DENSE WAVELENGTH DIVISION MULTIPLEXING SYSTEMS
A PERFORMANCE EVALUATION AND THE REALISATION OF A 10 Gbps LINK USING OptSim

A DISSERTATION SUBMITTED TOWARDS THE PARTIAL FULFILLMENT OF THE
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CERTIFICATION

This is to certify that this thesis dissertation titled **“Dense Division Multiplexing systems- a performance evaluation and the realization of a 10 Gbps link”**, submitted by Chandrakant Rawat, Mayank Gupta and Mayank Mittal towards the partial fulfillment of the requirement for the degree of Bachelor of Engineering in Electronics and Communication, is a bonafide record of their work carried out under the supervision and guidance of Dr. Muralidhar Kulkarni.

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ABSTRACT

Dense Division Multiplexing (DWDM) has grown to be the most popular communication system in high speed communications over the last decade. DWDM is a multi carrier system where different carriers are multiplexed onto one fiber, i.e. different signals are at different frequencies within the fiber and thus better utilization of the available bandwidth is possible. It has reduced susceptibility to most forms of impulse noise. Currently, DWDM is implemented to provide services like email, video and multimedia content as IP data over ATM and voice data over SONET/SDH over a single network. However, there are certain design considerations in an DWDM system, particularly in the link of 10 Gbps and more such as distortion effects, Peak to average Ratio (PAR) reduction, Forward Error Correction, Channel Estimation, Inter carrier Interference (ICI) reduction etc. In this thesis, we have studied channel parameters and the effect of varying these parameters in realizing a 10 Gbps link in DWDM systems. The simulations have been carried out using RSOFT OptSim.

To understand the importance of DWDM and optical networking, these capabilities must be seen in the context of the challenges faced by the communications industry. An enormous amount of bandwidth capacity is required to provide the services demanded by the consumers. In addition to this explosion in bandwidth demand, many service providers are coping with fiber exhaust in their networks. A major problem for carriers is the challenge of economically deploying and integrating various technologies in one physical infrastructure. DWDM provides the best solution to all these problems.

Dense wavelength division multiplexing (DWDM) is a fiber-optic transmission technique that employs light wavelengths to transmit data parallel-by-bit or serial-by-character. DWDM increases the capacity of embedded fiber by first assigning incoming optical signals to specific frequencies within the designated frequency band and the multiplexing the resulting signals out onto one fiber.

It is attempted to compute the Bit Error Rate (BER) and Peak to Average Power Ratio (PAR). These parameters have been simulated for variations in channel Signal to Noise Ratio (SNR), Number of sub-carriers, modulation schemes and guard band intervals.

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Introduction

The emergence of DWDM is one of the most recent and important phenomena in the development of fiber optic transmission technology. In the following discussion we briefly trace the stages of fiber optic technology and the place of DWDM in that development. We then examine the functions and components of a DWDM system, including the enabling technologies, and conclude with a high-level description of the operation of a DWDM system.

Evolution of Fiber Optic Transmission

The reality of fiber optic transmission had been experimentally proven in the nineteenth century, but the technology began to advance rapidly in the second half of the twentieth century with the invention of the fiberscope, which found applications in industry and medicine, such as in laparoscopic surgery.

After the viability of transmitting light over fiber had been established, the next step in the development of fiber optics was to find a light source that would be sufficiently powerful and narrow. The light-emitting diode (LED) and the laser diode proved capable of meeting these requirements. Lasers went through several generations in the 1960s, culminating with the semiconductor lasers that are most widely used in fiber optics today.

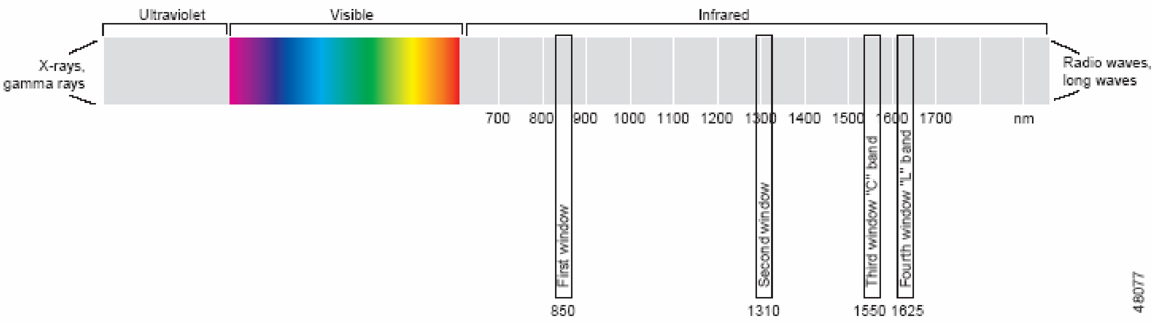
Light has an information-carrying capacity 10,000 times greater than the highest radio frequencies. Additional advantages of fiber over copper include the ability to carry signals over long distances, low error rates, immunity to electrical interference, security, and light weight. Aware of these characteristics, researchers in the mid-1960s proposed that optical fiber might be a suitable transmission medium. There was an obstacle, however, and that was the loss of signal strength, or *attenuation*, seen in the glass they were working with. Finally, in 1970, Corning produced the first communication-grade fibers. With attenuation less than 20 decibels per kilometer (dB/km), this purified glass fiber exceeded the threshold for making fiber optics a viable technology.

Innovation at first proceeded slowly, as private and government monopolies that ran the telephone companies were cautious. AT&T first standardized transmission at DS3 speed (45 Mbps) for multimode fibers. Soon thereafter, single-mode fibers were shown to be capable of transmission rates 10 times that of the older type, as well as spans of 32 km (20 mi). In the early 1980s, MCI, followed by Sprint, adopted single-mode fibers for its long-distance network in the U.S.

Further developments in fiber optics are closely tied to the use of the specific regions on the optical spectrum where optical attenuation is low. These regions, called *windows*, lie between areas of high absorption. The earliest systems were developed to operate around 850 nm, the first window in silica-based optical fiber. A second window (S band), at 1310 nm, soon proved to be superior because of its lower attenuation, followed by a third window (C band) at 1550 nm with an even lower optical loss.

Today, a fourth window (L band) near 1625 nm is under development and early deployment. These four windows are shown relative to the electromagnetic spectrum in Figure 2-1.

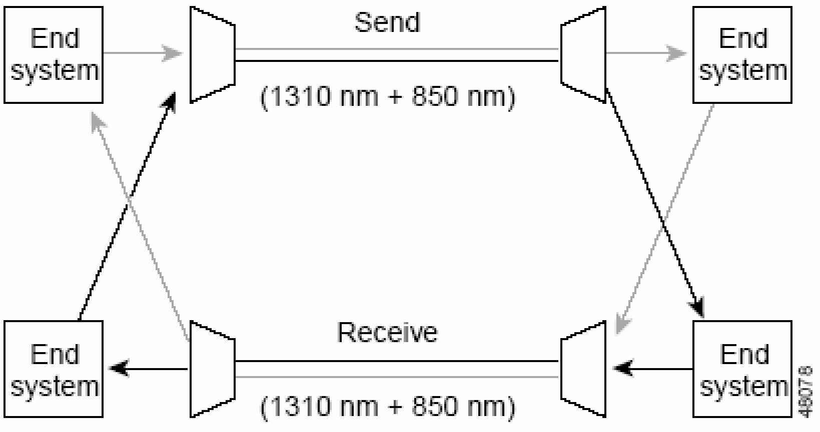
Figure 2-1 Wavelength Regions



Development of DWDM Technology

Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called *wideband WDM*. Figure 2-2 shows an example of this simple form of WDM. Notice that one of the fiber pair is used to transmit and one is used to receive. This is the most efficient arrangement and the one most found in DWDM systems.

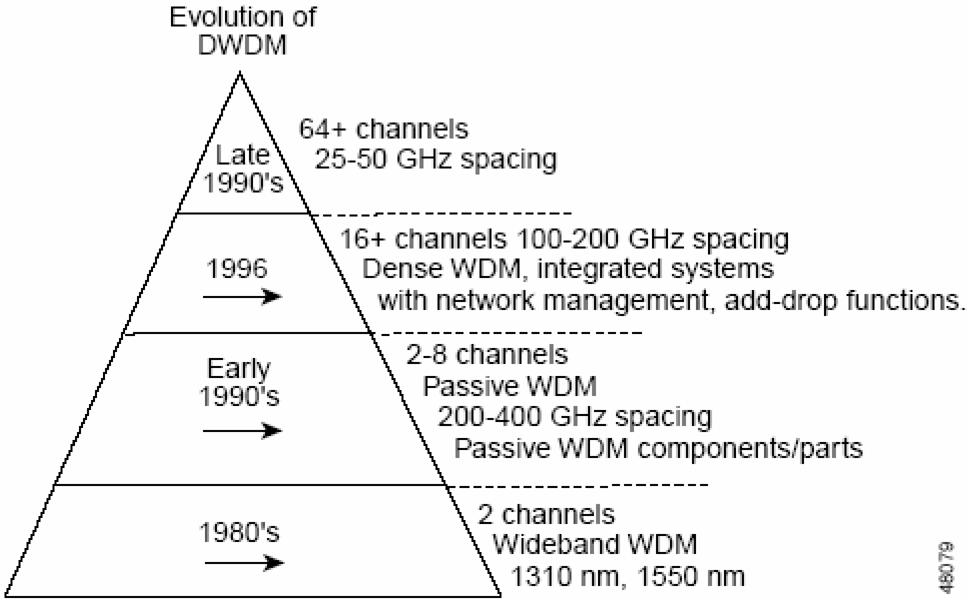
Figure 2-2 WDM with Two Channels



The early 1990s saw a second generation of WDM, sometimes called *narrowband WDM,* in which two to eight channels were used. These channels were now spaced at an interval of about 400 GHz in the 1550-nm window. By the mid-1990s, dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz. By the late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals.

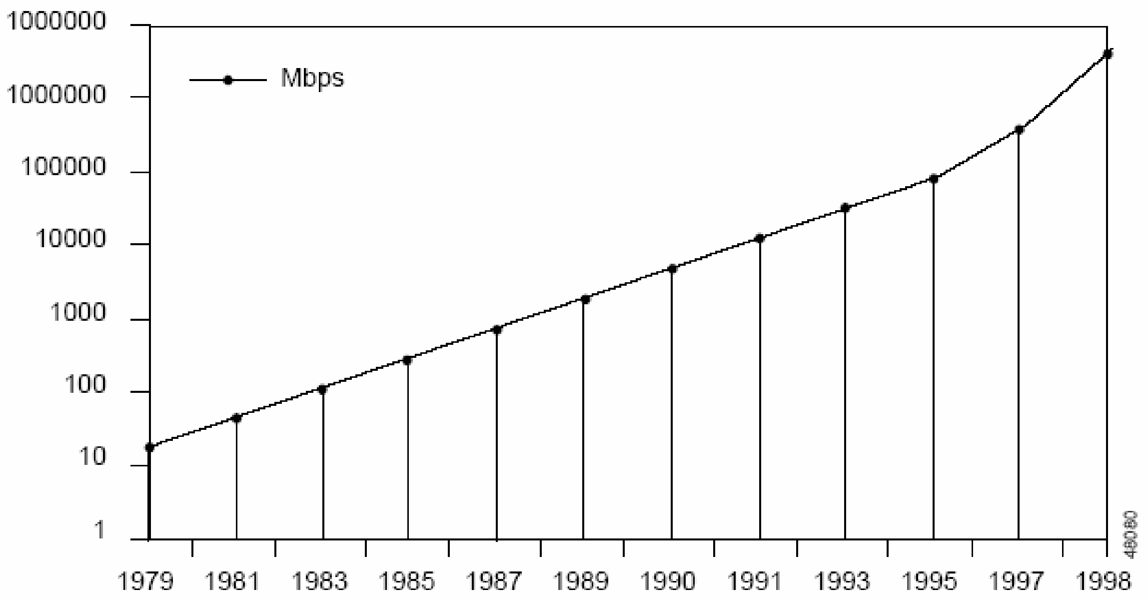
As Figure 2-3 shows, the progression of the technology can be seen as an increase in the number of wavelengths accompanied by a decrease in the spacing of the wavelengths. Along with increased density of wavelengths, systems also advanced in their flexibility of configuration, through add-drop functions, and management capabilities.

Figure 2-3 Evolution of DWDM



Increases in channel density resulting from DWDM technology have had a dramatic impact on the carrying capacity of fiber. In 1995, when the first 10 Gbps systems were demonstrated, the rate of increase in capacity went from a linear multiple of four every four years to four every year (see Figure 2-4).

Figure 2-4 Growth in Fiber Capacity

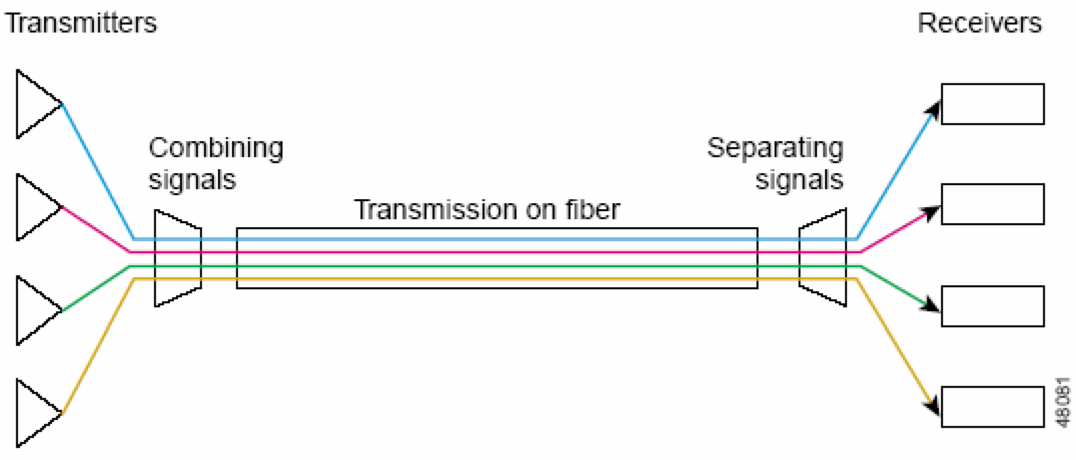


DWDM System Functions

At its core, DWDM involves a small number of physical-layer functions. These are depicted in Figure 2-5, which shows a DWDM schematic for four channels. Each optical channel occupies its own wavelength.

Wavelength is expressed (usually in nanometers) as an absolute point on the electromagnetic spectrum. The effective light at a given wavelength is confined narrowly *around* its central wavelength.

Figure 2-5 DWDM Functional Schematic



The system performs the following main functions:

- Generating the signal—The source, a solid-state laser, must provide stable light within a specific, narrow bandwidth that carries the digital data, modulated as an analog signal.
- Combining the signals—Modern DWDM systems employ multiplexers to combine the signals. There is some inherent loss associated with multiplexing and demultiplexing. This loss is dependent upon the number of channels but can be mitigated with optical amplifiers, which boost all the wavelengths at once without electrical conversion.
- Transmitting the signals—The effects of crosstalk and optical signal degradation or loss must be reckoned with in fiber optic transmission. These effects can be minimized by controlling variables such as channel spacings, wavelength tolerance, and laser power levels. Over a transmission link, the signal may need to be optically amplified.
- Separating the received signals—At the receiving end, the multiplexed signals must be separated out. Although this task would appear to be simply the opposite of combining the signals, it is actually more technically difficult.
- Receiving the signals—The demultiplexed signal is received by a photodetector.

In addition to these functions, a DWDM system must also be equipped with client-side interfaces to receive the input signal. This function is performed by transponders. On the DWDM sides are interfaces to the optical fiber that links DWDM systems.

Enabling Technologies

Optical networking, unlike SONET/SDH, does not rely on electrical data processing. As such, its development is more closely tied to optics than to electronics. In its early form, as described previously, WDM was capable of carrying signals over two widely spaced wavelengths, and for a relatively short distance. To move beyond this initial state, WDM needed both improvements in existing technologies and invention of new technologies. Improvements in optical filters and narrowband lasers enabled DWDM to combine more than two signal wavelengths on a fiber. The invention of the flat-gain optical amplifier, coupled in line with the transmitting fiber to boost the optical signal, dramatically increased the viability of DWDM systems by greatly extending the transmission distance.

Other technologies that have been important in the development of DWDM include improved optical fiber with lower loss and better optical transmission characteristics, EDFAs, and devices such as fiber Bragg gratings used in optical add/drop multiplexers.

Components and Operation

DWDM is a core technology in an optical transport network. The essential components of DWDM can be classified by their place in the system as follows:

- On the transmit side, lasers with precise, stable wavelengths
- On the link, optical fiber that exhibits low loss and transmission performance in the relevant wavelength spectra, in addition to flat-gain optical amplifiers to boost the signal on longer spans
- On the receive side, photo-detectors and optical de-multiplexers using thin film filters or diffractive elements.
- Optical add/drop multiplexers and optical cross-connect components

These and other components, along with their underlying technologies, are discussed in the following sections. While much of this information, particularly the pros and cons of various competing technologies, may be of more importance to a system designer than to an end user or network designer, it may also be of interest to other readers. Note as well that this is summary information and is not intended to be complete or authoritative.

Optical Fibers

The following discussion of DWDM components and technologies includes a refresher on optical fibers, with emphasis on their application for DWDM.

How Fiber Works

The main job of optical fibers is to guide lightwaves with a minimum of attenuation (loss of signal). Optical fibers are composed of fine threads of glass in layers, called the core and cladding, that can transmit light at about two-thirds the speed of light in a vacuum. Though admittedly an oversimplification, the transmission of light in optical fiber is commonly explained using the principle of *total internal reflection*. With this phenomenon, 100 percent of light that strikes a surface is reflected.

