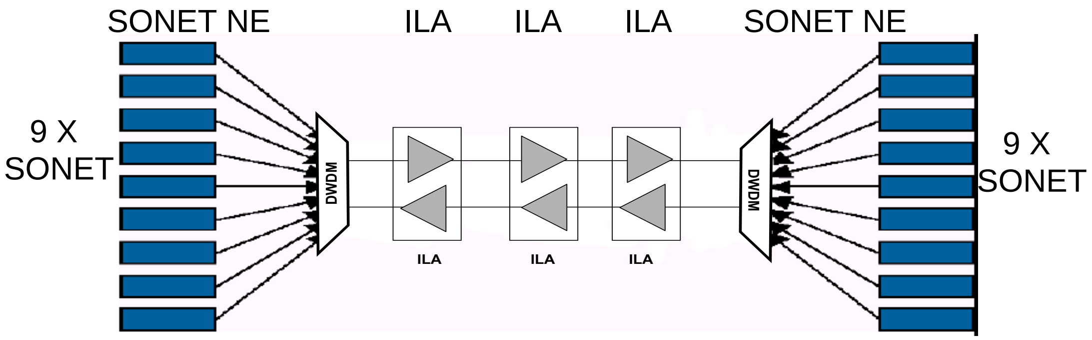

Figure 2: DWDM Transport

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[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.

Service Provider Advantages

The service provider uses an existing installed fiber plant more effectively by incorporating DWDM systems. Comparing Figure 1 to Figure 2, 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 1, the distances require three regenerator sites for traditional SONET traffic. In Figure 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. Thereby enabling faster speed to market of multiservice traffic offerings at a lower cost for new services to be transported over the DWDM system.

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 (FDM), time division (TDM), and wavelength division (WDM), with TDM and WDM being widely utilized by telephone and data service providers over optical circuits.

Time Division Multiplexing

Time-division multiplexing (TDM), as represented in Figure 3, 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.

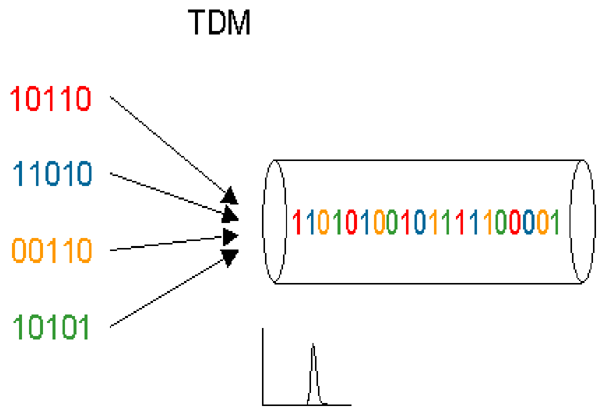


Figure 3: Time Division Multiplexing

Wavelength Division Multiplexing

WDM combines multiple optical TDM data streams onto one fiber through the use of multiple wavelengths of light. Each individual TDM data stream is sent over an individual laser transmitting a unique wavelength of light.

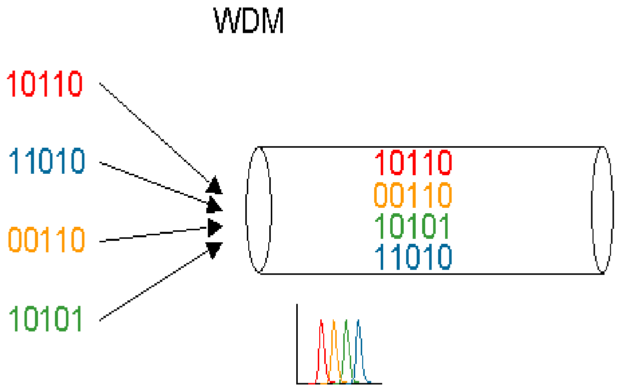


Figure 4: Wavelength Division Multiplexing

Varieties of WDM

Early WDM systems transported two or four wavelengths that were widely spaced. WDM and the “follow-on” technologies of CWDM and 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 km.

CWDM

Today, coarse WDM (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 km 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

Dense WDM common spacing may be 200, 100, 50, or 25 GHz with channel count reaching up to 128 or more channels at distances of several thousand kilometers with amplification and regeneration along such a route.

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 5 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)

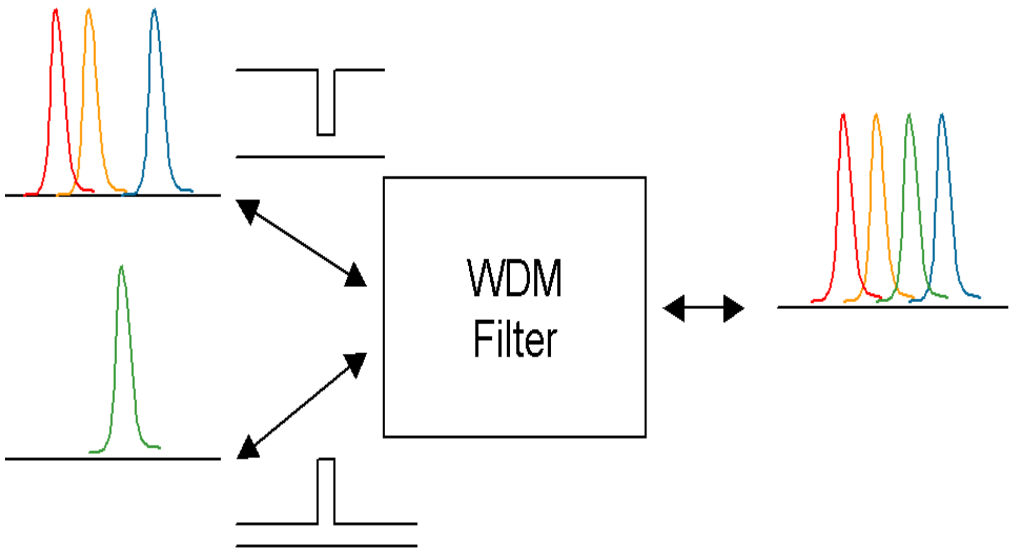


Figure 5: WDM Filters

Thin-Film Filter

The thin-film filter (TFF) is a device used in some optical networks to multiplex and demultiplex optical signals. The TFFs are devices that use many ultrathin layers of dielectric material coating deposited on a glass or polymer substrate. This substrate can be made to let only photons of a specific wavelength pass through, while all others are reflected. By integrating several of these components, you can then demultiplex several wavelengths. Figure 6 shows what happens with four wavelengths.

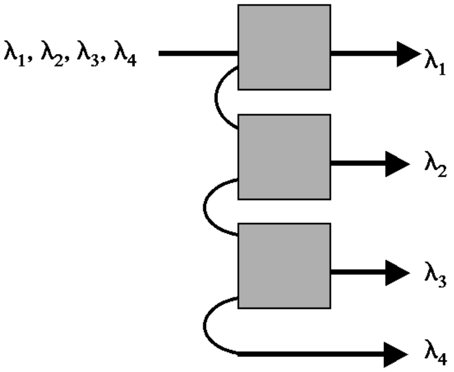


Figure 6: Thin-Film Filter Concept

The first TFF section passes wavelength 1 and reflects 2, 3 and 4 to the second, which then passes 2 and reflects 3 and 4. This allows for demultiplexing or multiplexing of optical signals.

Fiber Bragg Gratings

A Bragg Grating is made of a small section of fiber that has been modified by exposure to ultraviolet radiation to create periodic changes in the refractive index of the fiber. The result, shown in Figure 7, is that light traveling through the Bragg Grating is refracted and then reflected back slightly, usually occurring at one particular wavelength.

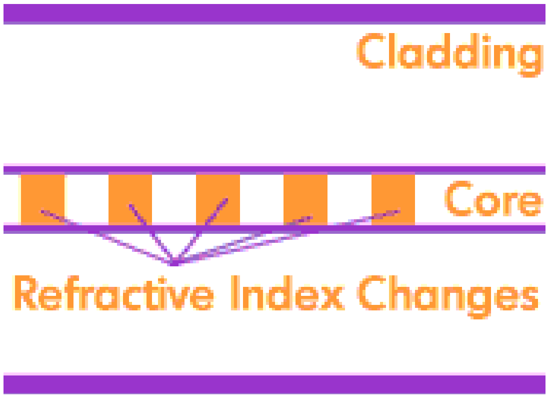


Figure 7: Fiber Bragg Grating

The reflected wavelength, known as the Bragg resonance wavelength, depends on the amount of refractive index change that has been applied to the Bragg grating fiber and this also depends on how distantly spaced these changes to refraction are.

Arrayed Waveguides

In the transmit direction, the AWG mixes individual wavelengths, also called lambdas (λ) from different lines etched into the AWG substrate (the base material that supports the waveguides) into one etched line called the output waveguide, thereby acting as a multiplexer. In the opposite direction, the AWG can demultiplex the composite λs onto individual etched lines. Usually one AWG is for transmit and a second one is for receive. Figure 8 illustrates the demultiplexing direction or receive.

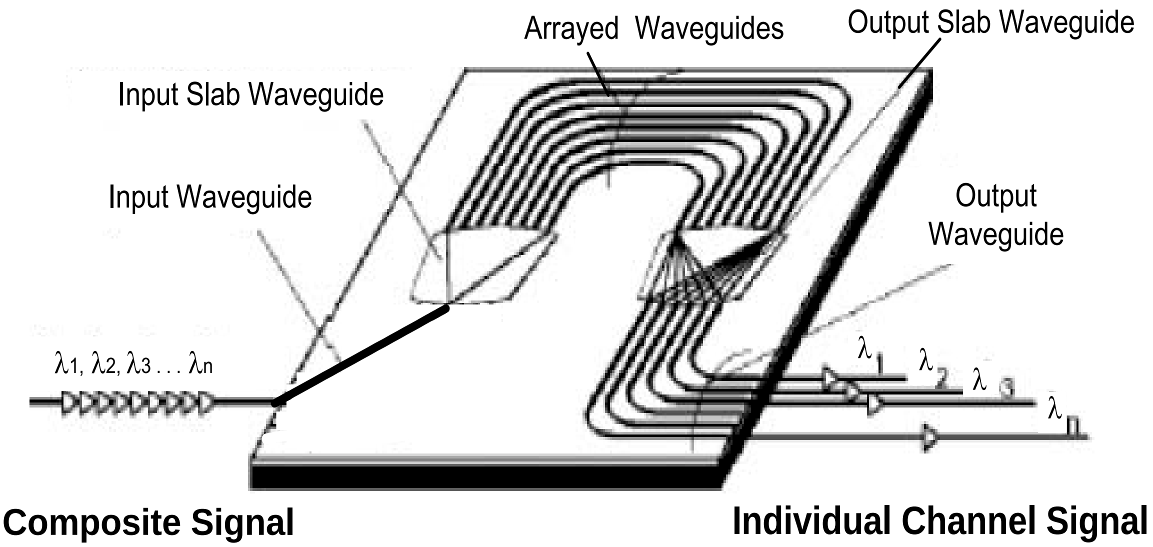


Figure 8: Arrayed Waveguide (Demultiplexer)

The AWG can replace multiple Bragg Gratings, each Bragg Grating only supports one wavelength and occupies the same physical space as an 8-λ AWG. Multiple Bragg Gratings also cost more than a single AWG.

For some applications, AWG offers a higher channel capacity at a lower cost per channel with a smaller footprint. This results in fewer components and provides for component integration (e.g., switching, variable optical attenuator).

Periodic Filters, Frequency Slicers, Interleavers

Figure 9 illustrates that periodic filters, frequency slicers, and interleavers are devices that can share the same functions and are usually used together. Stage 1 is a kind of periodic filter, an AWG. Stage 2 is representative of a frequency slicer on its input, in this instance, another AWG; and an interleaver function on the output, provided by six Bragg gratings. Six λs are received at the input to the AWG, which then breaks the signal down into odd λ and even λ. The odd λs and even λs go to their respective stage 2 frequency slicers and then are delivered by the interleaver in the form of six discrete interference-free optical channels for end customer use.

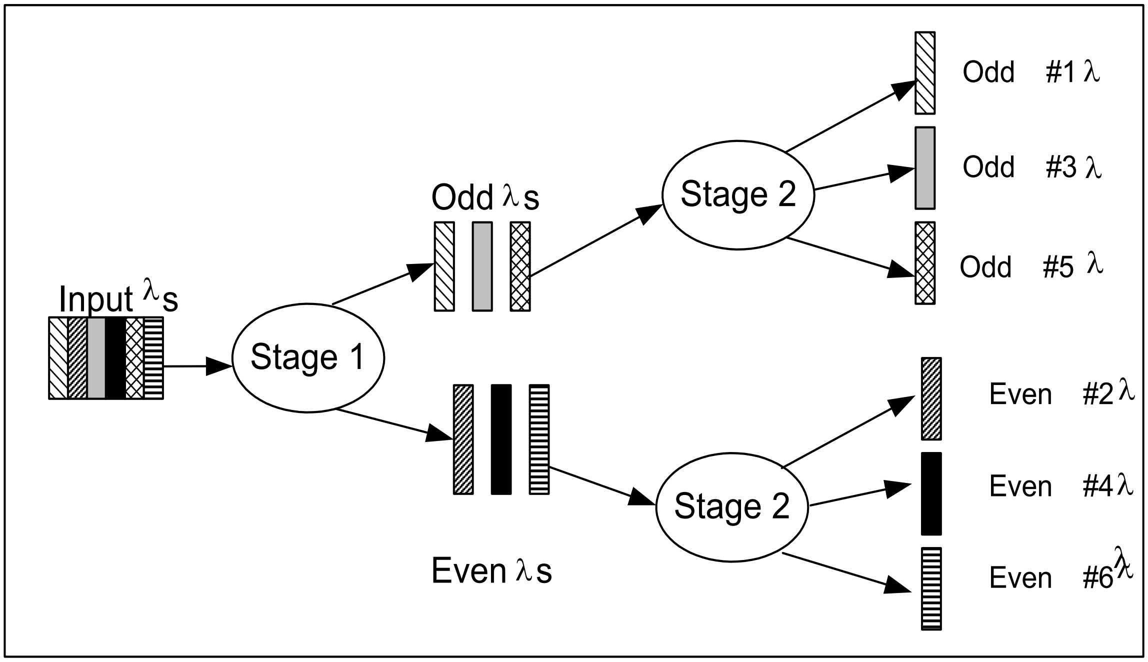


Figure 9: Combined Devices

By splitting a DWDM spectrum into multiple complementary sets of periodic spectra, the combined devices can create hierarchical suites of wavelengths for more complex wavelength routing and switching.

Optical Network

Figure 10 shows an optical network using DWDM techniques that consists of five main components:

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:
   - Pre-amplifier boosts signal pulses at the receive side
   - Post-amplifier boosts signal pulses at the transmit side (post amplifier) 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

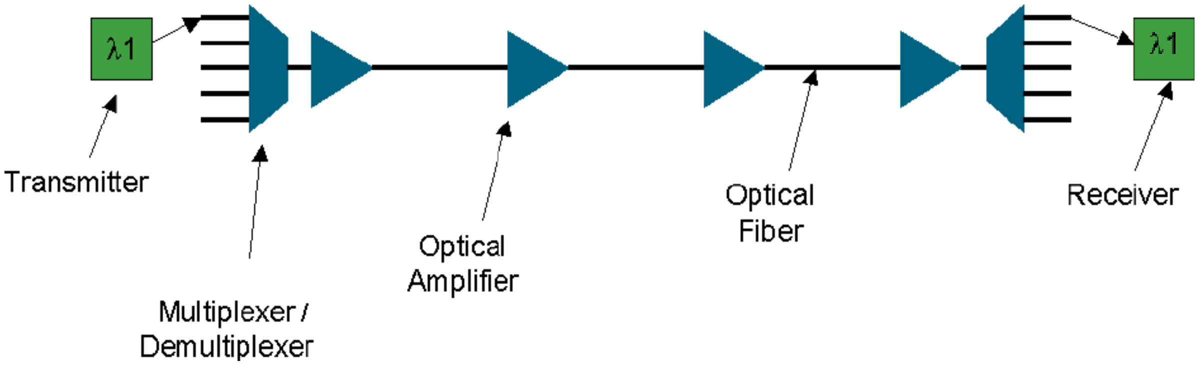


Figure 10: Optical Network Drawing

Tunable Laser

Figure 11 shows one method of transmission, the tunable laser.

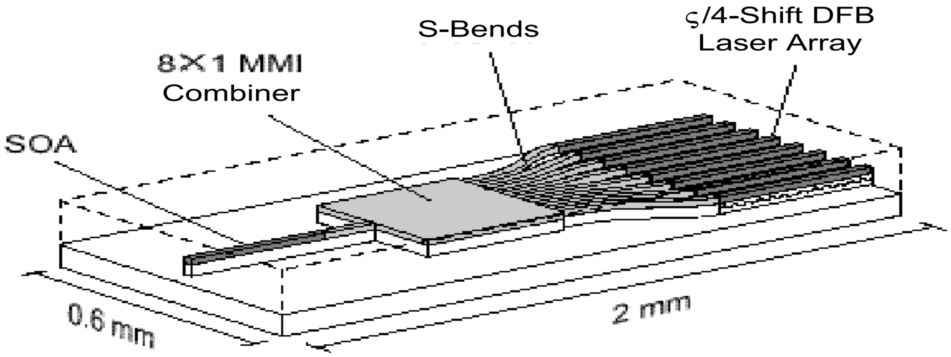


Figure 11: Tunable Laser

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.

Lasers as the Signal Source

Transmitters use lasers as the signal source shown in Figure 12. 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.

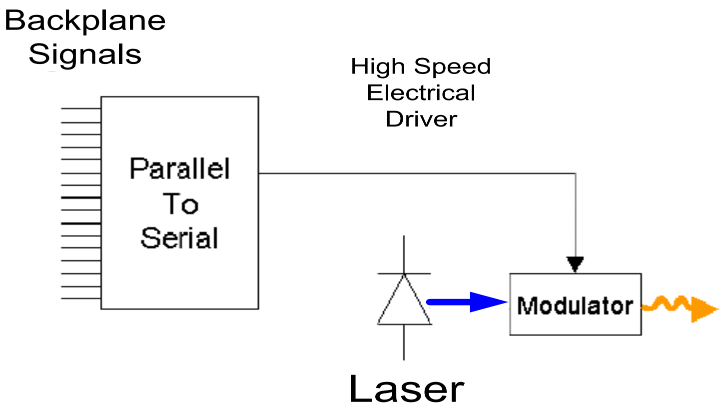


Figure 12: Laser Signal Sources

Amplifiers and Regeneration

Amplifiers are defined as type 1R, 2R, or 3R.

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

Figure 13 illustrates the effect on a degraded optical signal once it has been 1R, 2R, or 3R regenerated.

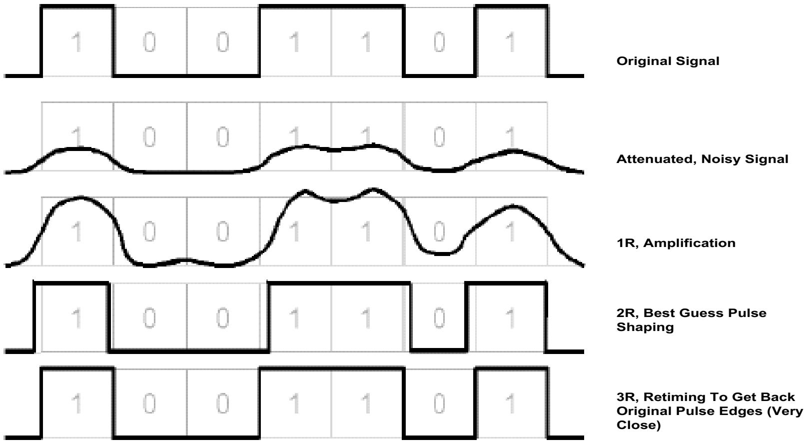


Figure 13: Regeneration

Network Routes and Regeneration

Figure 14 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.