By contrast, a mirror reflects about 90 percent of the light that strikes it.

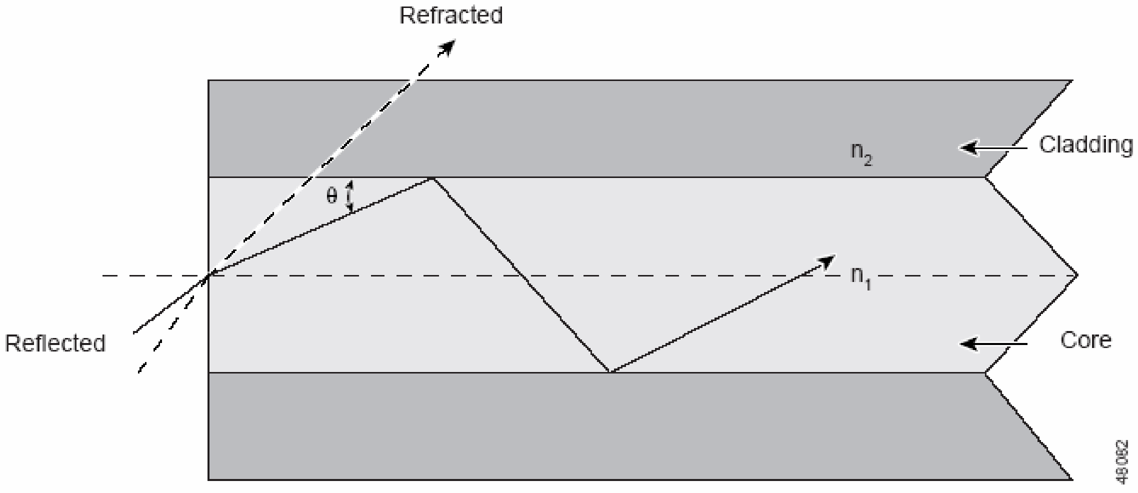
Light is either reflected (it bounces back) or refracted (its angle is altered while passing through a different medium) depending upon the angle of incidence (the angle at which light strikes the interface between an optically denser and optically thinner material).

Total internal reflection happens when the following conditions are met:

- Beams pass from a denser to a less denser material. The difference between the optical density of a given material and a vacuum is the material’s refractive index.
- The incident angle is less than the critical angle. The critical angle is the angle of incidence at which light stops being refracted and is instead totally reflected.

The principle of total internal reflection within a fiber core is illustrated in Figure 2-6. The core has a higher refractive index than the cladding, allowing the beam that strikes that surface at less than the critical angle to be reflected. The second beam does not meet the critical angle requirement and is refracted.

Figure 2-6 Principle of Total Internal Reflection

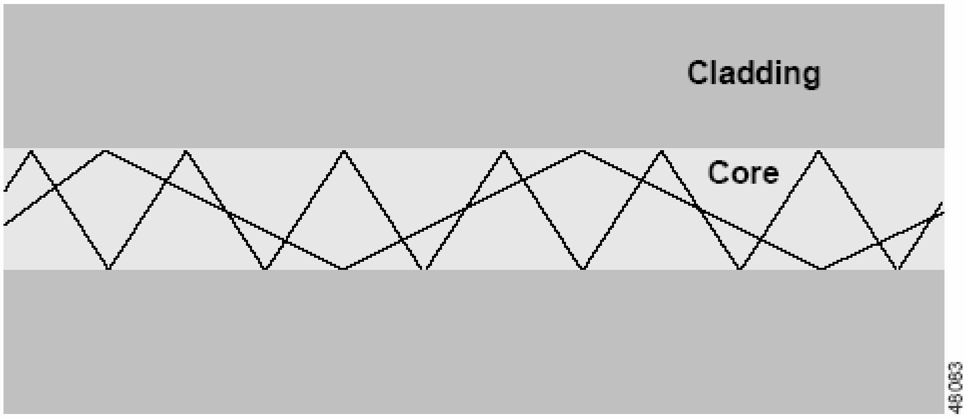


An optical fiber consists of two different types of highly pure, solid glass (silica)—the *core* and the *cladding*—that are mixed with specific elements, called *dopants*, to adjust their refractive indices. The difference between the refractive indices of the two materials causes most of the transmitted light to bounce off the cladding and stay within the core. The critical angle requirement is met by controlling the angle at which the light is injected into the fiber. Two or more layers of protective coating around the cladding ensure that the glass can be handled without damage.

Multimode and Single-Mode Fiber

There are two general categories of optical fiber in use today, multimode fiber and single-mode fiber. Multimode, the first type of fiber to be commercialized, has a larger core than single-mode fiber. It gets its name from the fact that numerous *modes*, or light rays, can be carried simultaneously through the waveguide. Figure 2-7 shows an example of light transmitted in the first type of multimode fiber, called *step-index*. Step-index refers to the fact that there is a uniform index of refraction throughout the core; thus there is a step in the refractive index where the core and cladding interface. Notice that the two modes must travel different distances to arrive at their destinations. This disparity between the times that the light rays arrive is called *modal dispersion*. This phenomenon results in poor signal quality at the receiving end and ultimately limits the transmission distance. This is why multimode fiber is not used in wide-area applications.

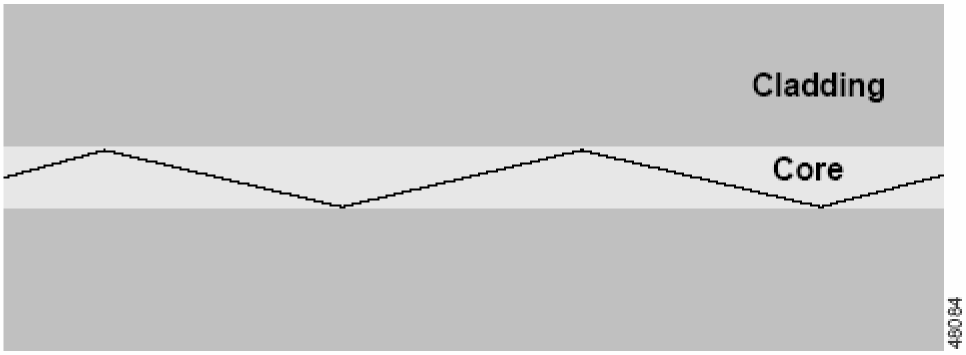
Figure 2-7 Reflected Light in Step-Index Multimode Fiber



To compensate for the dispersion drawback of step-index multimode fiber, graded-index fiber was invented. *Graded-index* refers to the fact that the refractive index of the core is graded—it gradually decreases from the center of the core outward. The higher refraction at the center of the core slows the speed of some light rays, allowing all the rays to reach their destination at about the same time and reducing modal dispersion.

The second general type of fiber, single-mode, has a much smaller core that allows only one mode of light at a time through the core (see Figure 2-8). As a result, the fidelity of the signal is better retained over longer distances, and modal dispersion is greatly reduced. These factors attribute to a higher bandwidth capacity than multimode fibers are capable of. For its large information-carrying capacity and low intrinsic loss, single-mode fibers are preferred for longer distance and higher bandwidth applications, including DWDM.

Figure 2-8 Reflected Light in Single-Mode Fiber



Single-Mode Fiber Designs

Designs of single-mode fiber have evolved over several decades. The three principle types and their ITU-T specifications are:

- Non-dispersion-shifted fiber (NDSF), G.652
- Dispersion-shifted fiber (DSF), G.653
- Non-zero dispersion-shifted fiber (NZ-DSF), G.655

As discussed earlier, and shown in Figure 2-1, there are four windows within the infrared spectrum that have been exploited for fiber transmission. The first window, near 850 nm, was used almost exclusively for short-range, multimode applications. Non-dispersion-shifted fibers, commonly called standard single-mode (SM) fibers, were designed for use in the second window, near 1310 nm. To optimize the fiber's performance in this window, the fiber was designed so that chromatic dispersion would be close to zero near the 1310-nm wavelength.

As optical fiber use became more common and the needs for greater bandwidth and distance increased, a third window, near 1550 nm, was exploited for single-mode transmission. The third window, or C band, offered two advantages: it had much lower attenuation, and its operating frequency was the same as that of the new erbium-doped fiber amplifiers (EDFAs). However, its dispersion characteristics were severely limiting. This was overcome to a certain extent by using narrower linewidth and higher power lasers. But because the third window had lower attenuation than the 1310-nm window, manufacturers came up with the dispersion-shifted fiber design, which moved the zero-dispersion point to the 1550-nm region.

Although this solution now meant that the lowest optical attenuation and the zero-dispersion points coincided in the 1550-nm window, it turned out that there are destructive nonlinearities in optical fiber near the zero-dispersion point for which there is no effective compensation. Because of this limitation, these fibers are not suitable for DWDM applications.

The third type, non-zero dispersion-shifted fiber, is designed specifically to meet the needs of DWDM applications. The aim of this design is to make the dispersion low in the 1550-nm region, but not zero.

This strategy effectively introduces a controlled amount of dispersion, which counters nonlinear effects such as four-wave mixing (see the "Other Nonlinear Effects" section on page 2-11) that can hinder the performance of DWDM systems.

Transmission Challenges

Transmission of light in optical fiber presents several challenges that must be dealt with. These fall into the following three broad categories:

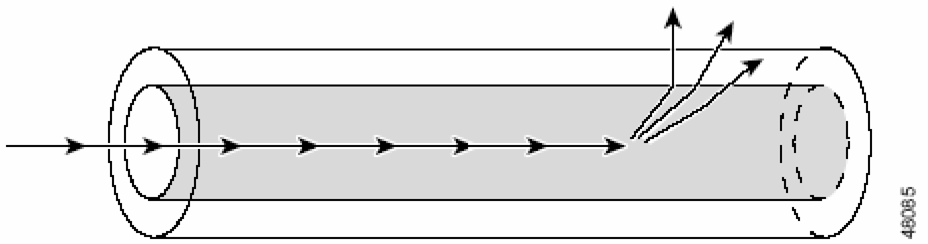
- Attenuation—decay of signal strength, or loss of light power, as the signal propagates through the fiber
- Chromatic dispersion—spreading of light pulses as they travel down the fiber
- Nonlinearities—cumulative effects from the interaction of light with the material through which it travels, resulting in changes in the lightwave and interactions between lightwaves

Each of these effects has several causes, not all of which affect DWDM. The discussion in the following sections addresses those causes that are relevant to DWDM.

Attenuation

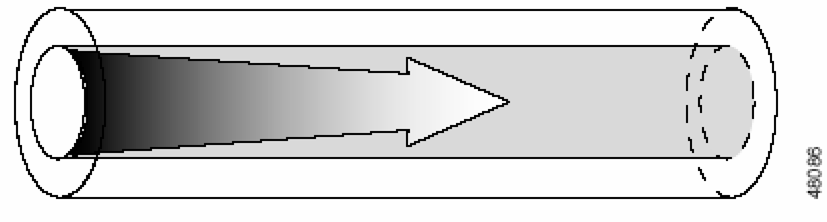
Attenuation in optical fiber is caused by intrinsic factors, primarily scattering and absorption, and by extrinsic factors, including stress from the manufacturing process, the environment, and physical bending. The most common form of scattering, *Rayleigh scattering*, is caused by small variations in the density of glass as it cools. These variations are smaller than the wavelengths used and therefore act as scattering objects (see Figure 2-9). Scattering affects short wavelengths more than long wavelengths and limits the use of wavelengths below 800 nm.

Figure 2-9 Rayleigh Scattering



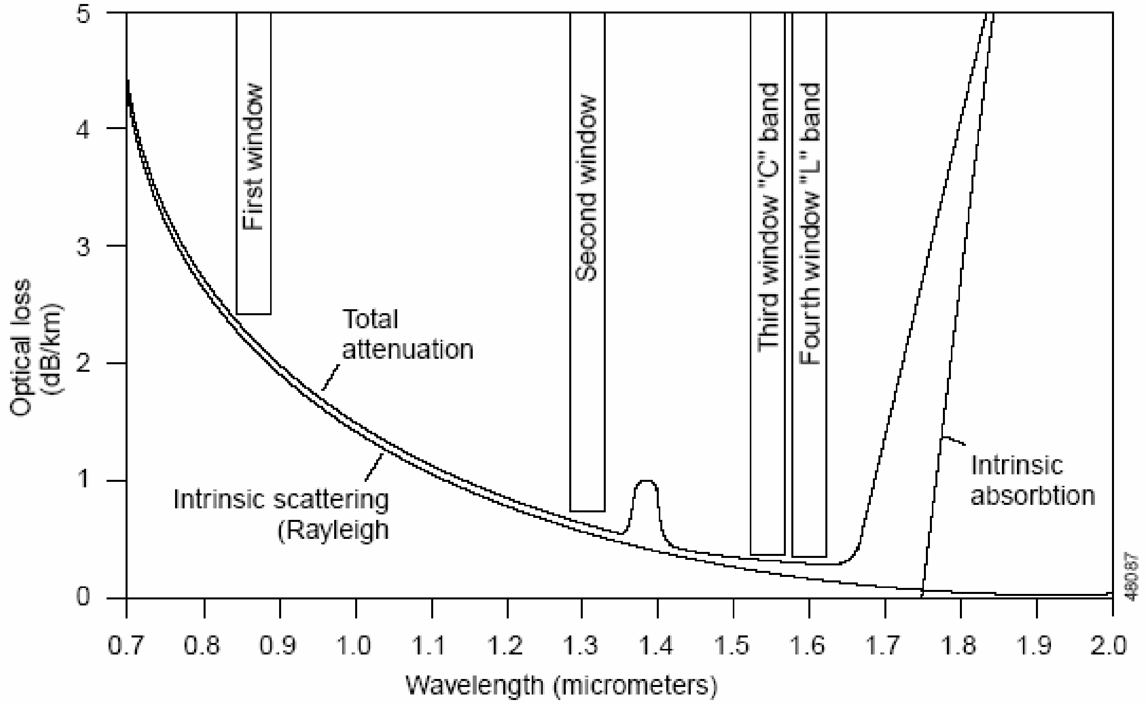
Attenuation due to absorption is caused by the intrinsic properties of the material itself, the impurities in the glass, and any atomic defects in the glass. These impurities absorb the optical energy, causing the light to become dimmer (see Figure 2-10). While Rayleigh scattering is important at shorter wavelengths, intrinsic absorption is an issue at longer wavelengths and increases dramatically above 1700 nm. However, absorption due to water peaks introduced in the fiber manufacturing process are being eliminated in some new fiber types.

Figure 2-10 Absorption



The primary factors affecting attenuation in optical fibers are the length of the fiber and the wavelength of the light. Figure 2-11 shows the loss in decibels per kilometer (dB/km) by wavelength from Rayleigh scattering, intrinsic absorption, and total attenuation from all causes.

Figure 2-11 Total Attenuation Curve

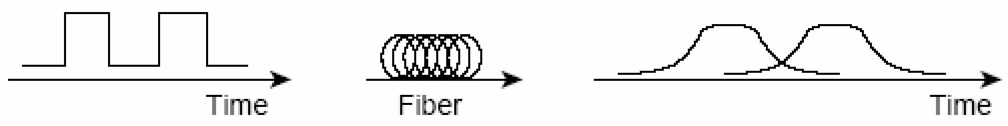


Attenuation in fiber is compensated primarily through the use of optical amplifiers.

Dispersion

Dispersion is the spreading of light pulses as they travel down optical fiber. Dispersion results in distortion of the signal (see Figure 2-12), which limits the bandwidth of the fiber.

Figure 2-12 Principle of Dispersion



Two general types of dispersion affect DWDM systems. One of these effects, chromatic dispersion, is linear while the other, polarization mode dispersion (PMD), is nonlinear.

Chromatic Dispersion

Chromatic dispersion occurs because different wavelengths propagate at different speeds. The effect of chromatic dispersion increases as the square of the bit rate. In single-mode fiber, chromatic dispersion has two components, material dispersion and waveguide dispersion. Material dispersion occurs when wavelengths travel at different speeds through the material. A light source, no matter how narrow, emits several wavelengths within a range. Thus, when this range of wavelengths travels through a medium, each individual wavelength arrives at a different time.

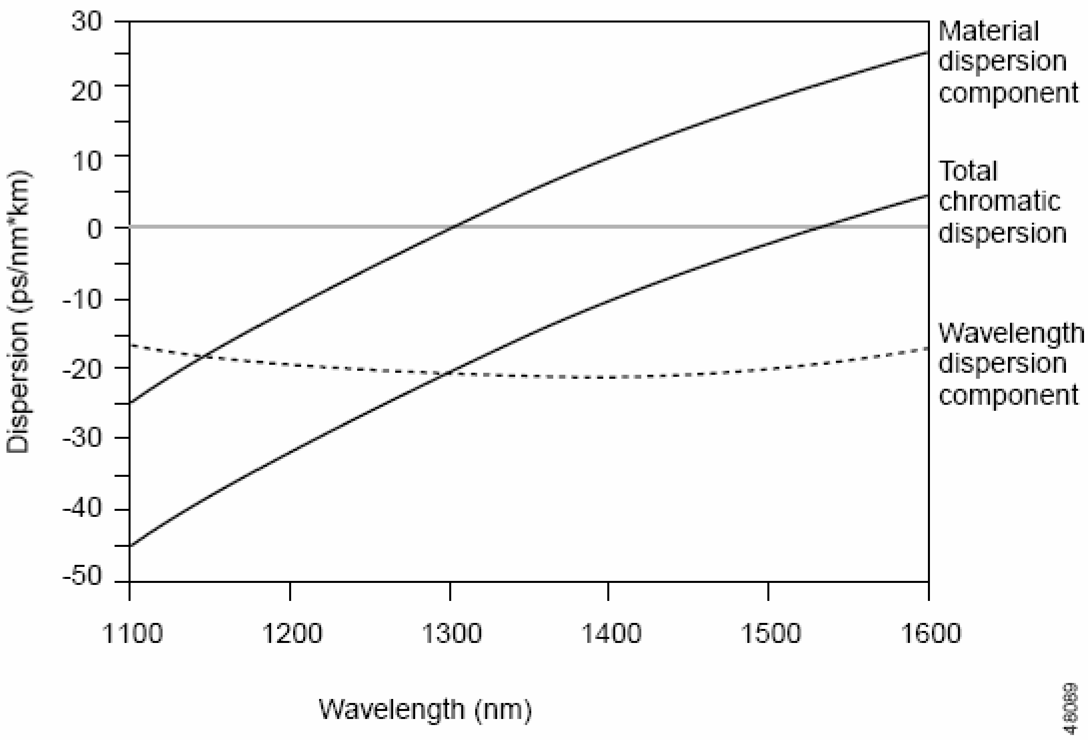
The second component of chromatic dispersion, waveguide dispersion, occurs because of the different refractive indices of the core and the cladding of fiber. The effective refractive index varies with wavelength as follows:

- At short wavelengths, the light is well confined within the core. Thus the effective refractive index is close to the refractive index of the core material.
- At medium wavelengths, the light spreads slightly into the cladding. This decreases the effective refractive index.
- At long wavelengths, much of the light spreads into the cladding. This brings the effective refractive index very close to that of the cladding.