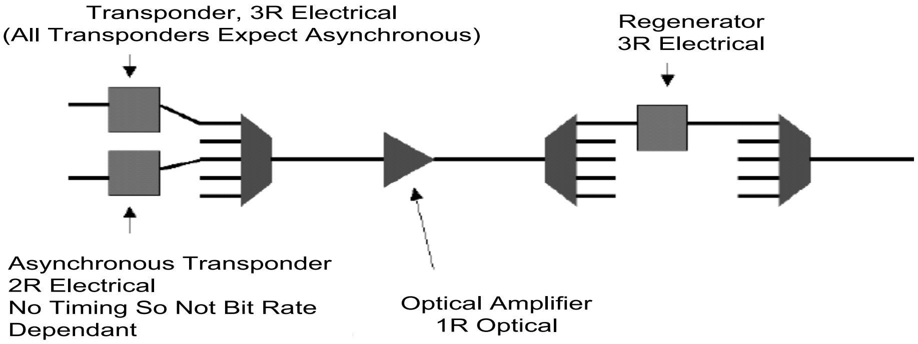


Figure 14: Network Regeneration

Erbium-Doped Fiber Amplifiers

Erbium-doped fiber amplifiers (EDFAs) provide the gain mechanism for DWDM amplification, depicted in Figure 15. 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.

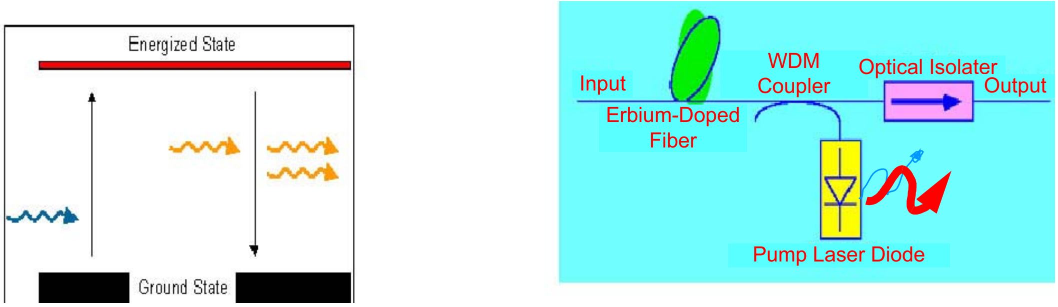


Figure 15: EDFA

The EDFA Amplifier

Figure 16 shows an erbium-doped fiber amplifier (EDFA) and is the last active component in the DWDM system on the transmit side (post amplifier). On the receive side, the preamplifier (a receive EDFA) is the first active component.

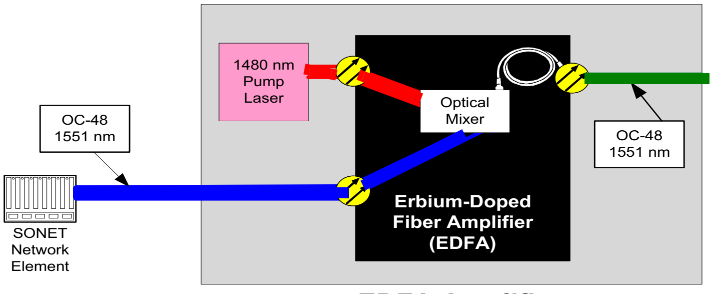


Figure 16: EDFA Amplifier

Fiber Bands

Three optical frequency bands are used today for fiber-optic DWDM networks. Figure 17 highlights C- and L-band, which are considered the most useful. The bands are:

- C-band (conventional) has a range from 1530 nm to 1570 nm.
- 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- and L-band amplifiers are required because EDFA must be optimized for either C-band or L-band amplification.

- 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.

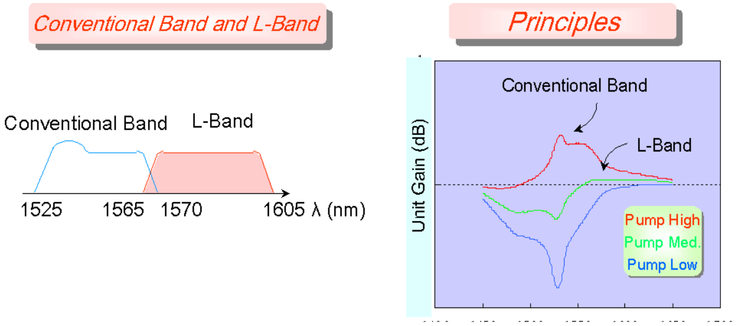


Figure 17: Fiber Bands and Amplifiers

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.

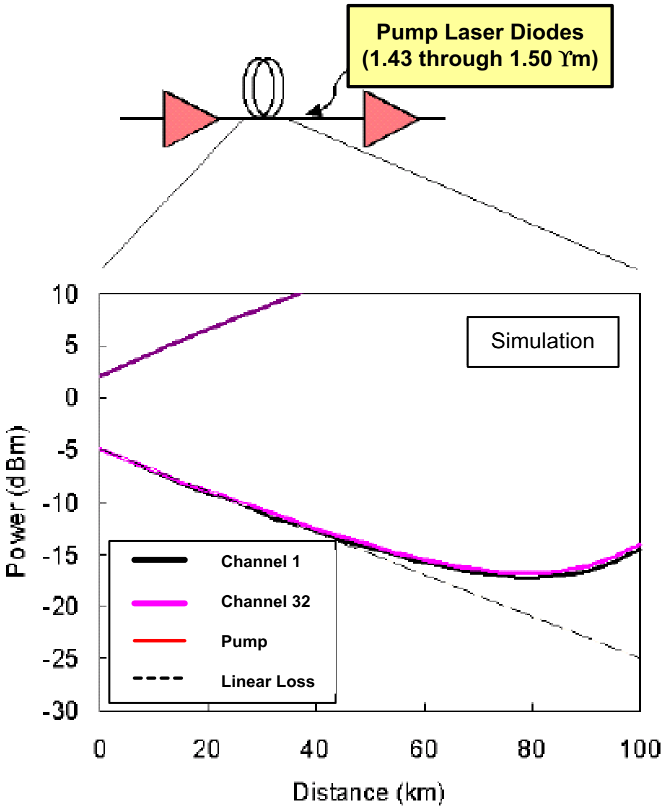
Raman Amplifiers

Originally Raman scattering was considered to be an impairment to fiber performance. However, recent discoveries have resulted in hybrid networks that use Raman amplification to obtain greater distance performance. Characteristics 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-, L-, and S-bands

Distributed Raman

Raman amplifiers, as shown in Figure 18, are coming into general use to accomplish operation over longer spans with fewer regeneration sites.



Raman Amplification

Distributed Amplification In Transmission Fibers

Reduced Effective Span Loss

OSNR Improvement

Figure 18: Distributed Raman Amplifiers

Other Optical Amplifiers

Silicon optical amplifiers (SOAs) are shown in Figure 19. These include rare-earth elements to make rare-earth-doped fibers into optical amplifiers such as:

- Tellurium (a compound of Tellurite and Oxygen [TeO_2])
- Thulium (commonly a compound of Thulium and Fluoride [TmF_3])

Most amplifiers are still experimental and include:

- EDFA: Erbium-doped fiber amplifier (1530–1565 nm)
- GS-EDFA: Gain-shifted EDFA (1570–1610 nm)
- EDTFA: Tellurium-based gain-shifted TDFA (1530–1610 nm)
- GS-TDFA: Gain-shifted thulium-doped fiber amplifier (1490–1530 nm)
- TDFA: Thulium-doped fluoride-based fiber amplifier (1450–1490 nm)
- RFA: Raman fiber amplifier (1420–1620 nm or more)

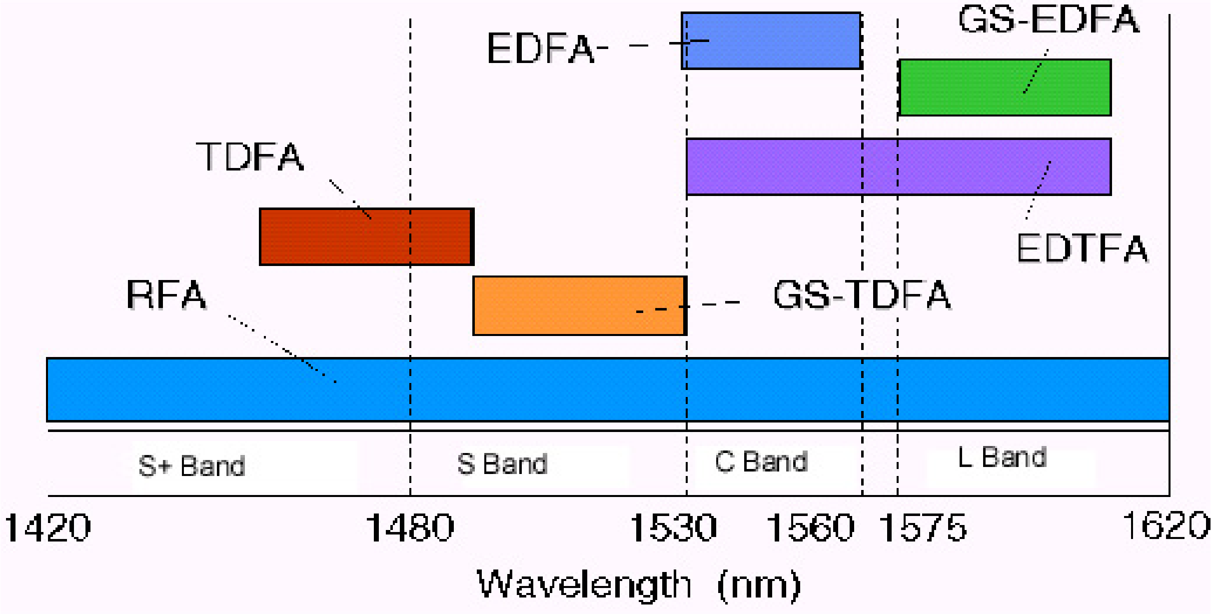


Figure 19: Optical Amplifiers

Optical Network Considerations

Optical fiber transmission using DWDM typically occurs at 1500 nm wavelengths. The DWDM system transmission shown in Figure 20 operates in the 1500 nm range due to performance effect, component cost, and the availability of optical amplifiers.