This result of the phenomenon of waveguide dispersion is a propagation delay in one or more of the wavelengths relative to others.

Total chromatic dispersion, along with its components, is plotted by wavelength in Figure 2-13 for dispersion-shifted fiber. For non-dispersion-shifted fiber, the zero dispersion wavelength is 1310 nm.

Figure 2-13 Chromatic Dispersion



Though chromatic dispersion is generally not an issue at speeds below OC-48, it does increase with higher bit rates due to the spectral width required. New types of zero-dispersion-shifted fibers greatly reduce these effects. The phenomenon can also be mitigated with dispersion compensators.

Polarization Mode Dispersion

Most single-mode fibers support two perpendicular polarization modes, a vertical one and a horizontal one. Because these polarization states are not maintained, there occurs an interaction between the pulses that results is a smearing of the signal.
Polarization mode dispersion (PMD) is caused by ovality of the fiber shape as a result of the manufacturing process or from external stressors. Because stress can vary over time, PMD, unlike chromatic dispersion, is subject to change over time. PMD is generally not a problem at speeds below OC-192.

Other Nonlinear Effects

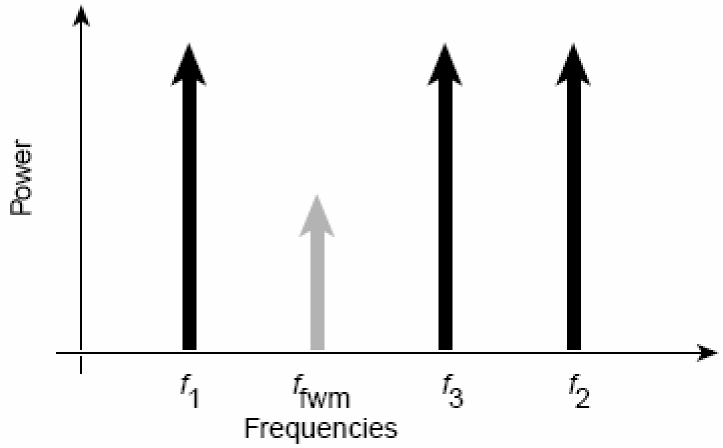
In addition to PMD, there are other nonlinear effects. Because nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM.

Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects *accumulate*.

They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. The most important types of nonlinear effects are stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, and four-wave mixing. In DWDM, four-wave mixing is the most critical of these types.

Four-wave mixing is caused by the nonlinear nature of the refractive index of the optical fiber. Nonlinear interactions among different DWDM channels creates sidebands that can cause interchannel interference. In Figure 2-14 three frequencies interact to produce a fourth frequency, resulting in cross-talk and signal-to-noise degradation.

Figure 2-14 Four-Wave Mixing



The effect of four-wave mixing is to limit the channel capacity of a DWDM system. Four-wave mixing cannot be filtered out, either optically or electrically, and increases with the length of the fiber. Due to its propensity for four-wave-mixing, DSF is unsuitable for WDM applications. This prompted the invention of NZ-DSF, which takes advantage of the fact that a small amount of chromatic dispersion can be used to mitigate four-wave mixing.

Summary

In the long-distance network, the majority of embedded fiber is standard single-mode (G.652) with high dispersion in the 1550-nm window, which limits the distance for OC-192 transmission. Dispersion can be mitigated to some extent, and at some cost, using dispersion compensators. Non-zero dispersion-shifted fiber can be deployed for OC-192 transport, but higher optical power introduces nonlinear effects.

In the short-haul network, PMD and nonlinear effects are not so critical as they are in long-haul systems, where higher speeds (OC-192 and higher) are more common. DWDM systems using optical signals of 2.5 Gbps or less are not subject to these nonlinear effects at short distances. The major types of single-mode fibers and their application can be summarized as follows:

- Non-dispersion-shifted fiber (standard SM fiber)—accounts for greater than 95 percent of deployed plant; suitable for TDM (single-channel) use in the 1310-nm region or DWDM use in the 1550-nm region (with dispersion compensators). This type of fiber can also support 10 Gigabit Ethernet standard at distances over 300 meters.
- Dispersion-shifted fiber—suitable for TDM use in the 1550-nm region, but unsuitable for DWDM in this region.
- Non-zero dispersion-shifted fiber—good for both TDM and DWDM use in the 1550-nm region.
- Newer generation fibers—includes types that allow the energy to travel further into the cladding, creating a small amount of dispersion to counter four-wave mixing, and dispersion-flattened fibers, which permit use of wavelengths farther from the optimum wavelength without pulse spreading.

Light Sources and Detectors

Light emitters and light detectors are active devices at opposite ends of an optical transmission system. Light sources, or light emitters, are transmit-side devices that convert electrical signals to light pulses.

The process of this conversion, or modulation, can be accomplished by externally modulating a continuous wave of light or by using a device that can generate modulated light directly. Light detectors perform the opposite function of light emitters. They are receive-side opto-electronic devices that convert light pulses into electrical signals.

Light Emitters—LEDs and Lasers

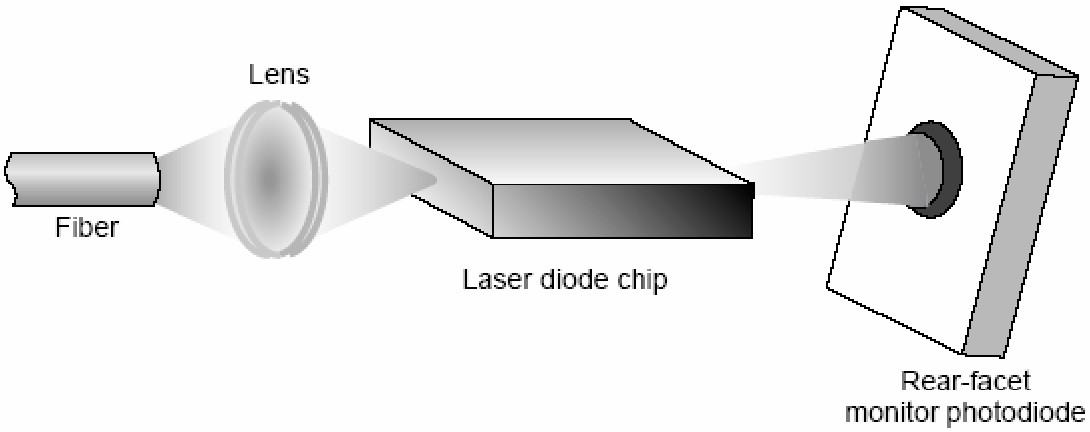
The light source used in the design of a system is an important consideration because it can be one of the most costly elements. Its characteristics are often a strong limiting factor in the final performance of the optical link. Light emitting devices used in optical transmission must be compact, monochromatic, stable, and long-lasting.

Two general types of light emitting devices are used in optical transmission, light-emitting diodes (LEDs) and laser diodes, or semiconductor lasers. LEDs are relatively slow devices, suitable for use at speeds of less than 1 Gbps, they exhibit a relatively wide spectrum width, and they transmit light in a relatively wide cone. These inexpensive devices are often used in multimode fiber communications.

Semiconductor lasers, on the other hand, have performance characteristics better suited to single-mode fiber applications.

Figure 2-15 shows the general principles of launching laser light into fiber. The laser diode chip emits light in one direction to be focused by the lens onto the fiber and in the other direction onto a photodiode. The photodiode, which is angled to reduce back reflections into the laser cavity, provides a way of monitoring the output of the lasers and providing feedback so that adjustments can be made.

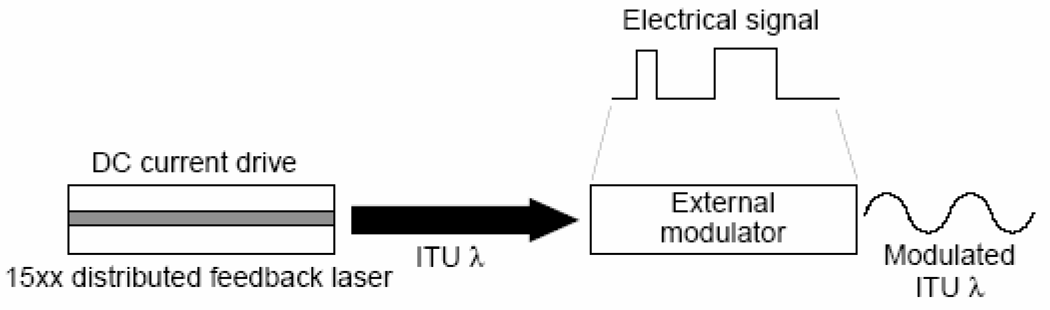
Figure 2-15 Typical Laser Design



Requirements for lasers include precise wavelength, narrow spectrum width, sufficient power, and control of *chirp* (the change in frequency of a signal over time). Semiconductor lasers satisfy nicely the first three requirements. Chirp, however, can be affected by the means used to modulate the signal.

In directly modulated lasers, the modulation of the light to represent the digital data is done internally. With external modulation, the modulation is done by an external device. When semiconductor lasers are directly modulated, chirp can become a limiting factor at high bit rates (above 10 Gbps). External modulation, on the other hand, helps to limit chirp. The external modulation scheme is depicted in Figure 2-16.

Figure 2-16 External Modulation of a Laser



Two types of semiconductor lasers are widely used, monolithic Fabry-Perot lasers, and distributed feedback (DFB) lasers. The latter type is particularly well suited for DWDM applications, as it emits a nearly monochromatic light, is capable of high speeds, has a favorable signal-to-noise ratio, and has superior linearity. DFB lasers also have center frequencies in the region around 1310 nm, and from 1520 to 1565 nm. The latter wavelength range is compatible with EDFAs. There are many other types and subtypes of lasers. Narrow spectrum tunable lasers are available, but their tuning range is limited to approximately 100-200 GHz. Under development are wider spectrum tunable lasers, which will be important in dynamically switched optical networks.

ITU Grid

Cooled DFB lasers are available in precisely selected wavelengths. The ITU draft standard G.692 defines a laser grid for point-to-point WDM systems based on 100-GHz wavelength spacings with a center wavelength of 1553.52 nm (see Table 2-1).

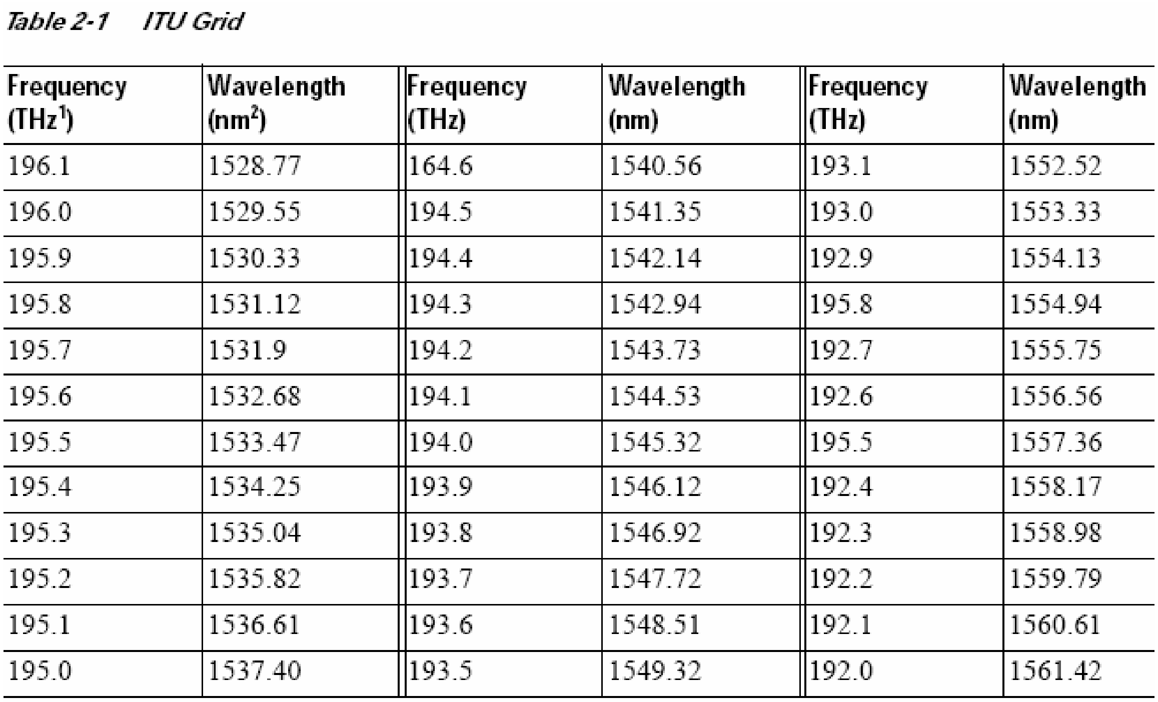


Table 2-1 ITU Grid

Frequency (THz[1])	Wavelength (nm[2])	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
196.1	1528.77	164.6	1540.56	193.1	1552.52
196.0	1529.55	194.5	1541.35	193.0	1553.33
195.9	1530.33	194.4	1542.14	192.9	1554.13
195.8	1531.12	194.3	1542.94	195.8	1554.94
195.7	1531.9	194.2	1543.73	192.7	1555.75
195.6	1532.68	194.1	1544.53	192.6	1556.56
195.5	1533.47	194.0	1545.32	195.5	1557.36
195.4	1534.25	193.9	1546.12	192.4	1558.17
195.3	1535.04	193.8	1546.92	192.3	1558.98
195.2	1535.82	193.7	1547.72	192.2	1559.79
195.1	1536.61	193.6	1548.51	192.1	1560.61
195.0	1537.40	193.5	1549.32	192.0	1561.42

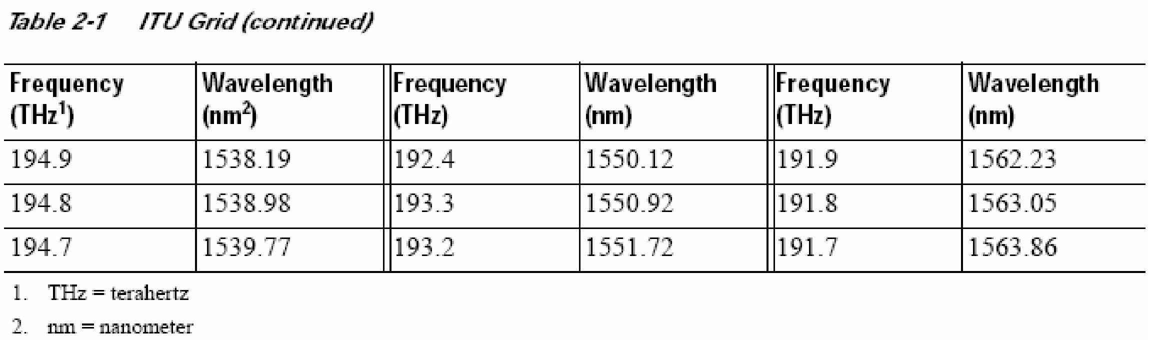


Table 2-1 ITU Grid (continued)

Frequency (THz[1])	Wavelength (nm[2])	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
194.9	1538.19	192.4	1550.12	191.9	1562.23
194.8	1538.98	193.3	1550.92	191.8	1563.05
194.7	1539.77	193.2	1551.72	191.7	1563.86

1. THz = terahertz
2. nm = nanometer

While this grid defines a standard, users are free to use the wavelengths in arbitrary ways and to choose from any part of the spectrum. In addition, manufacturers can deviate from the grid by extending the upper and lower bounds or by spacing the wavelengths more closely, typically at 50 GHz, to double the number of channels. The closer the spacing, the more channel crosstalk results. In addition, the impact of some fiber nonlinearities, such as FWM, increases. Spacing at 50 GHz also limits the maximum data rate per wavelength to 10 Gbps. The implications of the flexibility in implementation are twofold: There is no guarantee of compatibility between two end systems from different vendors,

and there exists a design trade-off in the spacing of wavelengths between number of channels and maximum bit rate.

Light Detectors

On the receive end, it is necessary to recover the signals transmitted at different wavelengths on the fiber. Because photo-detectors are by nature wideband devices, the optical signals are demultiplexed before reaching the detector.

Two types of photo-detectors are widely deployed, the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). PIN photodiodes work on principles similar to, but in the reverse of, LEDs. That is, light is absorbed rather than emitted, and photons are converted to electrons in a 1:1 relationship. APDs are similar devices to PIN photodiodes, but provide gain through an amplification process: One photon acting on the device releases many electrons. PIN photodiodes have many advantages, including low cost and reliability, but APDs have higher receive sensitivity and accuracy.

However, APDs are more expensive than PIN photodiodes, they can have very high current requirements, and they are temperature sensitive.

Optical Amplifiers

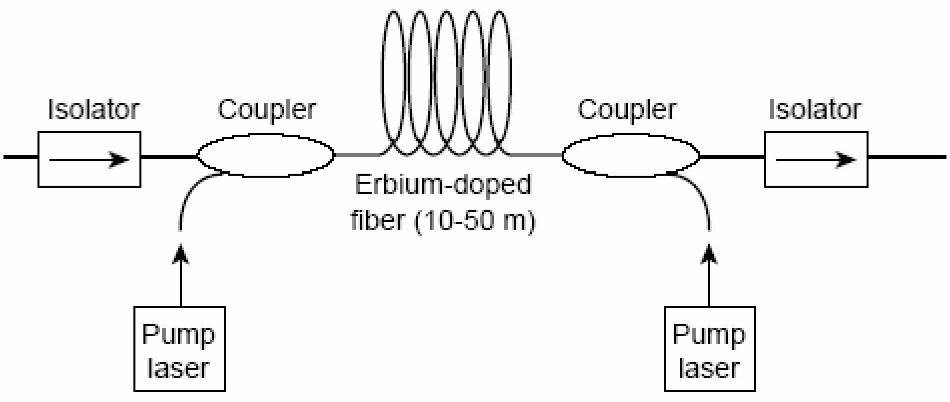
Due to attenuation, there are limits to how long a fiber segment can propagate a signal with integrity before it has to be regenerated. Before the arrival of optical amplifiers (OAs), there had to be a repeater for every signal transmitted, as discussed earlier and shown in Figure 1-11. The OA has made it possible to amplify all the wavelengths at once and without optical-electrical-optical (OEO) conversion. Besides being used on optical links, optical amplifiers also can be used to boost signal power after multiplexing or before demultiplexing, both of which can introduce loss into the system.

Erbium-Doped Fiber Amplifier

By making it possible to carry the large loads that DWDM is capable of transmitting over long distances, the EDFA was a key enabling technology. At the same time, it has been a driving force in the development of other network elements and technologies.

Erbium is a rare-earth element that, when excited, emits light around 1.54 micrometers—the low-loss wavelength for optical fibers used in DWDM. Figure 2-17 shows a simplified diagram of an EDFA. A weak signal enters the erbium-doped fiber, into which light at 980 nm or 1480 nm is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550-nm light. As this process continues down the fiber, the signal grows stronger. The spontaneous emissions in the EDFA also add noise to the signal; this determines the noise figure of an EDFA.

Figure 2-17 Erbium-Doped Fiber Amplifier Design



The key performance parameters of optical amplifiers are gain, gain flatness, noise level, and output power. EDFAs are typically capable of gains of 30 dB or more and output power of +17 dB or more. The target parameters when selecting an EDFA, however, are low noise and flat gain. Gain should be flat because all signals must be amplified uniformly. While the signal gain provided with EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters. Such filters are often built into modern EDFAs.

Low noise is a requirement because noise, along with signal, is amplified. Because this effect is cumulative, and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated and, therefore, the length of a single fiber link. In practice, signals can travel for up to 120 km (74 mi) between amplifiers. At longer distances of 600 to 1000 km (372 to 620 mi) the signal must be regenerated. That is because the optical amplifier merely amplifies the signals and does not perform the 3R functions (reshape, retime, retransmit). EDFAs are available for the C-band and the L-band.

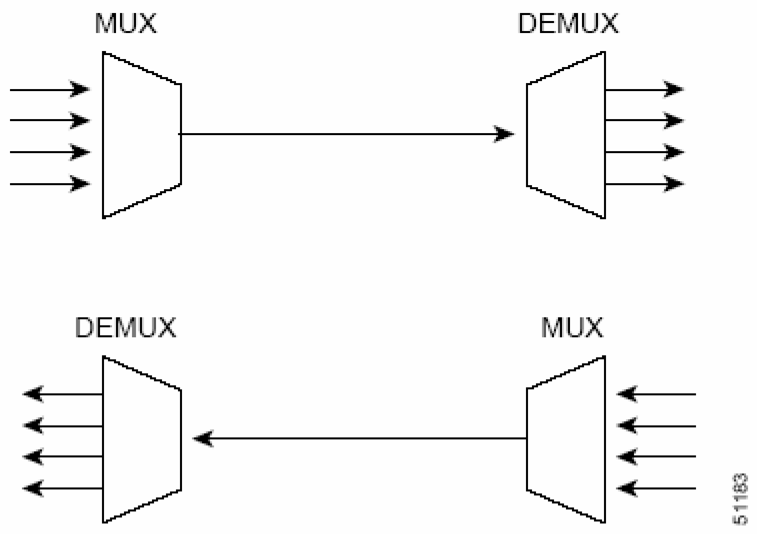
Multiplexers and De-multiplexers

Because DWDM systems send signals from several sources over a single fiber, they must include some means to combine the incoming signals. This is done with a multiplexer, which takes optical wavelengths from multiple fibers and converges them into one beam. At the receiving end the system must be able to separate out the components of the light so that they can be discreetly detected. De-multiplexers perform this function by separating the received beam into its wavelength components and coupling them to

individual fibers. Demultiplexing must be done before the light is detected, because photo-detectors are inherently broadband devices that cannot selectively detect a single wavelength.

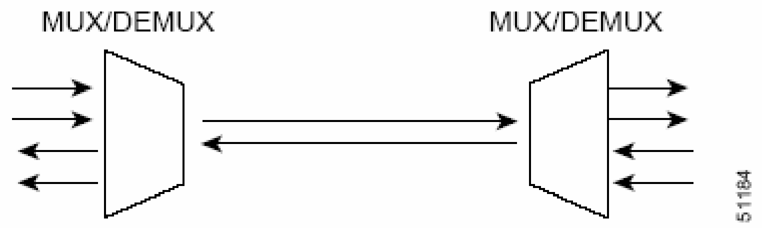
In a unidirectional system (see Figure 2-18), there is a multiplexer at the sending end and a demultiplexer at the receiving end. Two system would be required at each end for bidirectional communication, and two separate fibers would be needed.

Figure 2-18 Multiplexing and Demultiplexing in a Unidirectional System



In a bidirectional system, there is a multiplexer/demultiplexer at each end (see Figure 2-19) and communication is over a single fiber pair.

Figure 2-19 Multiplexing and Demultiplexing in a Bidirectional System

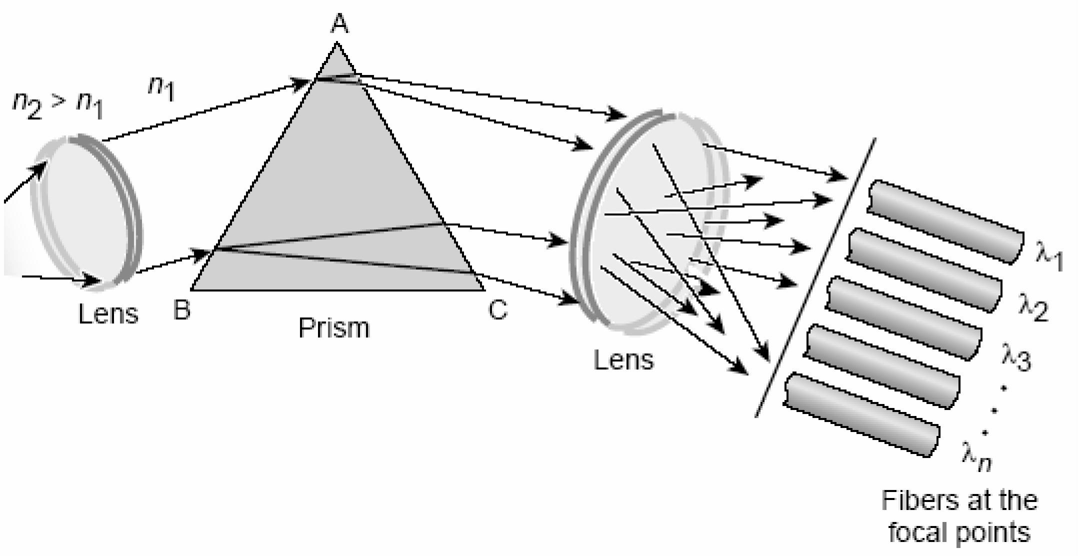


Multiplexers and de-multiplexers can be either passive or active in design. Passive designs are based on prisms, diffraction gratings, or filters, while active designs combine passive devices with tunable filters.
The primary challenges faced, in these devices is to minimize cross-talk and maximize channel separation. Cross-talk is a measure of how well the channels are separated, while channel separation refers to the ability to distinguish each wavelength.

Techniques for Multiplexing and Demultiplexing

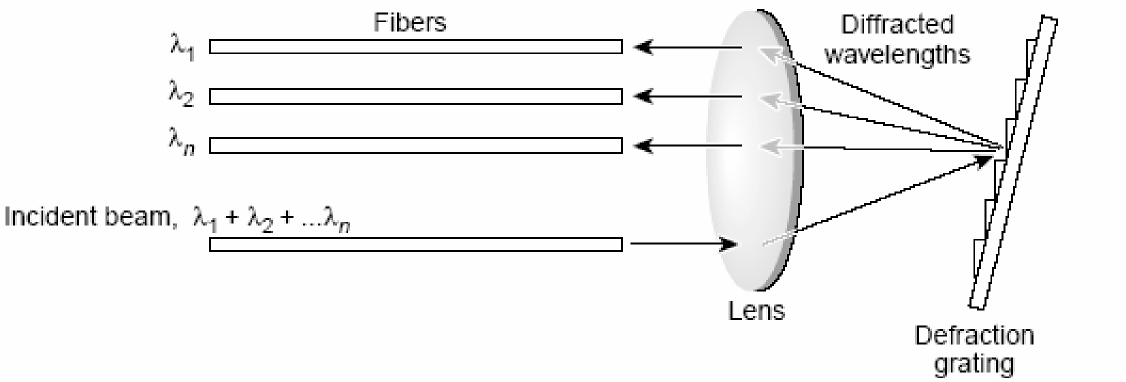
A simple form of multiplexing or demultiplexing of light can be done using a prism. Figure 2-20 demonstrates the demultiplexing case. A parallel beam of polychromatic light impinges on a prism surface; each component wavelength is refracted differently. This is the “rainbow” effect. In the output light, each wavelength is separated from the next by an angle. A lens then focuses each wavelength to the point where it needs to enter
a fiber. The same components can be used in reverse to multiplex different wavelengths onto one fiber.

Figure 2-20 Prism Refraction Demultiplexing



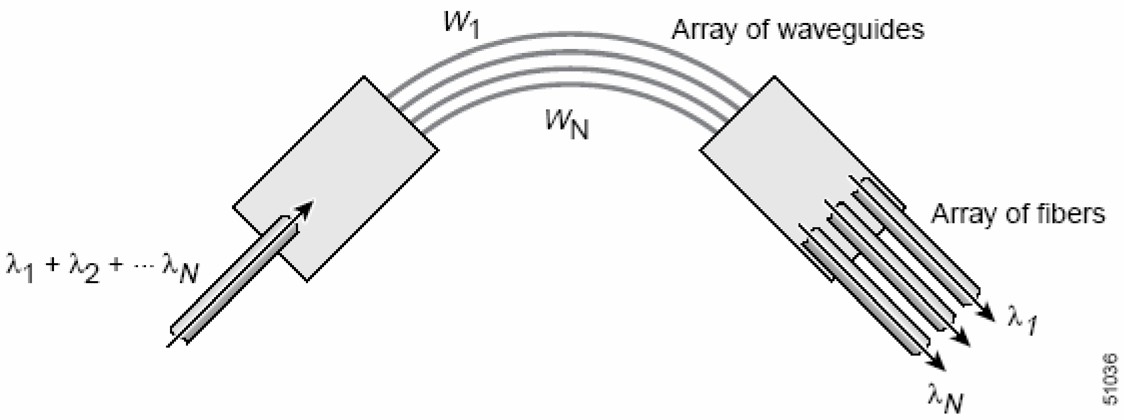
Another technology is based on the principles of diffraction and of optical interference. When a polychromatic light source impinges on a diffraction grating (see Figure 2-21), each wavelength is diffracted at a different angle and therefore to a different point in space. Using a lens, these wavelengths can be focused onto individual fibers.

Figure 2-21 Waveguide Grating Diffraction



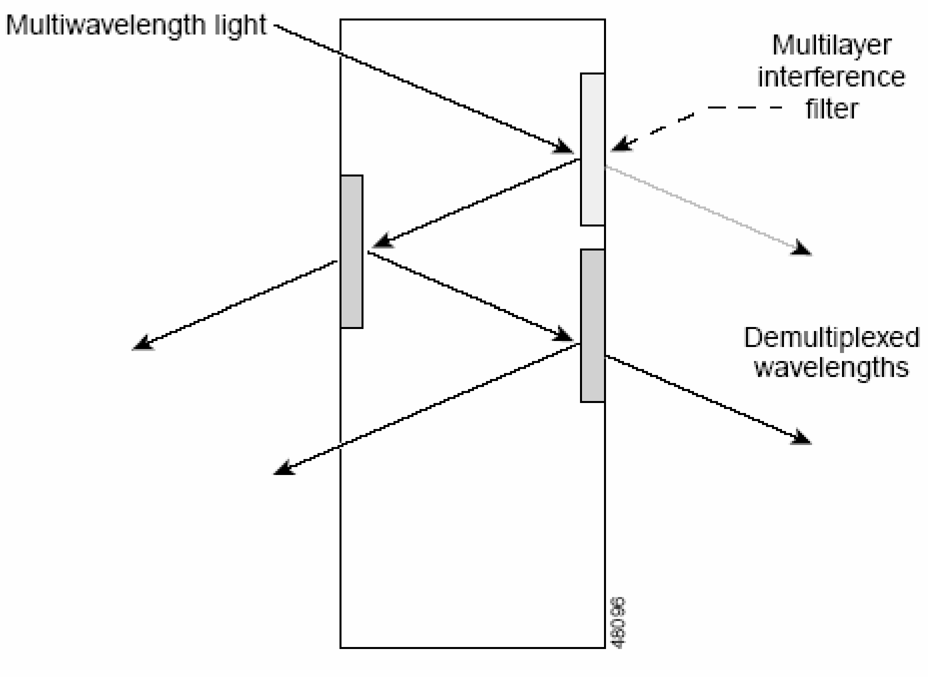
Arrayed waveguide gratings (AWGs) are also based on diffraction principles. An AWG device, sometimes called an optical waveguide router or waveguide grating router, consists of an array of curved-channel waveguides with a fixed difference in the path length between adjacent channels (see Figure 2-22). The waveguides are connected to cavities at the input and output. When the light enters the input cavity, it is diffracted and enters the waveguide array. There the optical length difference of each waveguide introduces phase delays in the output cavity, where an array of fibers is coupled. The process results in different wavelengths having maximal interference at different locations, which correspond to the output ports.

Figure 2-22 Arrayed Waveguide Grating



A different technology uses interference filters in devices called *thin film filters* or *multilayer interference filters*. By positioning filters, consisting of thin films, in the optical path, wavelengths can be sorted out (demultiplexed). The property of each filter is such that it transmits one wavelength while reflecting others. By cascading these devices, many wavelengths can be demultiplexed (see Figure 2-23).

Figure 2-23 Multilayer Interference Filters



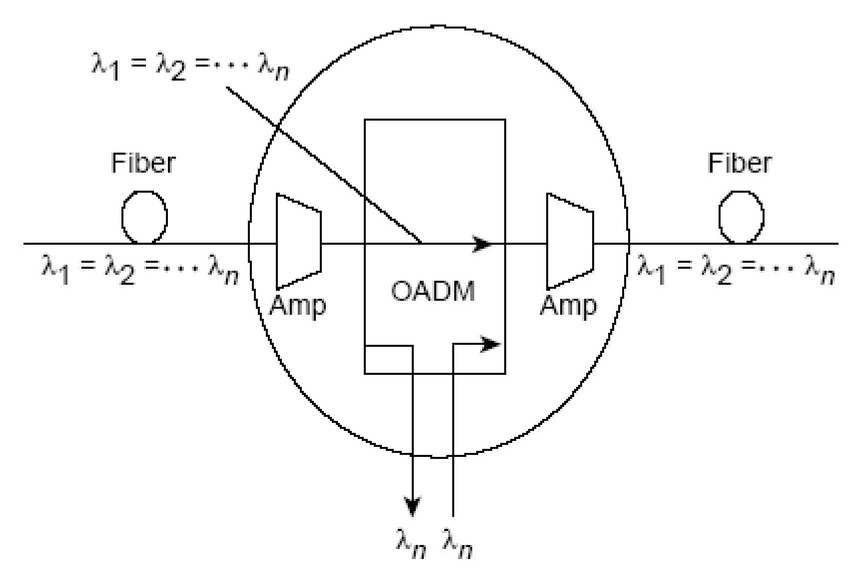
Of these designs, the AWG and thin film interference filters are gaining prominence. Filters offer good stability and isolation between channels at moderate cost, but with a high insertion loss. AWGs are polarization-dependent (which can be compensated), and they exhibit a flat spectral response and low insertion loss. A potential drawback is that they are temperature sensitive such that they may not be practical in all environments. Their big advantage is that they can be designed to perform multiplexing and demultiplexing operations simultaneously. AWGs are also better for large channel counts, where the use of cascaded thin film filters is impractical.

Optical Add/Drop Multiplexers

Between multiplexing and demultiplexing points in a DWDM system, as shown in Figure 2-18, there is an area in which multiple wavelengths exist. It is often desirable to be able to remove or insert one or more wavelengths at some point along this span. An optical add/drop multiplexer (OADM) performs this function. Rather than combining or separating all wavelengths, the OADM can remove some while passing others on. OADMs are a key part of moving toward the goal of all-optical networks.