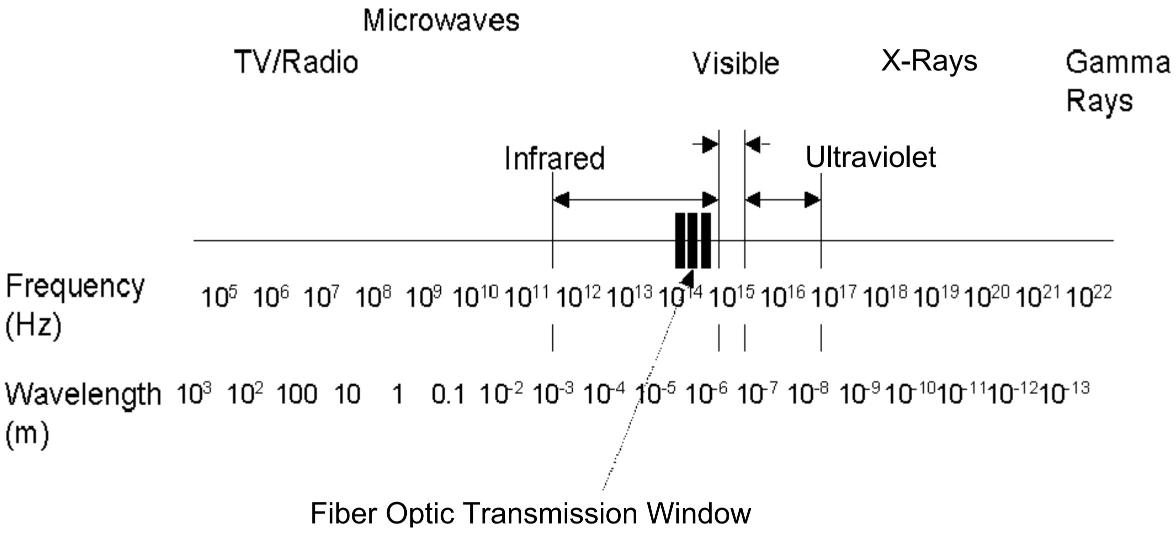


Figure 20: Optical Network Spectrum

Signal Bandwidth and Filtering

Figure 21 shows how signal bandwidth requirements change with data rate. Figure 21 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. NRZ and RZ coding are discussed later in this tutorial, see Figure 24 and Figure 25.

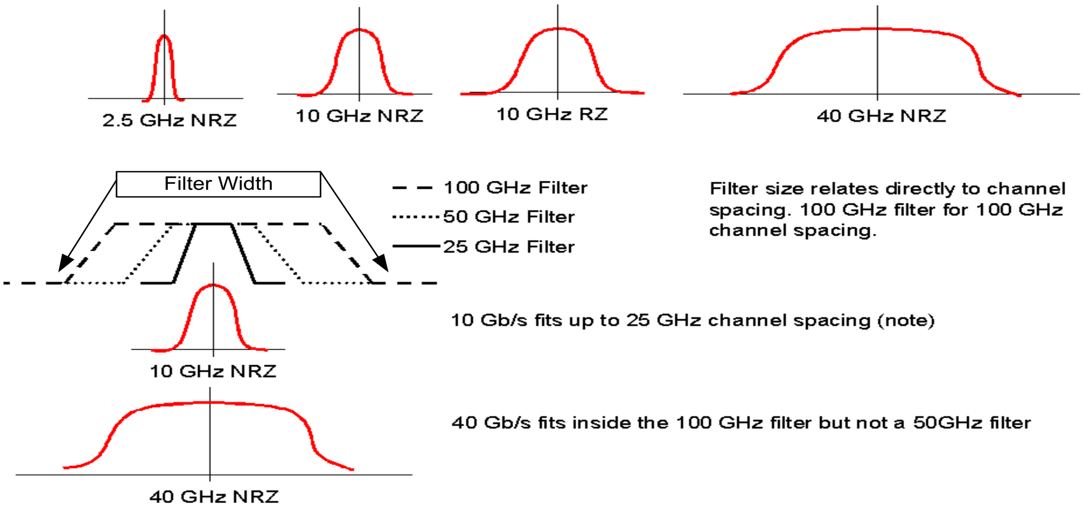


Figure 21: Signal Bandwidth

ITU-T Grid

The International Telecommunications Union-Telecommunications 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.

Signal Power in the System

Figure 22 shows how the decibel (dB) is the ratio between two values. For example, output power in Watts (A) compared to input power in Watts (B) used to represent attenuation of a fiber related to the Common (base 10) logarithm value:

$$\text{Attenuation} \quad dB = Log\,10 \left(\frac{A}{B} \right)$$

Figure 22: dB ratio

A dBm is a specific measurement referenced to 10^{-3} watts or 1 milliwatt (mW). Figure 23 shows the calculation, where X is the measured power in watts, for laser output measured in dBm:

$$dBm = 10\log\left(\frac{X}{1mW} \right)$$

Figure 23: Reference Power

The use of $10_{\log}$ as a factor in calculations allows technical personnel to confirm the readings they obtain from optical dB meters. Customarily, turn-up and maintenance personnel do not use the calculation method, instead optimizing the time required for the process of turn-up by using optical dB meters.

Coding Types

The electrical signals that carry different kinds of information are encoded when converted to optical signals for transmission, and decoded at the optical receiver and then converted back to an electrical signal. These types include non-return to zero (NRZ), return to zero (RZ), optical duobinary and carrier-suppressed return-to-zero (CS-RZ).

Non-Return to Zero

Non-return to zero (NRZ) is a method of transmission where the signal does not return to zero between bits (Figure 24). NRZ has the following attributes:

- A 1 represents light signal present for a complete bit period.
- A 0 is no light for a complete bit period.
- NRZ is more tolerant to dispersion effects.

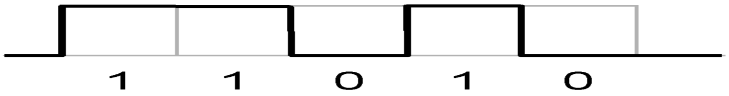


Figure 24: Non-Return to Zero

Return to Zero

Figure 25 shows return to zero (RZ), which is a method of transmission where the signal does return to zero between bits. RZ has the following attributes.

- A 1 results from the presence of light for one-half a bit period.
- A 0 is no light for a complete bit period.
- Less tolerant to dispersion, however, the effects of fiber loss are reduced.

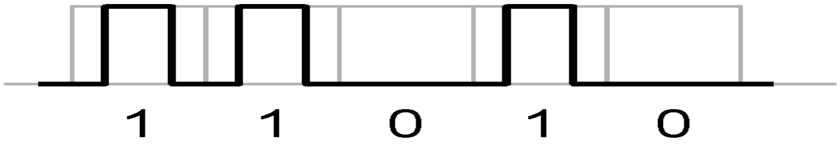


Figure 25: Return to Zero

Optical Duobinary

Optical Duobinary is a pseudo binary-coded signal as shown in Figure 26. This is a method of transmission where:

- The bit period is the same for all bits
- The 0 (zero) bit is represented by a one-half power level optical signal
- The 1 (one) bit is represented by:
  - A full power optical signal, if the quantity of 0 bits since the last 1 bit is even
  - By a 0 power level optical signal if the quantity of 0 bits since the last 1 bit is odd

Duobinary signals require less bandwidth than NRZ. Duobinary signaling also permits the detection of some errors without the addition of error-checking bits.

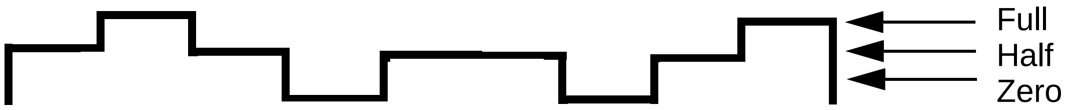


Figure 26: Optical Duobinary

Carrier Suppressed Return-to-Zero

Carrier-suppressed return-to-zero (CS-RZ) modulation has recently become commercially available. To increase the spectral efficiency maintaining good transmission performance, modified RZ formats with less spectral width and larger tolerance of optical power, such as CS-RZ, have been proposed for standardization to the Institute of Electrical and Electronics Engineers, Incorporated (IEEE).

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 27 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.