OADMs are similar in many respects to SONET ADM, except that only optical wavelengths are added and dropped, and no conversion of the signal from optical to electrical takes place. Figure 2-24 is a schematic representation of the add-drop process. This example includes both pre- and post-amplification; these components that may or may not be present in an OADM, depending upon its design.

Figure 2-24 Selectively Removing and Adding Wavelengths



There are two general types of OADMs. The first generation is a fixed device that is physically configured to drop specific predetermined wavelengths while adding others.

The second generation is reconfigurable and capable of dynamically selecting which wavelengths are added and dropped.

Thin-film filters have emerged as the technology of choice for OADMs in current metropolitan DWDM systems because of their low cost and stability. For the emerging second generation of OADMs, other technologies, such as tunable fiber gratings and circulators, will come into prominence.

Interfaces to DWDM

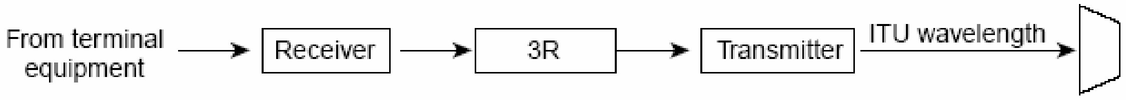
Most DWDM systems support standard SONET/SDH short-reach optical interfaces to which any SONET/SDH compliant client device can attach. In today's long-haul WDM systems, this is most often an OC-48c/STM-16c interface operating at the 1310-nm wavelength. In addition, other interfaces important in metropolitan area and access networks are commonly supported: Ethernet (including Fast Ethernet and Gigabit Ethernet), ESCON, Sysplex Timer and Sysplex Coupling Facility Links, and Fibre

Channel. The new 10 Gigabit Ethernet standard is supported using a very short reach (VSR) OC-192 interface over MM fiber between 10 Gigabit Ethernet and DWDM equipment.

On the client side there can be SONET/SDH terminals or ADMs, ATM switches, or routers. By converting incoming optical signals into the precise ITU-standard wavelengths to be multiplexed, *transponders* are currently a key determinant of the openness of DWDM systems. Within the DWDM system a transponder converts the client optical signal from back to an electrical signal and performs the 3R functions (see Figure 2-25). This electrical signal is then used to drive the WDM laser. Each transponder within the system converts its client's signal to a slightly different wavelength. The wavelengths from all of the transponders in the system are then optically multiplexed.

In the receive direction of the DWDM system, the reverse process takes place. Individual wavelengths are filtered from the multiplexed fiber and fed to individual transponders, which convert the signal to electrical and drive a standard interface to the client.

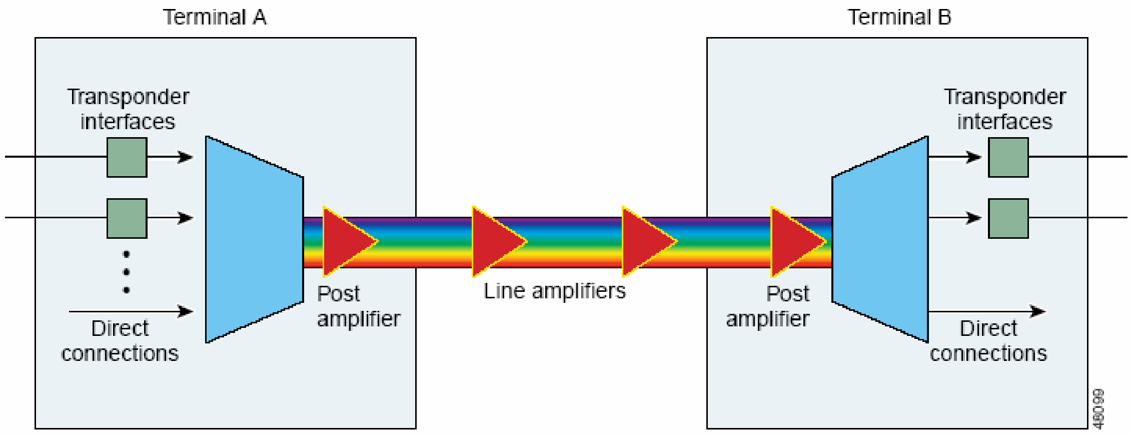
Figure 2-25 Transponder Functions



Operation of a Transponder Based DWDM System

Figure 2-26 shows the end-to-end operation of a unidirectional DWDM system.

Figure 2-26 Anatomy of a DWDM System



The following steps describe the system shown in Figure 2-26:

1. The transponder accepts input in the form of standard single-mode or multimode laser. The input can come from different physical media and different protocols and traffic types.

2. The wavelength of each input signal is mapped to a DWDM wavelength.

3. DWDM wavelengths from the transponder are multiplexed into a single optical signal and launched into the fiber. The system might also include the ability to accept direct optical signals to the multiplexer; such signals could come, for example, from a satellite node.

4. A post-amplifier boosts the strength of the optical signal as it leaves the system (optional).

5. Optical amplifiers are used along the fiber span as needed (optional).

6. A pre-amplifier boosts the signal before it enters the end system (optional).
7. The incoming signal is demultiplexed into individual DWDM lambdas (or wavelengths).

8. The individual DWDM lambdas are mapped to the required output type (for example, OC-48 single-mode fiber) and sent out through the transponder.

Introduction

In an optical communication system we use the intensity of the light to represent the digital data bits “1” and “0”. Normally, light on means 1 and light off is 0. The *data rate* or *bit rate* is the speed at which these bits are transmitted. Clearly, the temporal width of the light pulses we use to represent the bits must not exceed the bit time interval. If we look at the wavelength spectrum of an optical pulse coming from a laser source (Fig. 1), we see that the laser not only emits light at one wavelength but emits a small continuous spectrum around a *center wavelength* λ_0. Unfortunately, the different spectral components propagate through the fiber at different velocities due to a wavelength dependent refractive index. Thus, the pulse will spread in time. This is what we call *chromatic dispersion*. After propagating a certain length, the pulses will exceed the bit time interval and we get *intersymbol interference*, as illustrated in Fig. 3.2.

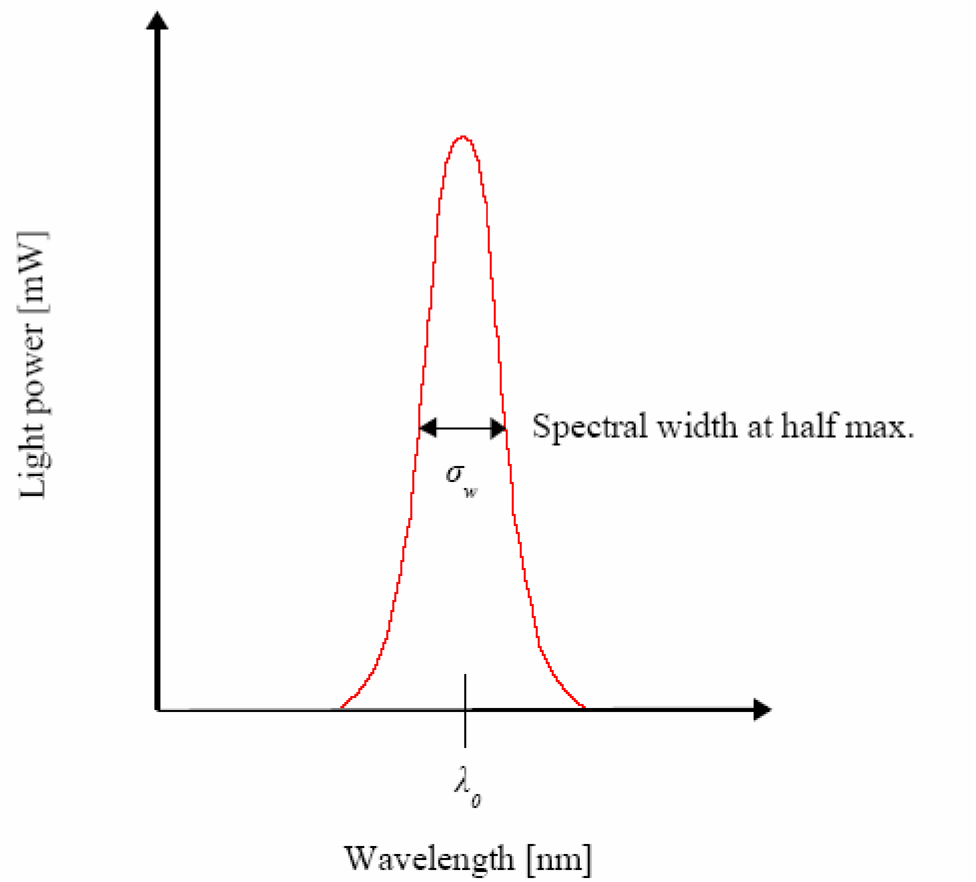
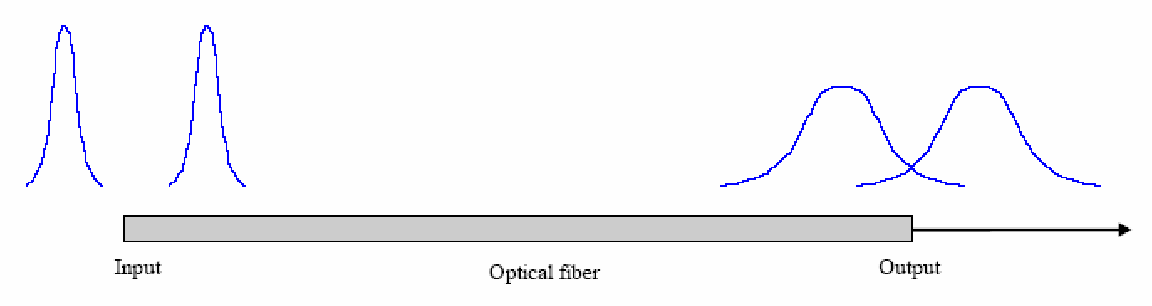


Fig.3. 1: Wavelength spectrum of a laser pulse. λ_0 *is the center wavelength. The spectral bandwidth* σ_w *is often denoted the full pulse width at half maximum value.*



` *Fig. 3.2: Two pulses before and after propagation through fiber. The pulses are spread in time and will eventually overlap (intersymbol interference).*

Dispersion

The *dispersion coefficient* $D(\lambda)$ is a parameter describing the relation between the initial spectral width σ_w of the pulse and the temporal pulse width σ_t at the fiber output due to chromatic dispersion. Its unit is ps/(nm-km). This parameter tells us how many picoseconds the pulse broadens per kilometer of fiber per nanometer of pulse spectral width [1]:

$$\sigma_t = |D(\lambda)|\sigma_w L \qquad (1)$$

L is the length of the fiber. An empirical formula used to estimate $D(\lambda)$ is [2]:

$$D(\lambda) = \lambda \frac{S_0}{4}\left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right] \qquad (2)$$

λ_0 is the reference wavelength,

i.e. the wavelength where the dispersion coefficient is 0, which is ~1312 nm for a standard single-mode fiber. S_0 is the dispersion slope, which tells us how much the dispersion changes with wavelength. These parameters are available from fiber specification sheets. OptSim uses Equation (2) to calculate chromatic dispersion. At common communication wavelengths around 1550 nm, the dispersion coefficient is positive, which means that shorter-wavelength components travel faster than the longer components. However, it is possible to produce fibers with customized coefficient values by altering the material composition and waveguide design.

NON LINEARITIES IN OPTICAL FIBER NETWORK AND EFFECT OF FOUR-WAVE MIXING ON DWDM NETWORKS.

Non-linear effects have become significant at high optical power levels and have become even more important since the development of the erbium-doped fiber amplifier (EDFA) and wavelength division multiplexed (WDM) systems. By increasing information spectral efficiency which can be done by increasing
channel bit rate, decreasing channel spacing or the combination of both, the effects of fiber non-linearity come to play even more decisive role. Although the individual power in each channel may
be below the one needed to produce non-linearities, the total power summed over all channels can quickly become significant. The combination of high total optical power and a large number of channels at closely spaced wavelengths is ideal for many kinds of

non-linear effects. For all these reasons it is important to understand non-linear phenomena and to be able to simply and accurately measure fiber non-linearities.

Non-linear effects in optical systems

The refractive index of silica, the major material of optical fiber, has a slight dependence on the intensity of the optical field. This dependence is known as the optical Kerr effect. The general expression for the refractive index n of silica includes a constant term $n0$ and a power density dependent term $n2S$, where $n2$ is
known as second-order refractive index.

$$n = n0 + n2S$$

Refractive index is a dimensionless parameter, optical power density is measured in Watts per square meter and therefore the second-order refractive index has units of square meter per Watts. Typical values of $n0$ and $n2$ are 1,5 and 2,5×10-20 m2/W, respectively. Silica has one of the lowest $n2$ of any optical material. It can easily be shown that high intensities are required to make the
intensity dependent term comparable to the constant one. In spite of this, appearance of non-linear phenomena in single or multi channel communication systems is frequent. Actually, non-linearities can occur at reasonable powers of few dBm in the fiber because of large distances and small effective core area.

Self-phase modulation (SPM)

The SPM refers to the self-induced phase shift experienced by an optical field during its propagation in fiber. The non-linear phase shift jNL is given by where *P* is optical power, *Aeff* is the effective fiber core area, and is the vacuum wavelength of the signal. The effective fiber length *Leff* determines the distance where non-linear effects are stronger. The *Leff* is given as *Leff*=(1-*e*-a*L*)/a, where *L* is the fiber length, a is the fiber attenuation coefficient. The polarization parameter *m* depends on the polarization characteristics of the fiber and the input signal polarization state. For pulses in digital communication systems the phase is delayed at the pulse maximum relative to the wings. The effect of the non-linear phase shift is producing new frequencies and the power spectrum is broadening during signal propagation. The amount of broadening depends on the fiber length, peak input power and fiber dispersion. Greater frequency width then increases pulse spreading through group-velocity dispersion.

Modulation instability (MI)

The modulation instability is a phenomenon of spontaneous modulation of the continuous-wave (CW) laser. It refers to the selective amplification of noise and it occurs only in the anomalous dispersion regime (D>0). Actually, the MI originates from the interplay between Kerr effect and anomalous dispersion, and gives rise to two spectral gain bands, symmetrically located with respect to the pump frequency w0±W. The MI spectral gain coefficient is given by

$$g(\Omega)=|\beta\Omega|\sqrt{2\omega_{\mathrm{MI}}^{2}-\Omega^{2}},$$

where $\beta=-(\lambda^2/2\pi c)D$, $\omega_{\mathrm{MI}}=\sqrt{2\gamma P/|\beta|}$ (the modulation instability frequency), and P is optical power.

Cross-phase modulation (XPM)

When two or more optical waves propagate inside the fiber, the refractive index seen by a particular wave depends not only on the intensity of that wave but also on the intensity of other copropagating waves. The nonlinear phase shift for the *j*th channel depends on the power of that and other channels and is given by

$$\varphi_{NL,j}=\frac{2\pi}{\lambda}\cdot\frac{n_2}{A_{eff}}\cdot L_{eff}\cdot m\cdot\left(P_j+2\sum_{m\neq j}^{M}P_m\right),$$

where *Pj* is the channel power and *M* is the total number of channels. The factor 2 indicates that XPM is twice as effective as SPM for the same amount of power. Similar as SPM, XPM manifests as an alteration of the optical phase of a channel, which translates into intensity distortion through group-velocity dispersion.

Four-wave mixing (FWM)

Four-wave mixing is another effect produced by the intensity-dependent refractive index. It occurs when two or more wavelengths of light propagate together through an optical fiber. Providing a condition known as phase matching is satisfied, light is generated at new frequencies using optical power from the original signals. The FWM generated power is given by

$$P_{i,j,k} = \left(\frac{D}{3}\right)^2 \left(\frac{2\pi n_2 L_{eff}}{\lambda A_{eff}}\right)^2 P_i P_j P_k e^{-\alpha L} \eta,$$

where *D* is degenerescency factor and h stands for FWM efficiency. FWM has very serious implications multichannel WDM communication systems. The power in existing signals will be reduced as some is transferred to the new mixing products. If the new frequencies also happen to fall on allocated channels, then the overall system performance will be degraded by crosstalk.

Phase matching only occurs for particular combinations of fiber dispersion and signal frequencies. In particular, phase matching is achieved for signals with very similar frequencies propagating near the zero dispersion wavelength of the fiber. When *N* channels are launched in the fiber, the number of generated mixing products is

$$M = \frac{N^2}{2} \cdot (N-1).$$

When a high-power optical signal is launched into a fiber, the linearity of the optical response is lost. One such nonlinear effect, which is due to the third-order electric susceptibility is called the optical Kerr effect. Four-wave mixing (FWM) is a type of optical Kerr effect, and occurs when light of two or more different wavelengths is launched into a fiber. Generally speaking FWM occurs when light of three different wavelengths is lauched into a fiber, giving rise to a new wave (know as an idler), the wavelength of which does not coincide with any of the others. FWM is a kind of optical parametric oscillation. In the transmission of dense wavelength-division multiplexed (DWDM) signals, FWM is to be avoided, but for certain applications, it provides an effective technological basis for fiber-optic devices. FWM also provides the basic technology for measuring the nonlinearity and chromatic dispersion of optical fibers.

FOUR WAVE MIXING METHOD

In the first case, the non-linear coefficient of FUT is measured by FWM method using two 1550 nm DFB lasers, which generate two continuous waves of wavelengths separation Dl. The two waves of equal power are sent to two EDFAs, combined and sent to FUT. The polarizations of the waves are adjusted using PCs and a polarizer until they become linear and parallel to each other. After propagation, the output signal is fed to an optical spectrum analyzer to get the power ratio between the pumps power and the harmonics power, generated by FWM.

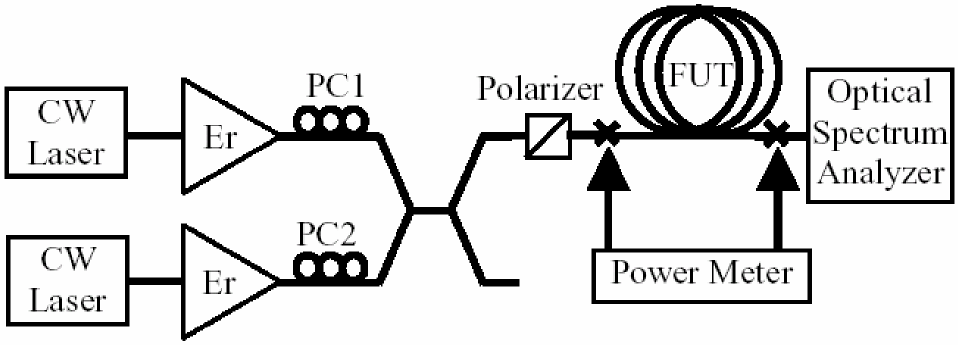
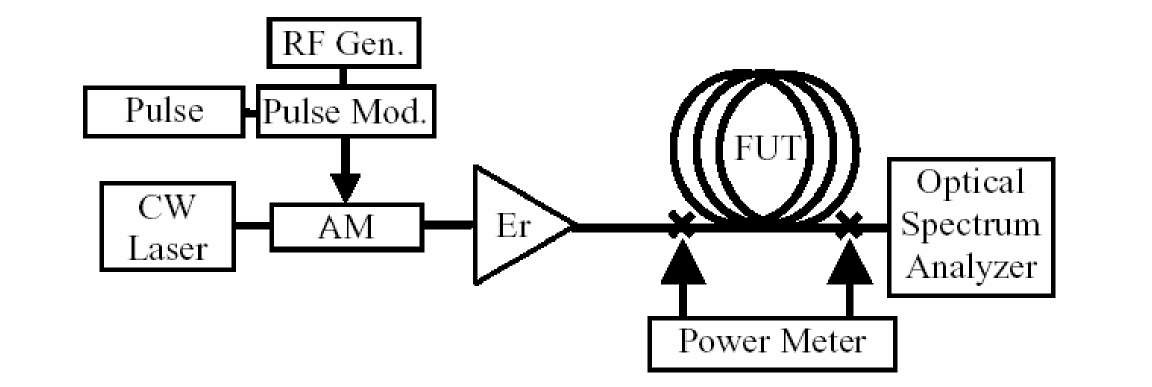


Fig. 9 FWM method with two CW lasers

Fig3.3

In FWM method, presented recently, two CW lasers are replaced by one externally modulated laser source. Carrier suppressed amplitude modulation (AM) with a train of RF pulses of given width and repetition period gives two sidebands, separated by twice the RF modulation frequency. The sidebands, having the same polarization and equal power, are amplified using one EDFA only. High peak powers are obtained by using low duty cycles. This simple measurement scheme employs one laser source only. It is polarization independent and enables high sensitivity, which leads to higher accuracy.



Simulation of Fiber Optic Link

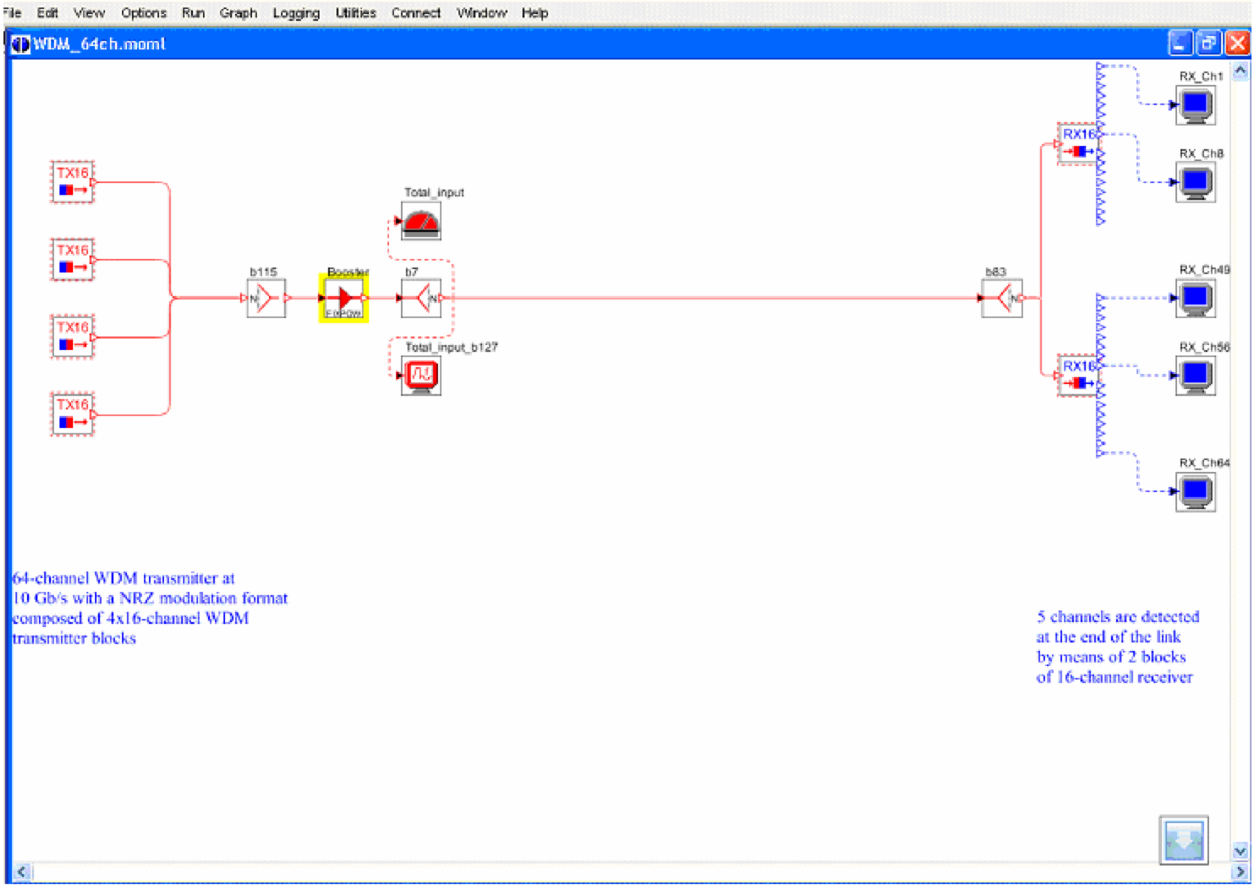
Supervisor: **Dr. MURALIDHAR KULKARNI**

Motivation

The objective of thesis exercise is to study the performance of an optical high-speed network. We will use the simulation tool OptSim to calculate common performance parameters in a basic fiber optic link. Thus, we will also learn how to characterize a transmission system.

The Fiber Optic Link

We will consider a basic fiber optic link with a four 16 channel transmitters(compound components), a standard single-mode fiber, booster(EDFA) and a receiver(5 channels are detected), as shown in Fig. 3.4.



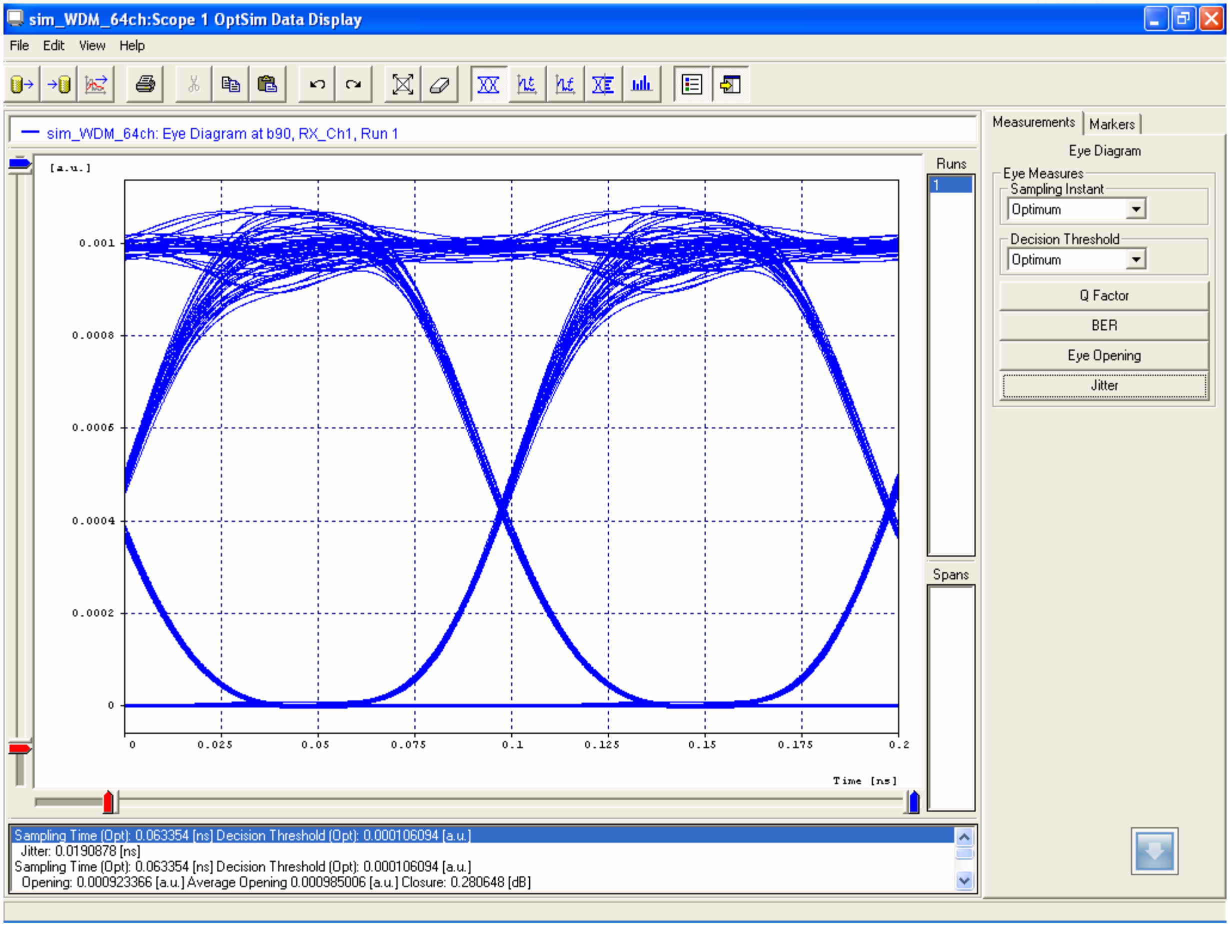
64-channel WDM transmitter at 10 Gb/s with a NRZ modulation format composed of 4x16-channel WDM transmitter blocks

5 channels are detected at the end of the link by means of 2 blocks of 16-channel receiver

Fig. 3.4: Basic fiber optic link with test and monitoring components.

OptSim does not count the number of errors, as one would do when measuring BER in a lab, but estimates the BER from the *eye diagram* in order to decrease the simulation time.
The data signal is converted into an optical signal where no light means logical 0 and presence of light means 1.

A receiver needs a minimum optical input power in order to keep BER below a given maximum value [4]. By coupling the light from the laser directly into the receiver (except for a variable attenuator between the laser and the receiver), we can measure BER versus power. This is a *back-to-back* measurement, which is the reference to which we compare all other measurements. The leftmost graph in Fig. 4 shows a back-to-back measurement. Inserting fibers, amplifiers and other components into the transmission path will introduce impairments like noise and dispersion, and we need to increase the power in order to maintain the same BER. The value of this power increase is termed the *power penalty* and is often defined at BER=10^{-9}. The power required to achieve BER=10^{-9} is called the *sensitivity*. The second plot in Fig. 4 is the BER of the complete system, and in this case there is a power penalty of 3 dB.



Sampling Instant: Optimum

Decision Threshold: Optimum

```
Sampling Time (Opt): 0.063354 [ns] Decision Threshold (Opt): 0.000106094 [a.u.]
 Jitter: 0.0190878 [ns]
Sampling Time (Opt): 0.063354 [ns] Decision Threshold (Opt): 0.000106094 [a.u.]
 Opening: 0.000923366 [a.u.] Average Opening 0.000985006 [a.u.] Closure: 0.280648 [dB]
```

Fig. 3.5: Eye diagram obtained at channel 1 as calculated by OptSim. The top line is the signal level of 1s, while the bottom line is the signal level of 0s.

The last monitor in the system, “Eye_Diagram”, is an oscilloscope that displays a superposition of many bits. This produces an eye like diagram (see Fig. 3.5) in which the eye opening is a measure of the degradation of the link. An open eye with sharp lines means good performance, while noise and intersymbol interference appears as spreading of the rails.

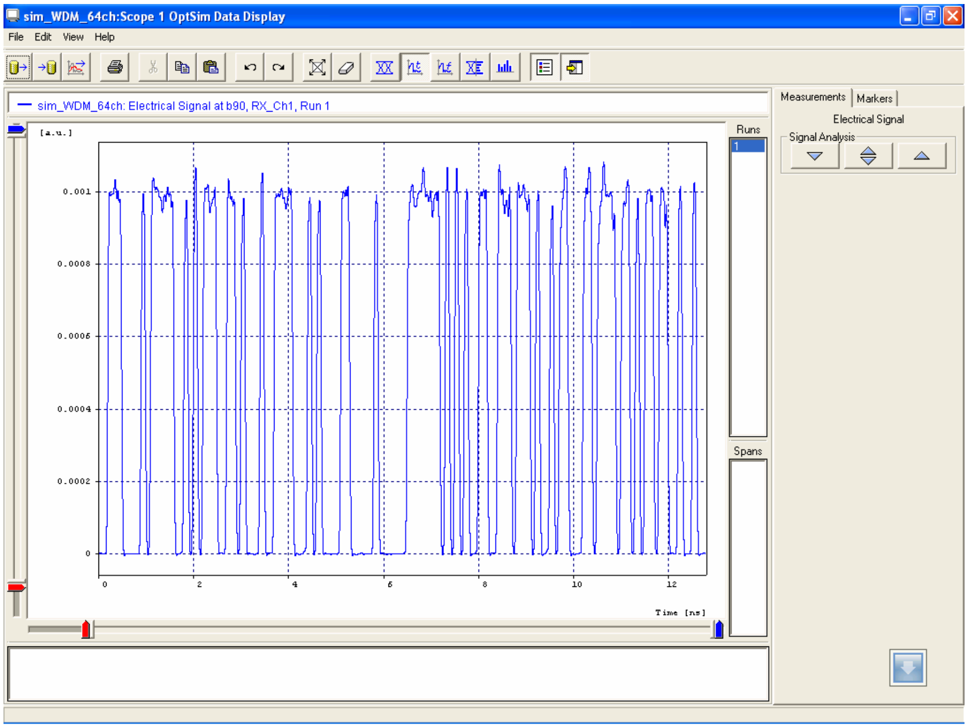
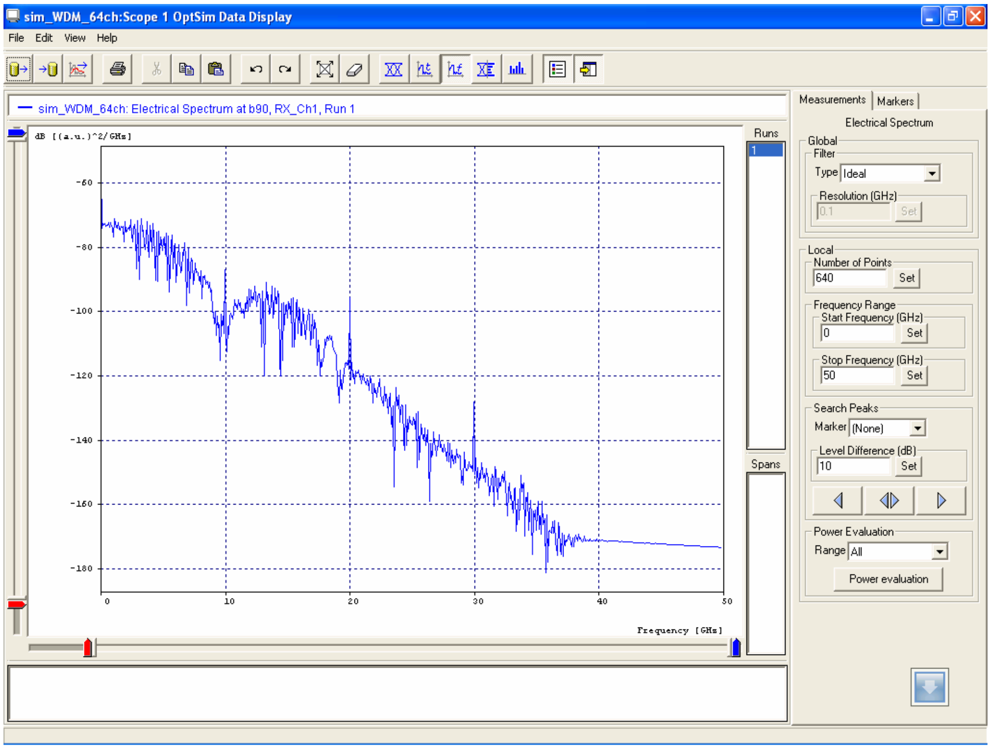
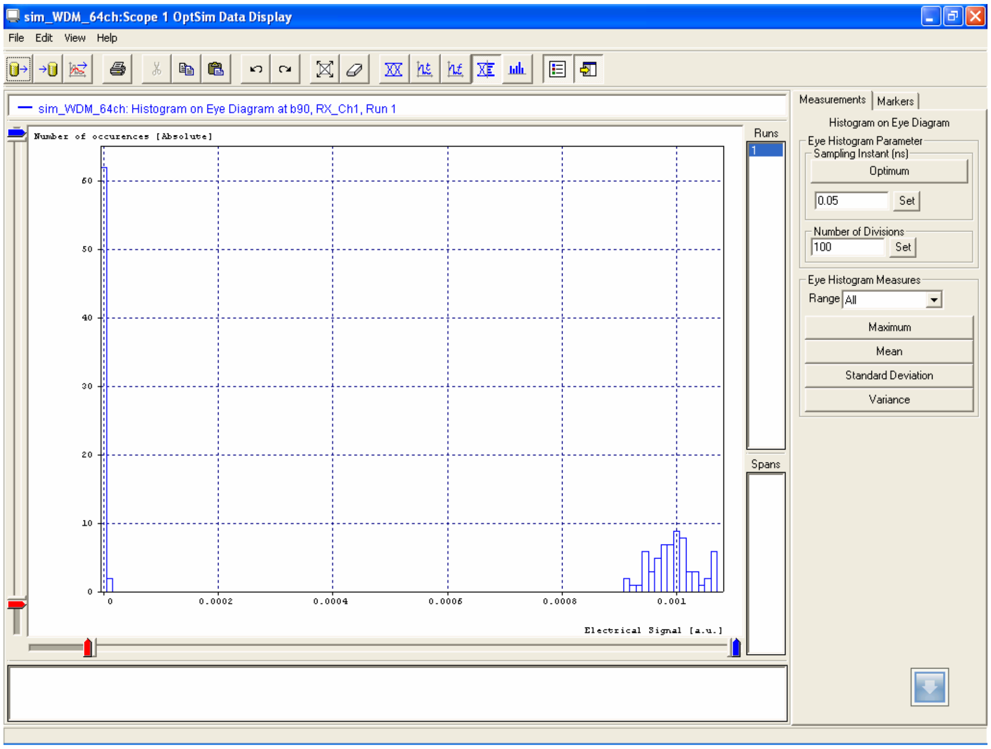


Fig. 3.6: Electrical signal at channel 1 as calculated by OptSim.