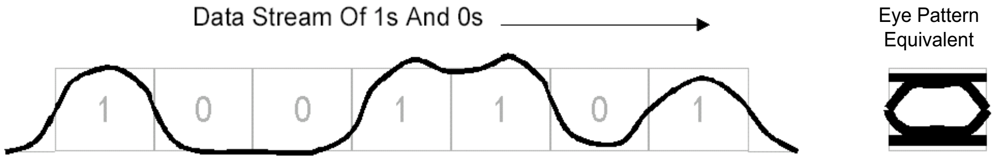
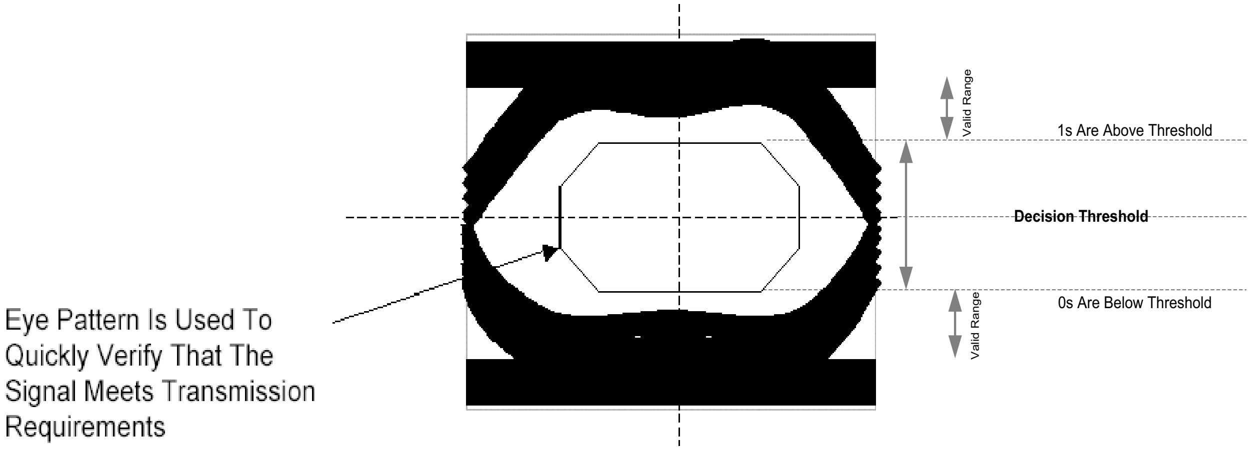


Figure 27: Eye Pattern vs. Data Stream

The eye pattern display in Figure 28 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 and 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.

Distortion of the signal waveform due to intersymbol interference and noise appears as closure of the eye pattern.



Eye Pattern Is Used To Quickly Verify That The Signal Meets Transmission Requirements

Figure 28: Eye Pattern Display

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 29). The FEC code bytes are used at the end of a transmitted frame by the receiving system to find and correct errors.

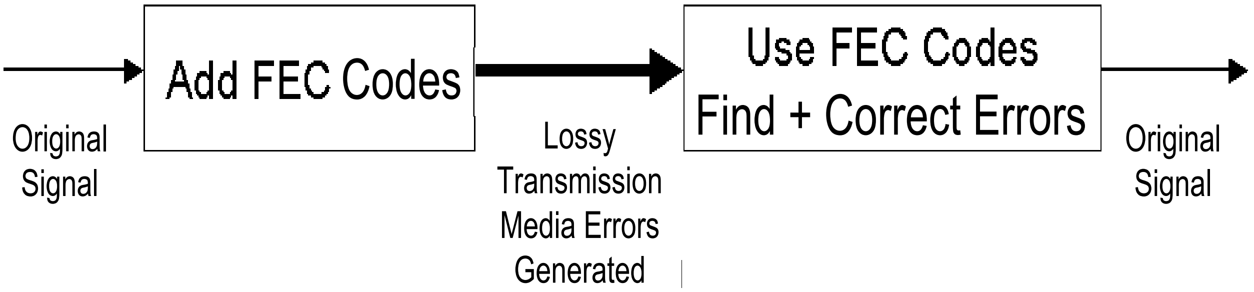


Figure 29: Forward Error Correction

Q-Factor

The Q-factor is a measure of how noisy a pulse is for diagnostic purposes. The eye pattern oscilloscope will typically generate a report that shows what the Q-factor number is as opposed to the “ideal” Q-factor, and is displayed in Figure 30. A larger number in the result means that the pulse is relatively free from noise. The arrows show the desired points that are the farthest apart. They show that the eye is open as much as possible and indicates that the data can recovered easily with low effects from noise.

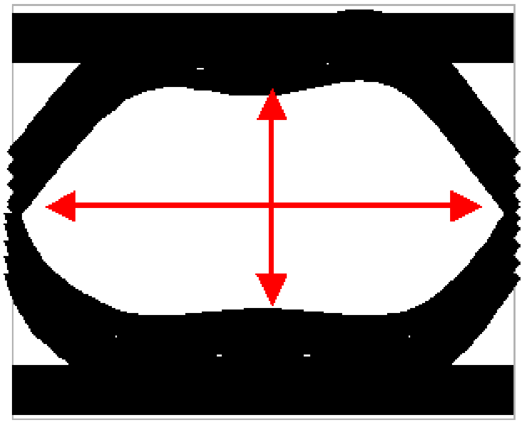


Figure 30: Q-Factor

Optical Signal-to-Noise Ratio

Figure 31, 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 = $10\log_{10}(P_s/P_n)$).

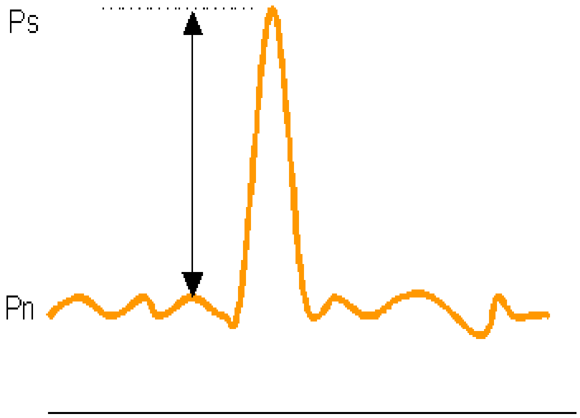


Figure 31: OSNR

Types of Forward Error Correction

The two main kinds of forward error correction (FEC) used in optical transmission are in-band and out-of-band. In-band is sometimes called “simple” FEC.

In-Band FEC

In-Band 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 29 is representative of In-band FEC.

Out-of-Band FEC

OOB-FEC is the type used for DWDM systems. FEC bytes are added on top of the signal to be carried (Figure 32). 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. OOB-FEC yields concurrent 5 x10^{-15} BER to 10^{-15} BER performance. 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”, rather it is an improvement in the OSNR. This can permit greater distance between ILA sites on the optical span

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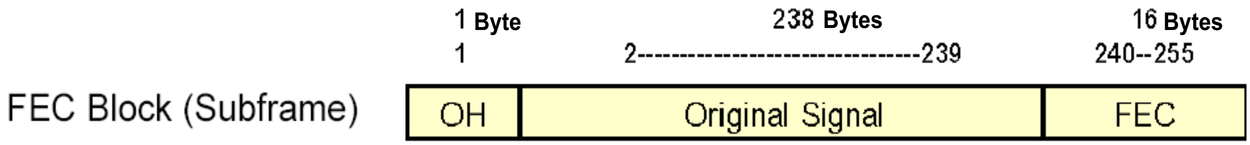

Figure 32: OOB-FEC Example

Receiver Parameters

Receivers use a photo diode to convert energy from photons (Figure 33) back to electrons.

- PIN photodiodes–Simplest and fastest
- Avalanche photodiodes (APDs)–Slower but more sensitive to light, better receiver

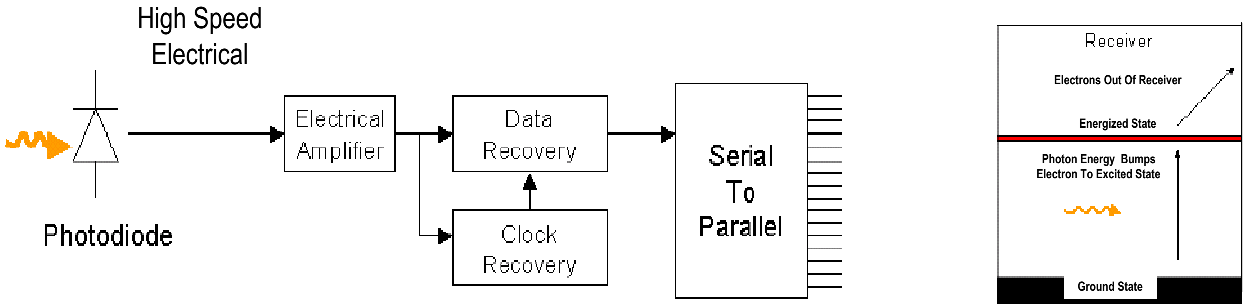

Figure 33: Receiver Parameters

Noise Figure

The noise figure shown in Figure 34 is the ratio of SNR in to SNR out. This calculation is used to assist in the design of the routes needed in a DWDM network. A calculator with 10Log function is best to use if it is necessary to make this calculation.

Noise Figure (Depending On Architecture)
Ideal 3 dB
Good 5-9 dB

Formula For OSNR Assuming Identical Fiber Spans

$$OSNR = P_{out} - L - NF - 10LogN - 10Log\left[h\nu\Delta\nu_0\right]$$

Pout	**Power Ouput Of Amplifier**
L	**Fiber Attenuation Per Span**
NF	**Amplifier Noise Figure**
N	**Number Of Spans**
Hv÷V_0	**Photonic Constants**

Figure 34: Noise Figure

Nonlinear OSNR Impairments

Impairments on the DWDM route cause changes in the Optical Signal-to-Noise Ratio that can be compensated for by proper use of preemphasis. Figure 35 shows the composite DWDM signal before the application of preemphasis. The transmit power levels (S) are flat, but the receive OSNRs (R) are not flat. To optimize optical signals for transmission, equalization is used to adjust the signal across the complete network, as shown in Figure 35. This is called preemphasis and adjusts transmit powers to optimize the receiver signal-to-noise ratios.