Type: Ideal
Resolution (GHz): 0.1
Number of Points: 640
Start Frequency (GHz): 0
Stop Frequency (GHz): 50
Marker: (None)
Level Difference (dB): 10
Range: All

Fig. 3.7: Electrical spectrum at channel 1 as calculated by OptSim.


sim_WDM_64ch:Scope 1 OptSim Data Display

sim_WDM_64ch: Histogram on Eye Diagram at b90, RX_Ch1, Run 1

Histogram on Eye Diagram

Eye Histogram Parameter

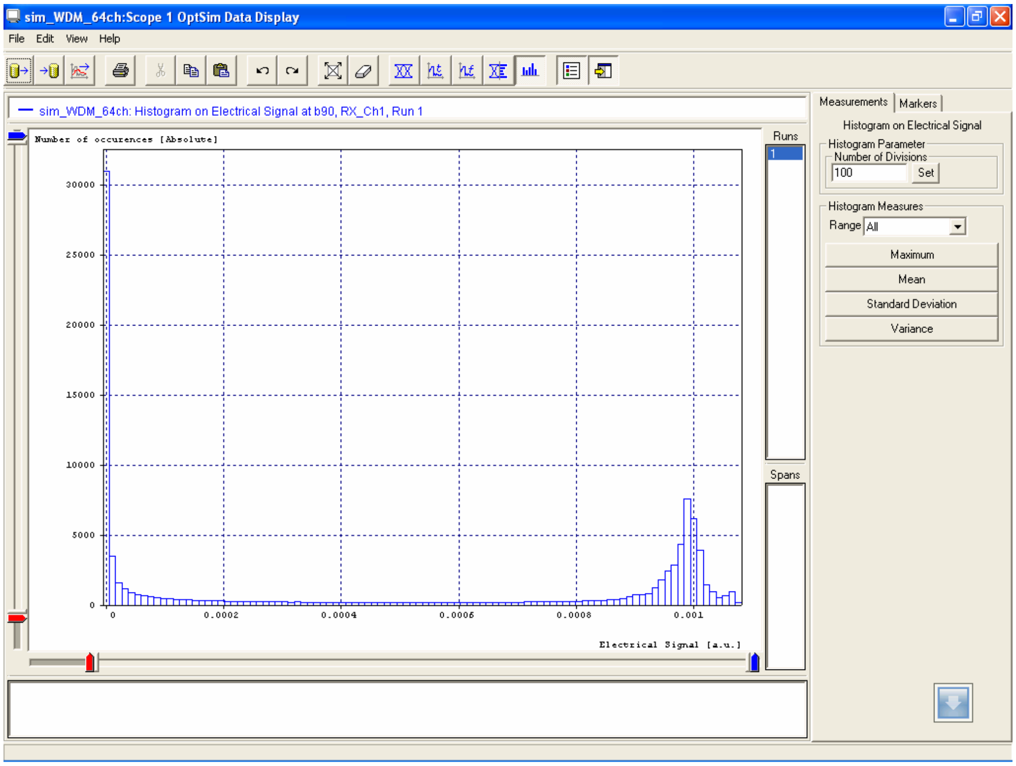
Sampling Instant (ns): 0.05

Number of Divisions: 100

Eye Histogram Measures

Range: All

Fig. 3.8: histogram on eye diagram at channel 1 as calculated by OptSim.


sim_WDM_64ch:Scope 1 OptSim Data Display

sim_WDM_64ch: Histogram on Electrical Signal at b90, RX_Ch1, Run 1

Histogram on Electrical Signal

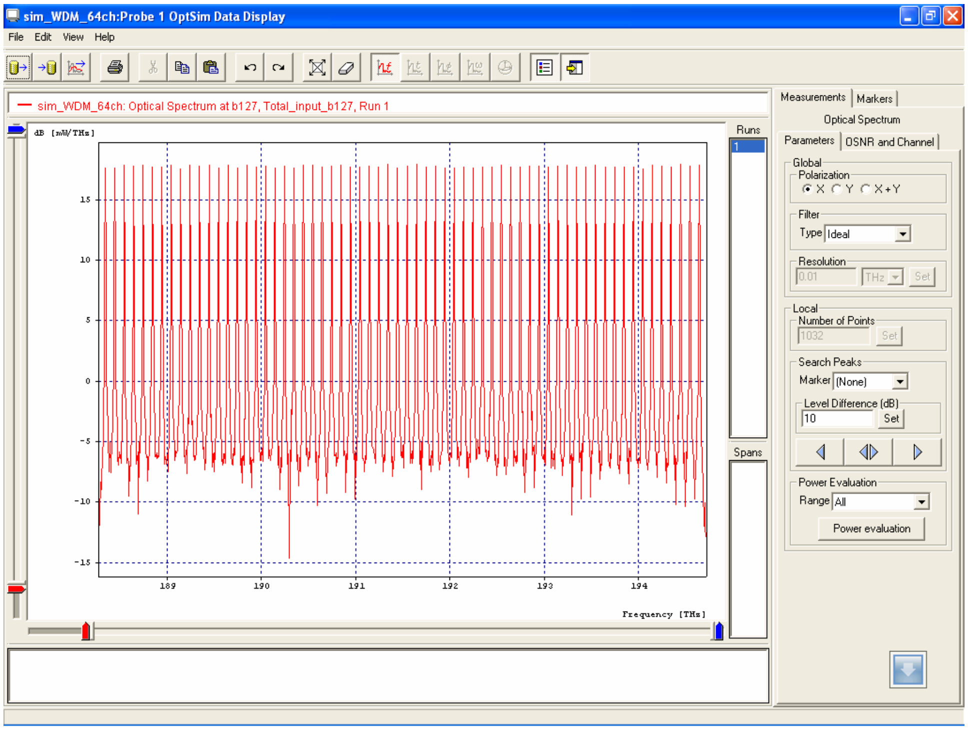
Histogram Parameter

Number of Divisions: 100

Histogram Measures

Range: All

Fig. 3.9: histogram on electrical signal at channel 1 as calculated by OptSim.



sim_WDM_64ch:Probe 1 OptSim Data Display

sim_WDM_64ch: Optical Spectrum at b127, Total_input_b127, Run 1

Polarization: ● X ○ Y ○ X+Y

Filter Type: Ideal

Resolution: 0.01 THz

Number of Points: 1032

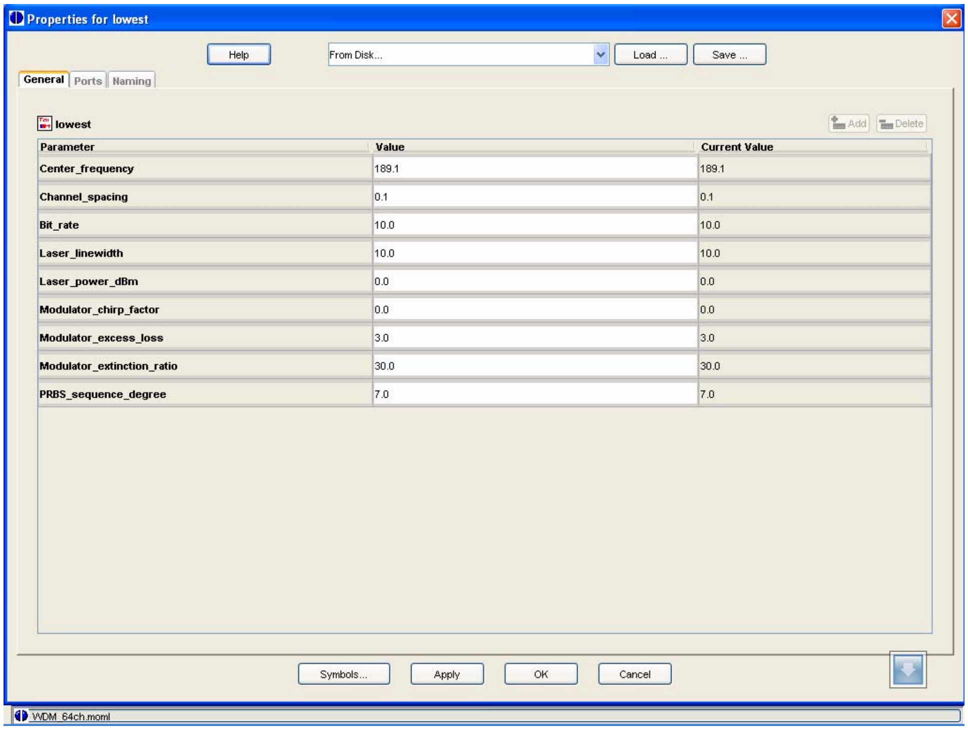
Search Peaks Marker: (None)

Level Difference (dB): 10

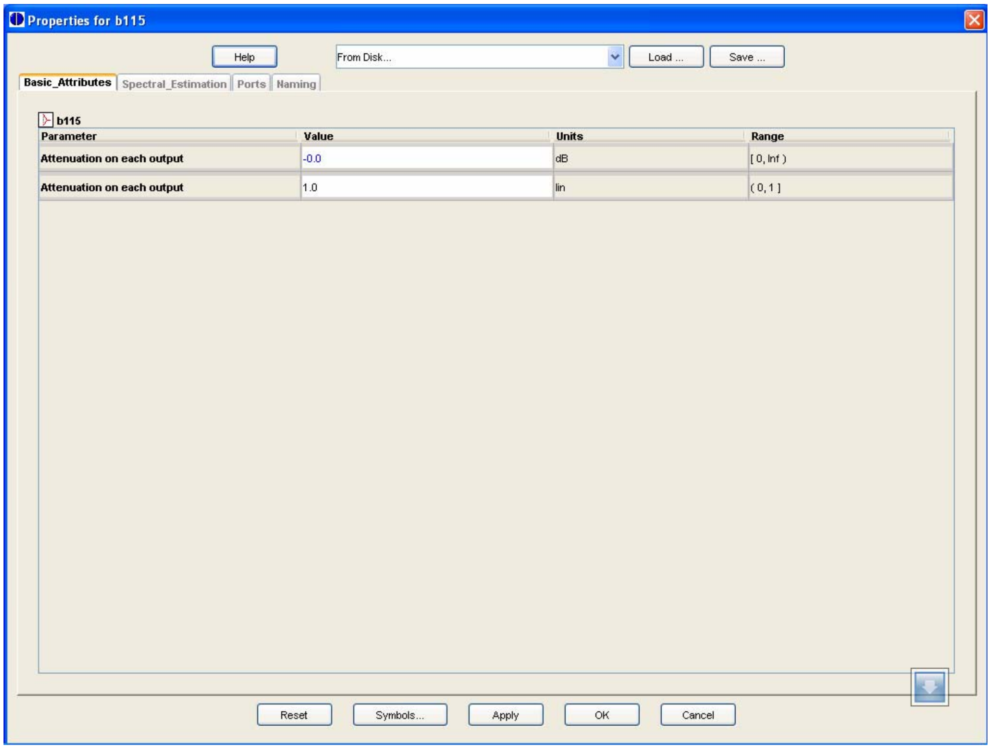
Power Evaluation Range: All

Fig. 3.10:Total input optical spectrum as calculated by OptSim.

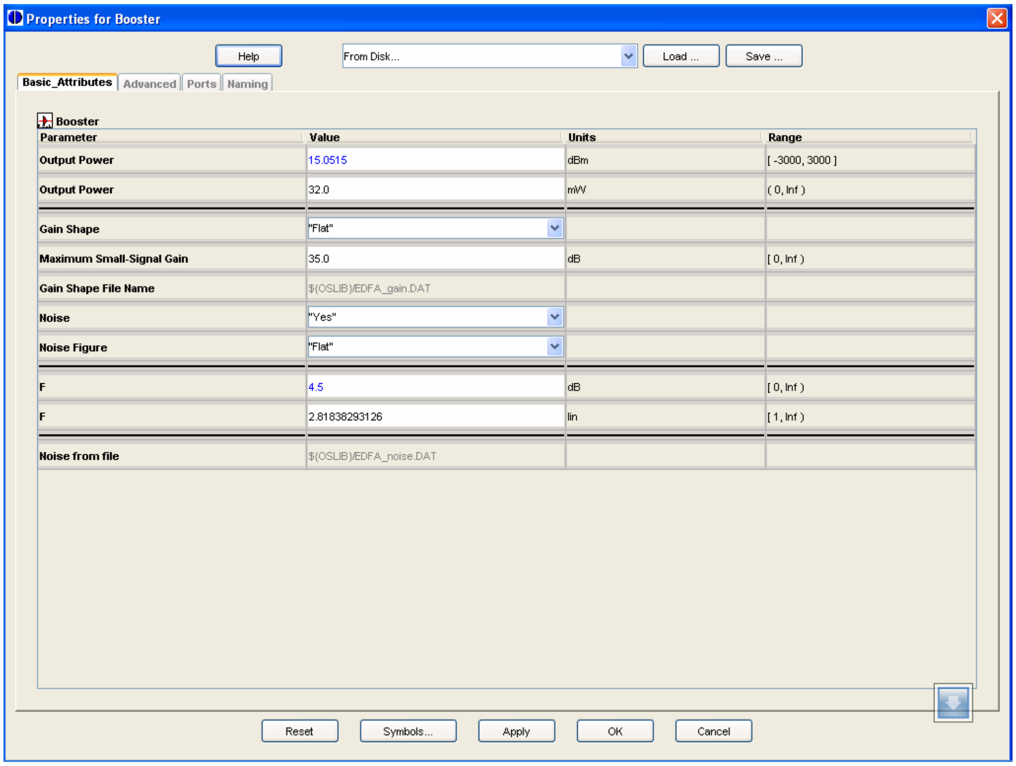
SCREENSHOTS



Parameter	Value	Current Value
Center_frequency	189.1	189.1
Channel_spacing	0.1	0.1
Bit_rate	10.0	10.0
Laser_linewidth	10.0	10.0
Laser_power_dBm	0.0	0.0
Modulator_chirp_factor	0.0	0.0
Modulator_excess_loss	3.0	3.0
Modulator_extinction_ratio	30.0	30.0
PRBS_sequence_degree	7.0	7.0

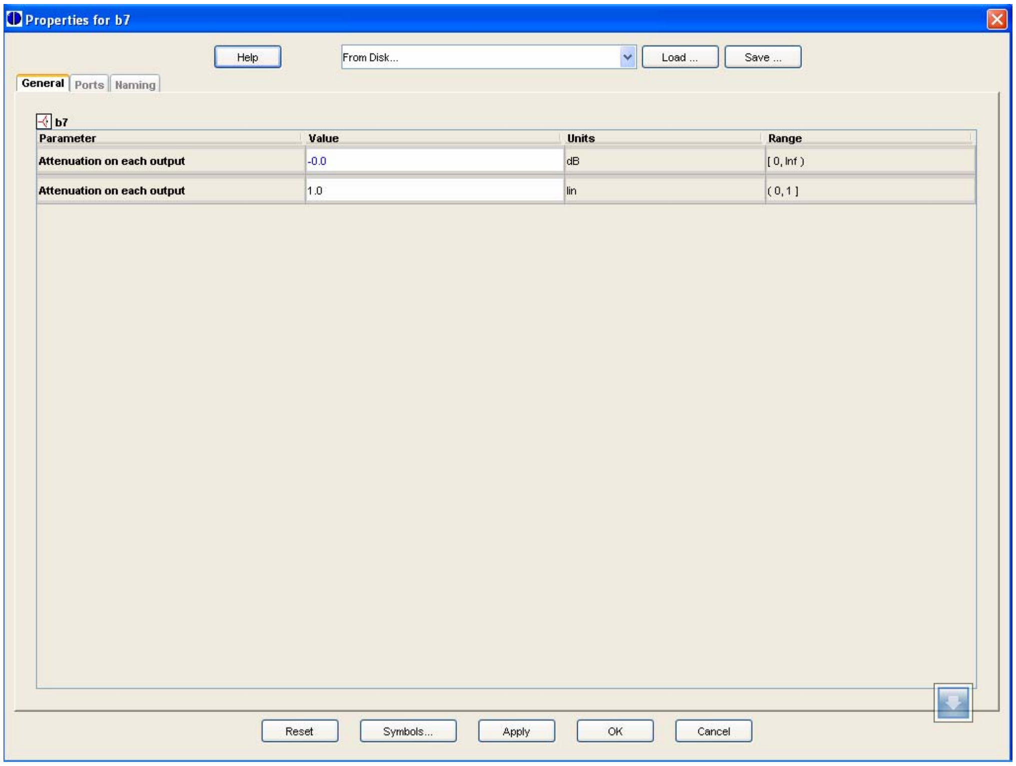


Parameter	Value	Units	Range
Attenuation on each output	-0.0	dB	[0, Inf)
Attenuation on each output	1.0	lin	(0, 1]