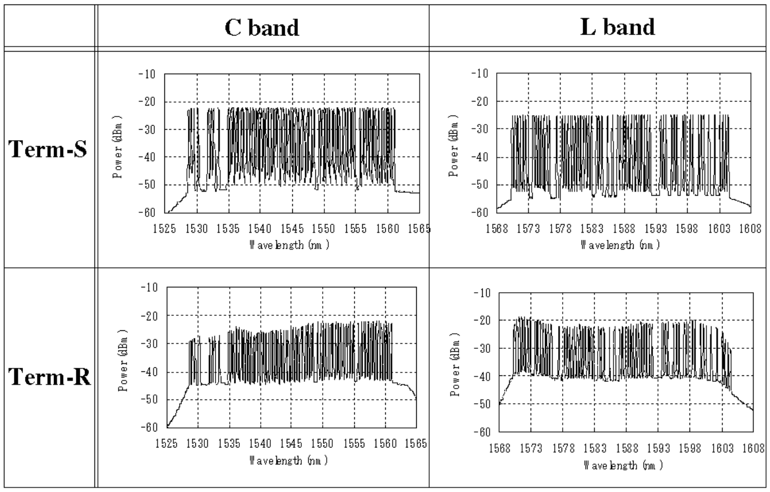

Figure 35: Before Preemphasis

Spectrum after Preemphasis

Received signals are smoother as a result of preemphasis, as Figure 36 illustrates. After the insertion of preemphasis, the receive OSNRs are the same, however the transmission powers vary.

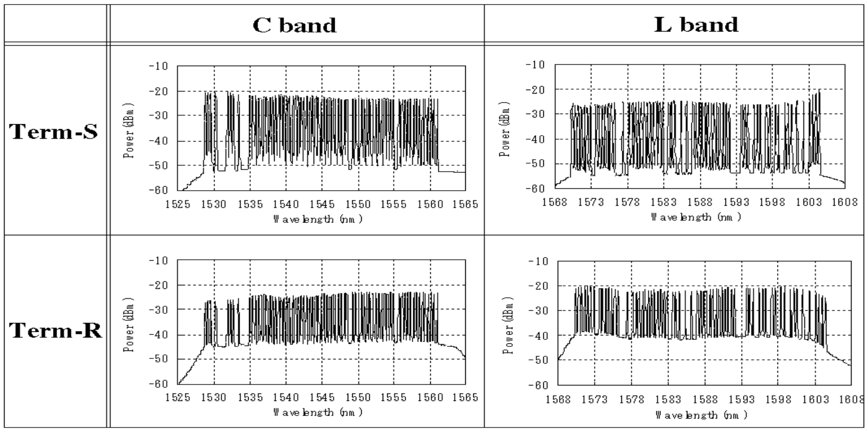

Figure 36: After Preemphasis

The Optical Media

Figure 37 shows the optical fiber that will transport photons. Photons that are launched into the core of a fiber cannot get out until they reach the other end. The optical fiber can be thought of as a small glass tube with mirrored walls.

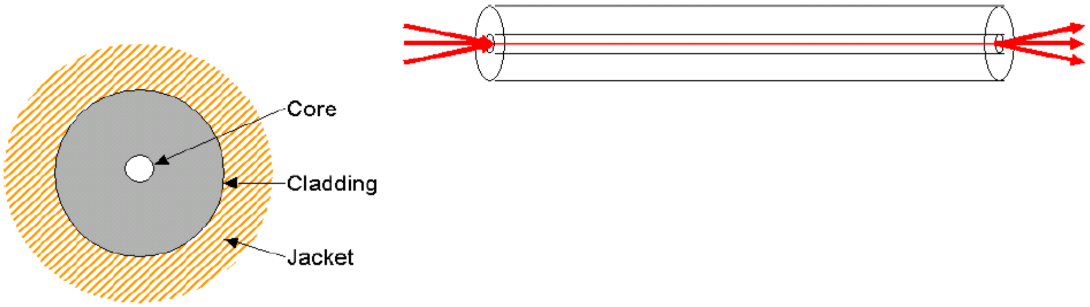

Figure 37: Optical Media

Optical Fiber Characteristics

The velocity factor, sometimes called propagation delay, of single mode fiber types is 67% of the speed of light. The speed of light is 300,000 kilometers per second (kps) in free space. Single mode fiber has a velocity factor of 201,000kps per second.

Fibers

The two classes of fiber used in telecommunications are multimode fiber (MMF) and single-mode fiber (SMF), Figure 38 illustrates the different modes of operation.

Multimode Fiber

- MMF is a fiber that supports multiple “lanes” of light.
- Multiple electromagnetic transmission modes are carried on MMF.
- Each lane is a different speed so that a pulse of light gets distorted sooner than in SMF.

Single-Mode Fiber

- One “lane” of light with minimum distortion

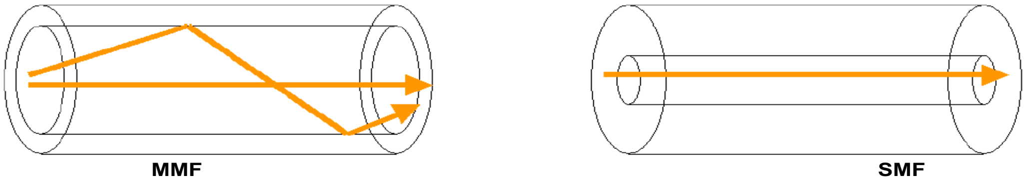

Figure 38: MMF and SMF

SMF Fiber Designs

There are many types of MMF and SMF. For telecommunications transmission, the characteristics of the two main varieties of SMF are shown in Figure 39.

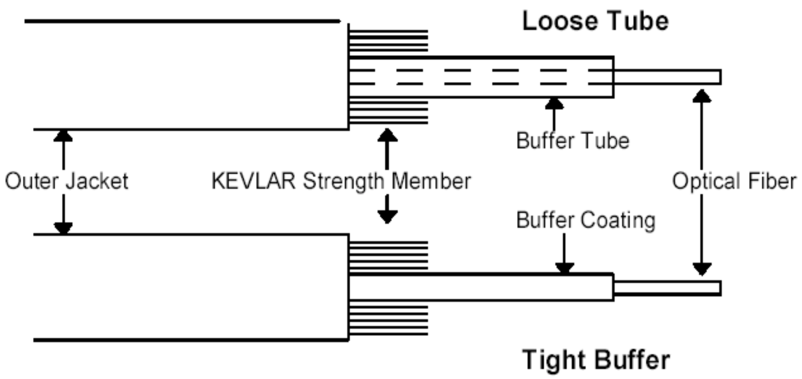

Figure 39: Fiber Mechanical Construction

The three main groups include:

- Non–dispersion-shifted fiber (NDSF), standard single-mode fiber (SMF or SSMF); the dispersion zero point is near 1310 nm λ
- Dispersion-shifted fiber (DS) has a zero point around 1550 nm λ
- Non–zero dispersion-shifted fiber (NZ-DSF) has a zero point around other λs

The detailed list of fibers includes:

- SMF or SSMF
    - Corning SMF-28
    - Lucent SMF
- DSF
    - Corning SMF/DS
    - Lucent DSF
- NZ-DSF
    - Lucent TrueWave® Classic
    - Lucent TrueWave Plus
    - Lucent TrueWave RS (Reduced Slope)
    - Corning LS
    - Corning LEAF® (Large Effective Area Fiber)
    - Alcatel TeraLight™

Fiber Attenuation

All transmission fiber suffers from the losses brought about by attenuation, as shown in Figure 40. 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 has been greatly reduced on today's fibers, allowing almost optimum minimum attenuation.

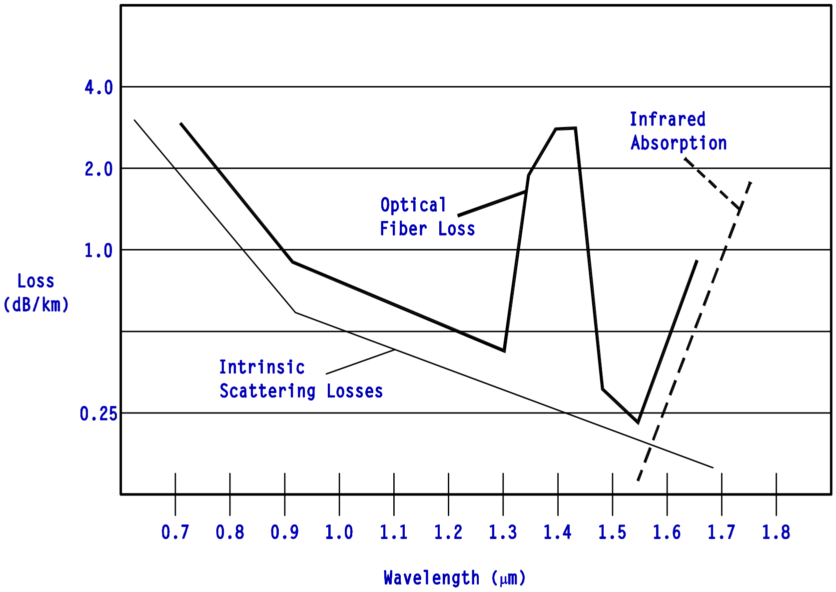

Figure 40: Fiber Attenuation

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

The S-band has the greatest attenuation, and is seldom used in DWDM design. The C- and L-bands have the most even rates of loss, as shown in Figure 41, and this is the portion of optical fiber that is most useful.

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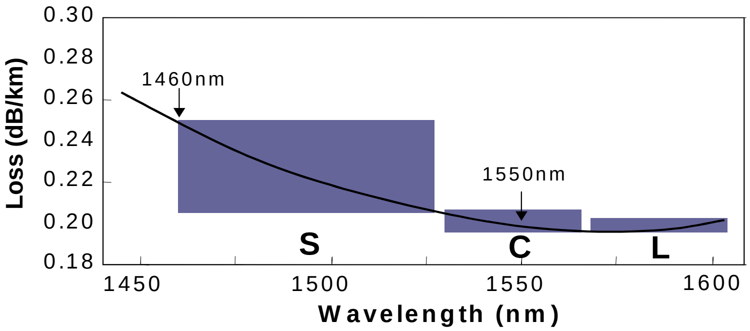

Figure 41: Fiber Signal Loss in S-, C-, and L-Bands

Attenuation of Optical Signal

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

Fiber nonlinearities limit 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 42.

- Amplifiers add 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 intersymbol interference[1] restricts the transmission distance.

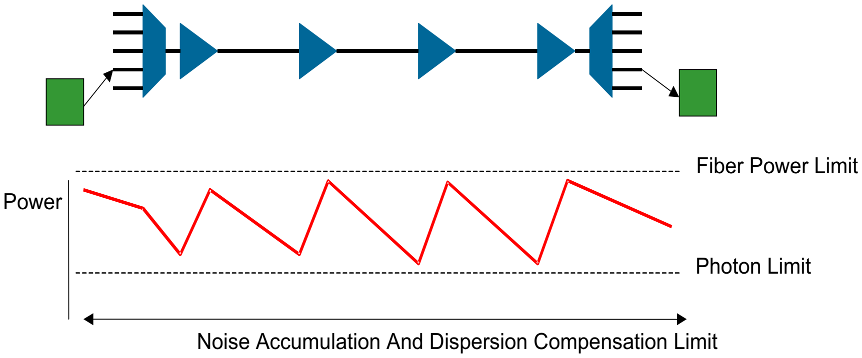

Figure 42: Power Levels

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[1] intersymbol interference: 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, i.e., between individual signal elements. At a certain threshold, intersymbol interference will compromise the integrity of the received data. Intersymbol interference attributable to the statistical nature of quantum mechanisms sets the fundamental limit to receiver sensitivity. Intersymbol interference may be measured by eye patterns. Extraneous energy from the signal in one or more keying intervals that interferes with the reception of the signal in another keying interval. The disturbance caused by extraneous energy from the signal in one or more keying intervals that interferes with the reception of the signal in another keying interval.

Cross-Talk in DWDM Systems

Compensating for Cross-Talk in DWDM Systems

Some dispersion is required in WDM networks, as shown in Figure 43, because it keeps down cross-talk by minimizing stimulated Brillouin scattering.

Some early fibers (DSF) sought to eliminate dispersion.

- Not very good for WDM, too much cross-talk
- Limits power levels in the system; greatly reduces span budgets

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

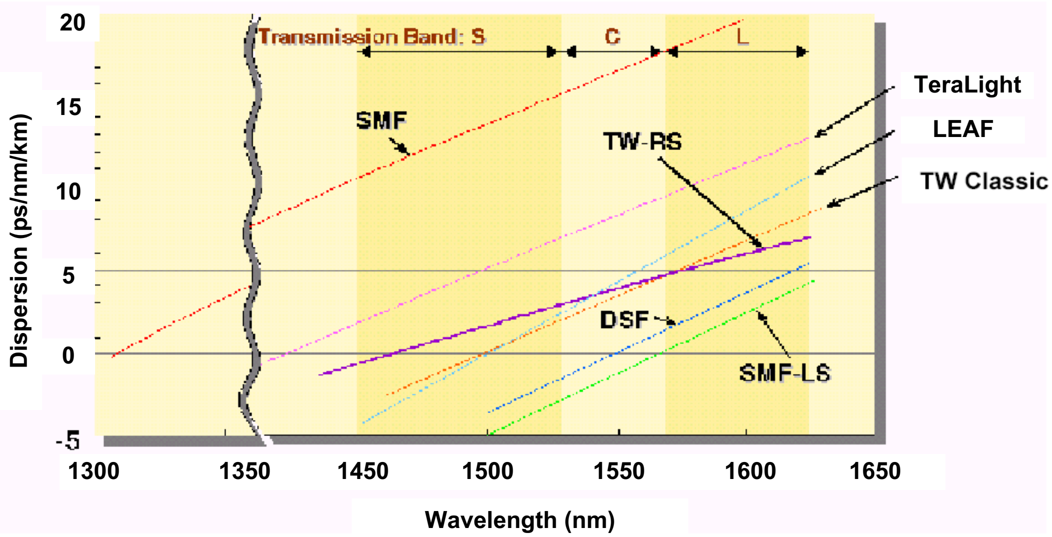


Figure 43: Dispersion and WDM

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 the real networks.

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 44 illustrates the common fiber type delay profiles. The Erbium window represents the minimum slope of chromatic dispersion.

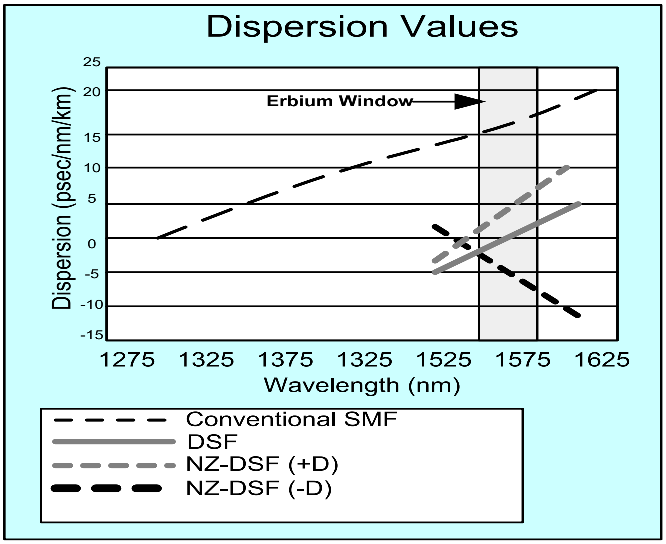
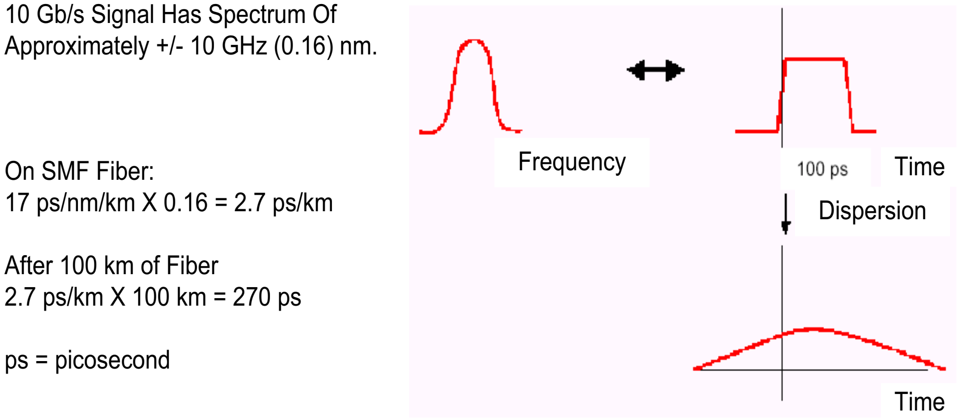


Figure 44: Chromatic Dispersion

Each signal has a spectrum that is affected by dispersion. The faster the rate of transmission, the greater the dispersion effects of shown in Figure 45.


10 Gb/s Signal Has Spectrum Of
Approximately +/- 10 GHz (0.16) nm.

On SMF Fiber:
17 ps/nm/km X 0.16 = 2.7 ps/km

After 100 km of Fiber
2.7 ps/km X 100 km = 270 ps

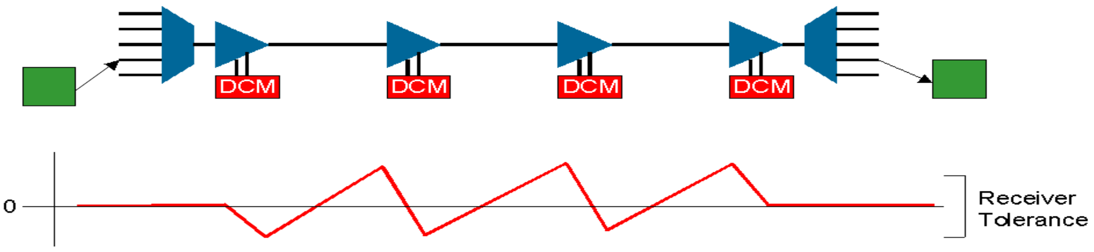
ps = picosecond

Figure 45: Dispersion Effects

Chromatic Dispersion Tolerance

- Standard SMF fiber has an average of 17 ps/nm/km of dispersion
- A 10-Gb/s receiver can tolerate about 800 ps/nm of dispersion
- A 500-km system generates 17 ps/nm/km x 500 km = 8500 ps/nm of dispersion

The DWDM system must compensate for dispersion to support 10-Gb/s transmission using methods like those shown in Figure 46.



X Axis is Time and Y Axis is The Change In Dispersion Between Modules

Figure 46: Compensation Modules

- 2.5-Gb/s transmission is 16 times less sensitive than 10 Gb/s
- 2.5-Gb/s signals tolerate up to 12,200 ps/nm without problems
- 40-Gb/s transmission is 16 times more sensitive than 10 Gb/s; only tolerates 50 ps/nm and requires special attention to dispersion compensation

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) is a free space dispersion device

Dispersion Slope and Limits

Because dispersion varies with wavelength, it is difficult to compensate all wavelengths simultaneously. This becomes more difficult over longer distances. New compensators are providing better “slope” compensation. (Slope is variance of dispersion with wavelength.) Figure 47 shows both slope and limits.

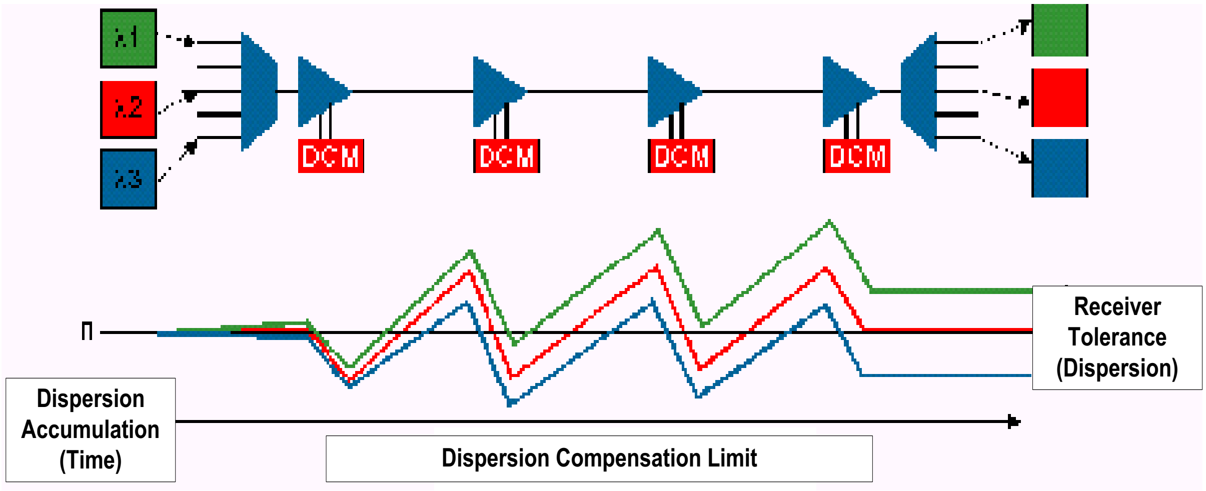


Figure 47: Dispersion Slope and Limits

The dispersion limit of the system depends on many factors:

- Receiver tolerance
    - Depends on pulse type; NRZ is better than RZ pulses.
    - Depends on data rate.
    - Depends on transmitter chirp.
- Variability of fiber dispersion
    - Dispersion of fiber has a range of values.
    - Some temperature dependence occurs.
- Variability of DCM values
    - Includes slope of dispersion and manufacturing tolerances.
- Variability of components in network elements (NEs).
- Receiver dispersion tolerance must be less than sum of dispersion variances.

Chirp

Chirp is an abrupt change of the center wavelength of a laser, caused by laser instability. When the modulator pulses the laser there is a difference in the refractive index of the laser output 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 48). It is a common effect in devices that generate optical pulses (optical modulators), and interacts with fiber dispersion and thereby may provide 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.

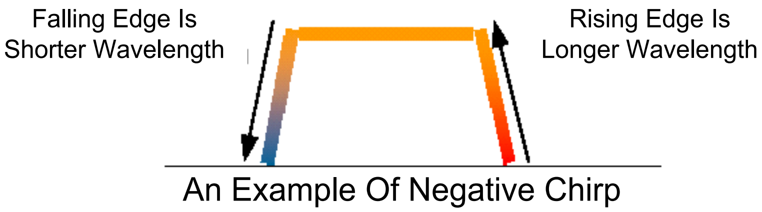


Figure 48: Chirp

Polarization Mode Dispersion

Light has polarization. Comparable to polarized sunglasses, some light is vertical and some is horizontal, as depicted in Figure 49. Different polarizations travel at different velocities, because fiber is not perfectly round. Different velocities cause dispersion.

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 solutions that helped manage the PMD effects.

- The outside vapor deposition method produced low PMD fibers (Corning).
- The inside vapor deposition method produced high PMD fibers (Lucent).

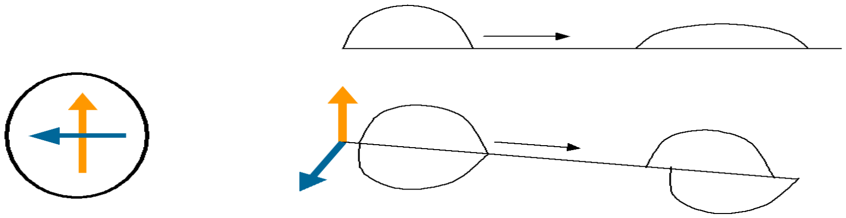


Figure 49: Polarization Mode Dispersion

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.

$$0.5ps/\sqrt{km}$$

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 km; 40 Gb/s with 2.5 ps tolerance has an effective range of 25 km (PMD compensation is required). Research is underway to make even lower PMD fibers is. New LEAF fiber, with 0.1 ps/km, allows distances of up to 10,000 km of 10 Gb/s or 625 km of 40 Gb/s.

Polarization Mode Dispersion Compensation

A PMD compensator (PMDC) compensates for polarization mode dispersion. The PMDC device has tunable PMD (Figure 50) and is new to optical networking.

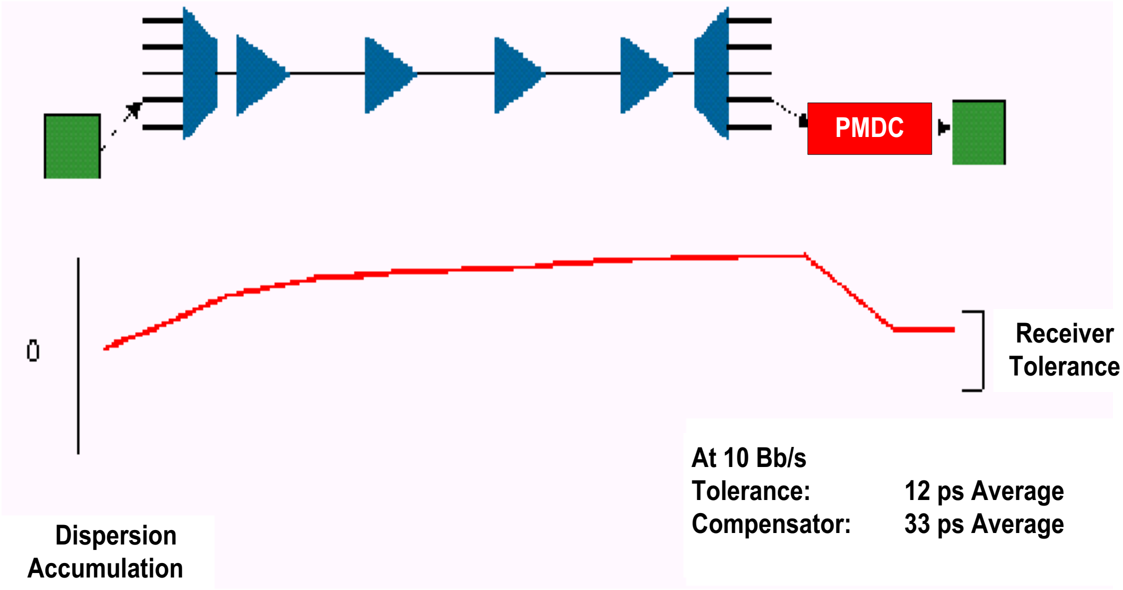


Figure 50: PMD Compensation

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

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 A ______________________ can be used as a optical multiplexer.

(A) thick-film filter

(B) thin-film filter

(C) 980 nm laser diode

(D) 1480 nm laser diode

3 The five components of a DWDM network include transmitter, receiver, optical amplifier, _____________________, and _______________.

(A) Multiplexer/demultiplexer and optical fiber

(B) SONET, voice-over IP, and dispersion

(C) All of the above

(D) None of the above

4 Retime, amplify, and reshape describes ____ regenerators.

(A) 1R

(B) 2R

(C) 3R

(D) None of the above

5 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

6 Signal bandwidth for 10-Gb/s signals is _____ gigahertz (GHz).

(A) 20

(B) 40

(C) 10

(D) 5

7 The Q-factor is ___________________________________.

(A) how fast traffic is transported—Q = quickness

(B) the fiber route measurement of loss

(C) a measure of how noisy a pulse is

(D) None of the above

8 ____ FEC provides approximately _________ system gain.

(A) In the band, 9 dB

(B) Out of band, 6 dB

(C) All of the above

(D) None of the above

9 Laser chirp is __________________________________.

(A) not allowed in FNC equipment

(B) typically between –1 and +1

(C) offered by different companies

(D) None of the above

10 _______ is caused by looking at the invisible laser light coming out of a fiber.

(A) Eye damage

(B) Blindness

(C) All of the above

(D) None of the above

11 Conventional DWDM usually uses the ____-band.

(A) C

(B) X

(C) L

(D) S

12 RAMAN amplifiers are ________________ than EDFA.

(A) more efficient

(B) less efficient

(C) more expensive

(D) less expensive

13 Distributed RAMAN uses _________ to increase the ________ signal level.

(A) the fiber in the ground itself, received

(B) the fiber in the ground itself, transmitted

(C) All of the above

(D) None of the above

14 ______________ provide a __________ signal.

(A) Laser diodes, minimal power signal

(B) Postemphasis, rougher

(C) Preemphasis, steep gain slope from high to low

(D) Pre emphasis, smoother

15 ____________ dispersion causes _____________.

(A) Polarization mode, signal failure

(B) Chromatic, flattening and widening of the signal

(C) Chromatic, polarization mode

(D) None of the above

Self-Evaluation Sheet (Electronic)

If you get fewer than 12 correct, FNC recommends that you review using the clickable Lookup Answer that lets you jump to the source of the information in the question missed. If you are using this tutorial on paper, go to the Lookup Answer page to find the information. Click to go back to “DWDM Self-Evaluation” on page 38.

Table 1: Answers

Question	Correct Answer	Lookup Answer
1	D	page 3
2	B	page 6
3	A	page 10
4	C	page 13
5	B	page 17
6	A	page 17
7	C	page 23
8	B	page 22
9	C	page 34
10	D	page 11
11	A	page 26
12	A	page 15
13	C	page 15
14	D	page 26
15	B	page 32

Table 2: DWDM Acronyms

Acronym	Description/Explanation
1R	Regenerator that reamplifies optical signal
2R	Regenerators that reamplify and reshape
3R	Regenerators 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
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.

Table 2: DWDM Acronyms (Continued)

Acronym	Description/Explanation
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 Telecommunications Union-Telecommunications Standardization Sector
LAN	local area network
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

Table 2: DWDM Acronyms (Continued)

Acronym	Description/Explanation
OSI	Open Systems Interconnection (standard set of protocols)
OSNR	optical signal-to-noise ratio
OXC	optical cross-connect
PIN	simple photodiode
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
TCP	Transmission Control Protocol
TDFA	thallium-doped fluoride-based amplifier
TDM	time-division multiplex/multiplexing/multiplexer

Table 2: DWDM Acronyms (Continued)

Acronym	Description/Explanation
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)

Table 3: 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.