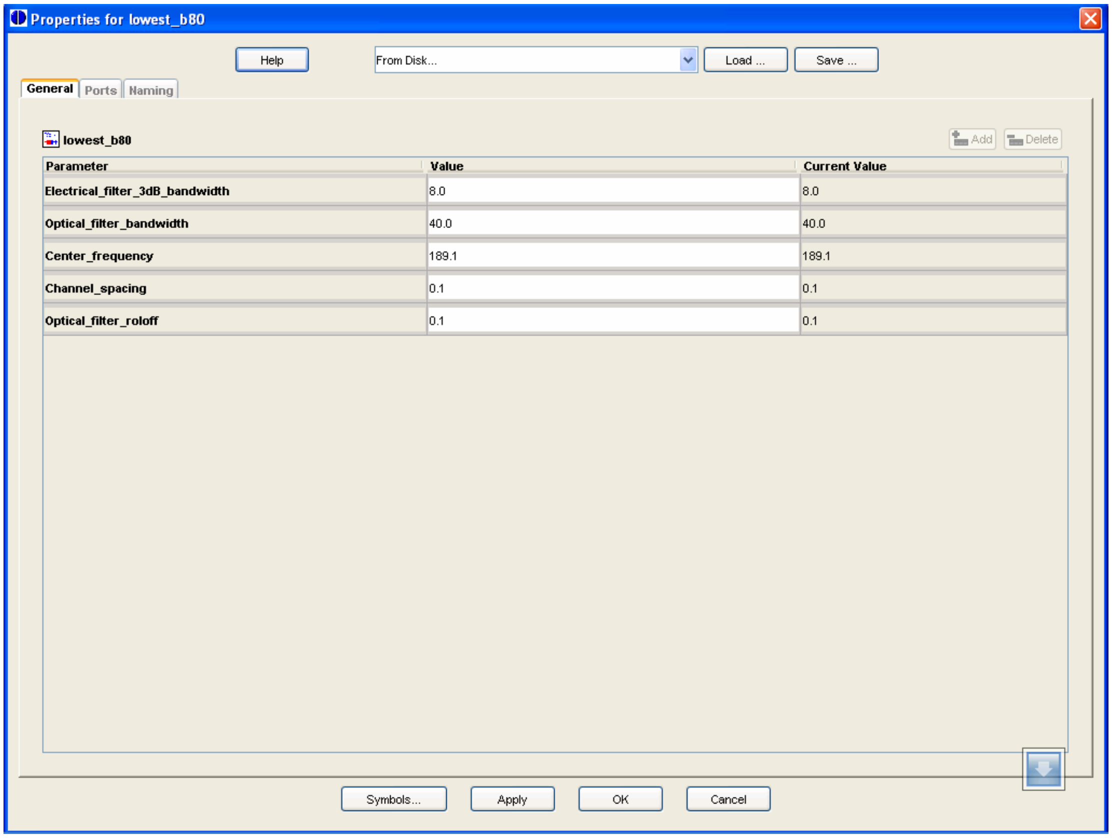
Booster

Parameter	Value	Units	Range
Output Power	15.0515	dBm	[-3000, 3000]
Output Power	32.0	mW	(0, Inf)
Gain Shape	"Flat"		
Maximum Small-Signal Gain	35.0	dB	[0, Inf)
Gain Shape File Name	$(OSLIB)/EDFA_gain.DAT		
Noise	"Yes"		
Noise Figure	"Flat"		
F	4.5	dB	[0, Inf)
F	2.81838293126	lin	[1, Inf)
Noise from file	$(OSLIB)/EDFA_noise.DAT		



b7

Parameter	Value	Units	Range
Attenuation on each output	-0.0	dB	[0, Inf)
Attenuation on each output	1.0	lin	(0, 1]



Parameter	Value	Current Value
Electrical_filter_3dB_bandwidth	8.0	8.0
Optical_filter_bandwidth	40.0	40.0
Center_frequency	189.1	189.1
Channel_spacing	0.1	0.1
Optical_filter_roloff	0.1	0.1

Simulations

The System Simulation Parameters

The system we want to simulate has the following characteristics:

Transmitter Section

☐ 64-channels WDM transmitter

☐ bit rate: 10 Gbit/s

☐ modulation format: rectangular Non-Return-to-Zero (NRZ)

☐ optical modulator: external Mach-Zehnder, 3 dB insertion loss

☐ lower channel frequency: 189.1THz

☐ channel spacing: 100 GHz

☐ optical source: CW laser (10 MHz spectral width), -30 dBm peak power

☐ booster: EDFA, fixed output power 0 dB with real gain shape, Noise Figure 4.5 dB

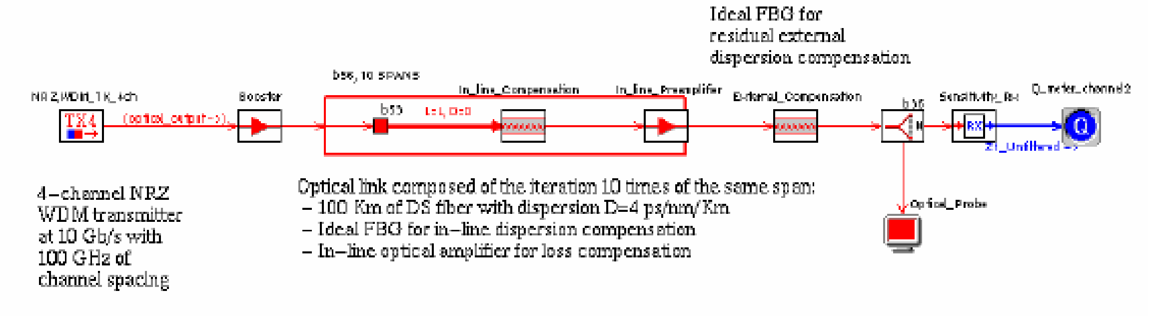
Link Section

☐ link type: 2 span of 50 km, Lucent TrueWave optical fiber

☐ Raman amplification: 2 counter-propagating pumps at 1438 nm and 1452 nm with power of 600 mW and 400 mW respectively

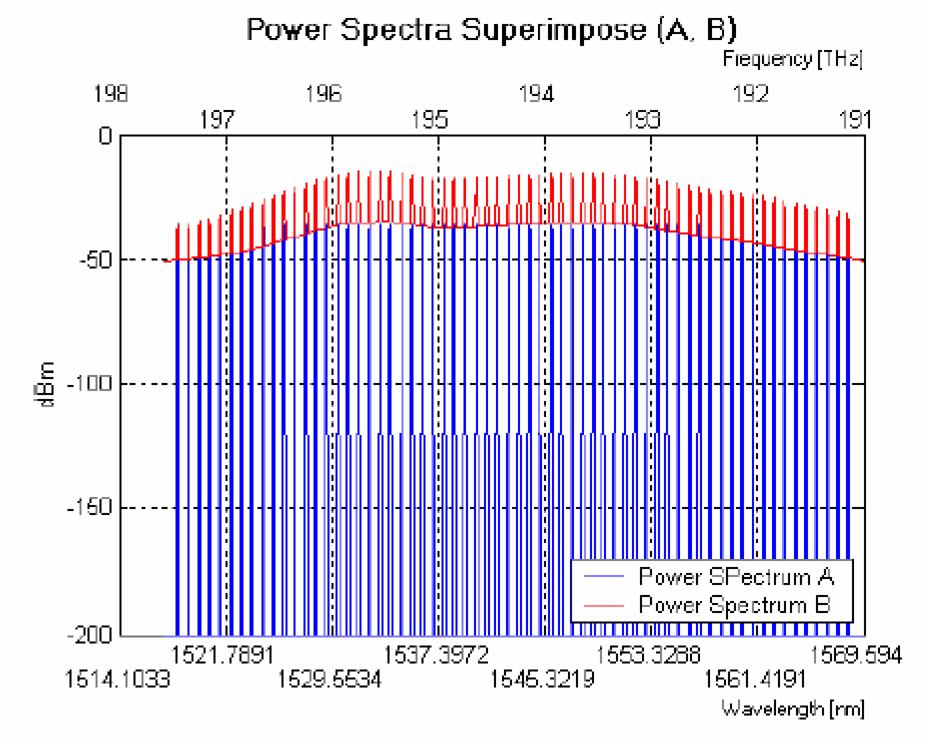
☐ amplification: EDFA placed every 50 Km, fixed output power 0 dB with ideal flat gain profile, Noise Figure 4.5 dB

With the SPT Data Display toolkit we want to analyze the optical gain, noise figure, OSNR, channel powers and power spectra at the beginning of the link section (output of the compound component 64 channels WDM transmitter) and at the end of the link section (output of the ideal EDFA second span).



Power Spectrum

By default the **Power Spectrum** option is selected in **Plot Type**. The diagram shows 2 superimposed power spectra at the output of the 64-channels WDM transmitter (power spectrum A) and at the output of the ideal EDFA second span (power spectrum B).



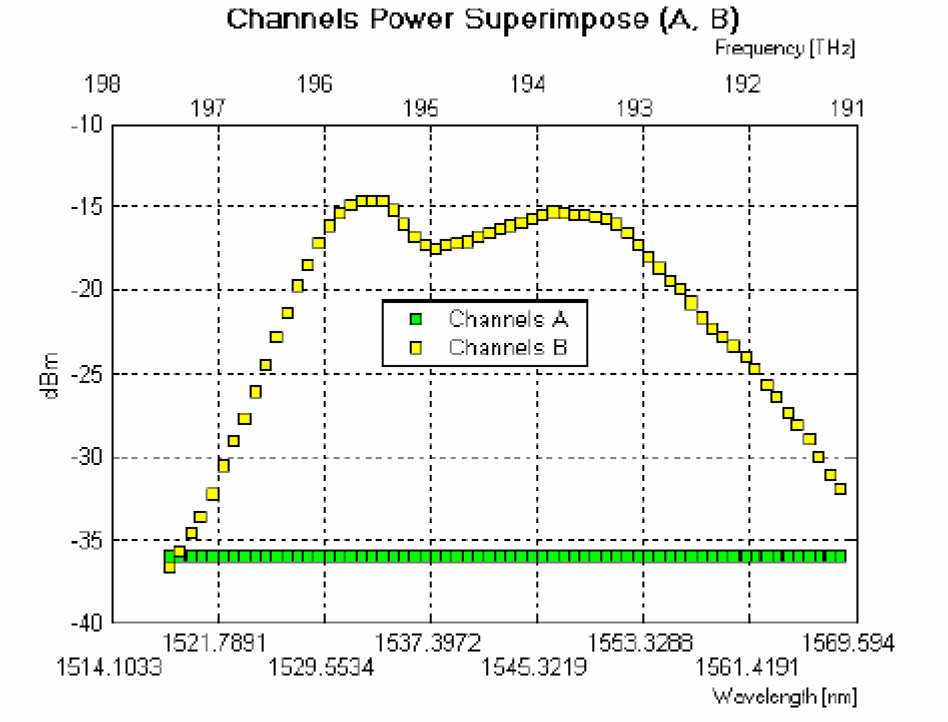
The spectra are filtered with a rectangular transfer function of 0.125 THz bandwidth as specified in the **Rectangular Filter Resolution** parameter.

You can zoom in a particular with the mouse just dragging a rectangle on the diagram. To restore the original range of view double-click any point of the diagram.

Select the **Single** option in **Plot Mode** to display a single power spectrum.

Channels Power

Select the **Channels Power** option in **Plot Type**. The diagram shows 2 superimposed curves with all the channel power values at the output of the 64 channels WDM transmitter (power spectrum A) and at the output of the ideal EDFA second span (power spectrum B).

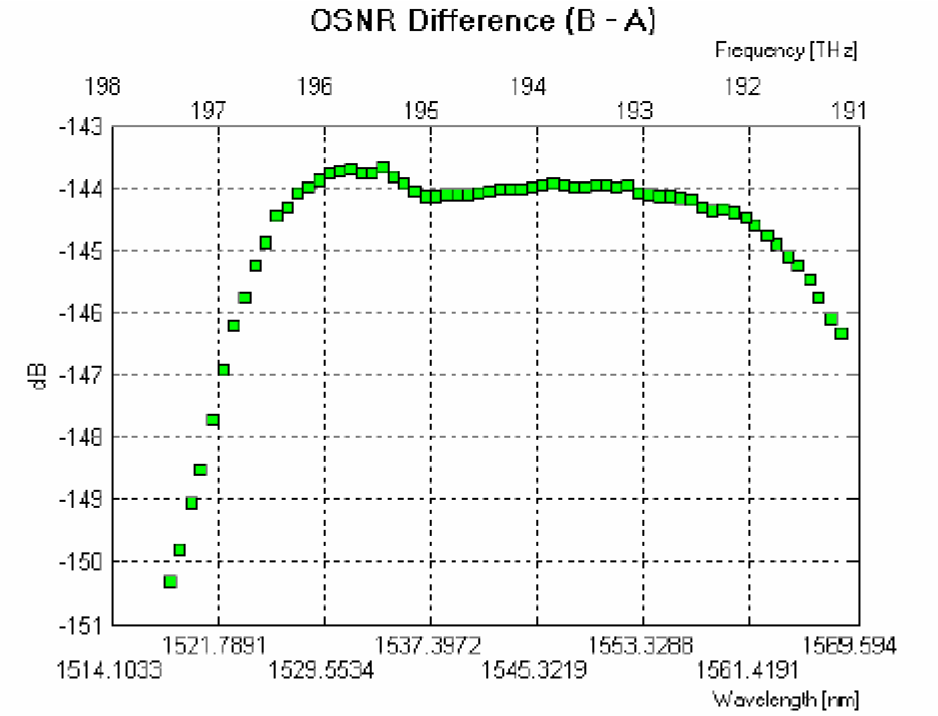


The Channels Power Diagram

The channels are detected using a 10 dB peak level as specified in the □Lev parameter. Again you can select the Single option in Plot Mode to display a single power spectrum.

OSNR

Select the **OSNR** option in **Plot Type**. The diagram shows the difference for each channel of the OSNR values measured at the output of the 64 channels WDM transmitter (power spectrum A) and at the output of the ideal EDFA second span (power spectrum B).

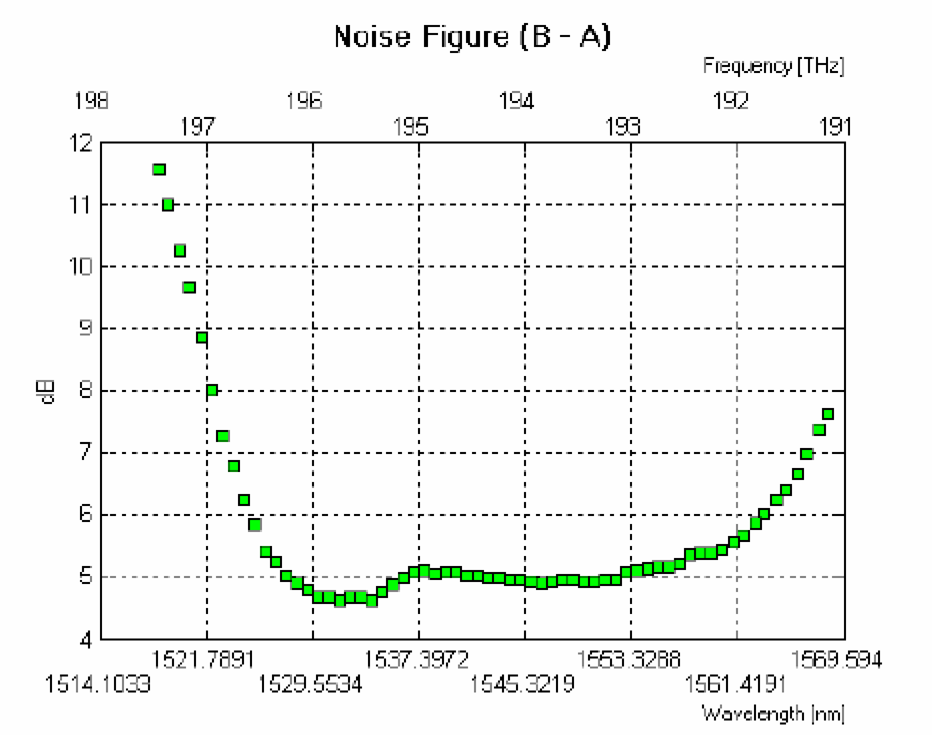


The OSNR diagram

You can select the **Superimpose** option in **Plot Mode** to display the two curves of channel OSNR values at the point A and B. You can select also the **Single** option in **Plot Mode** to display a single curve.

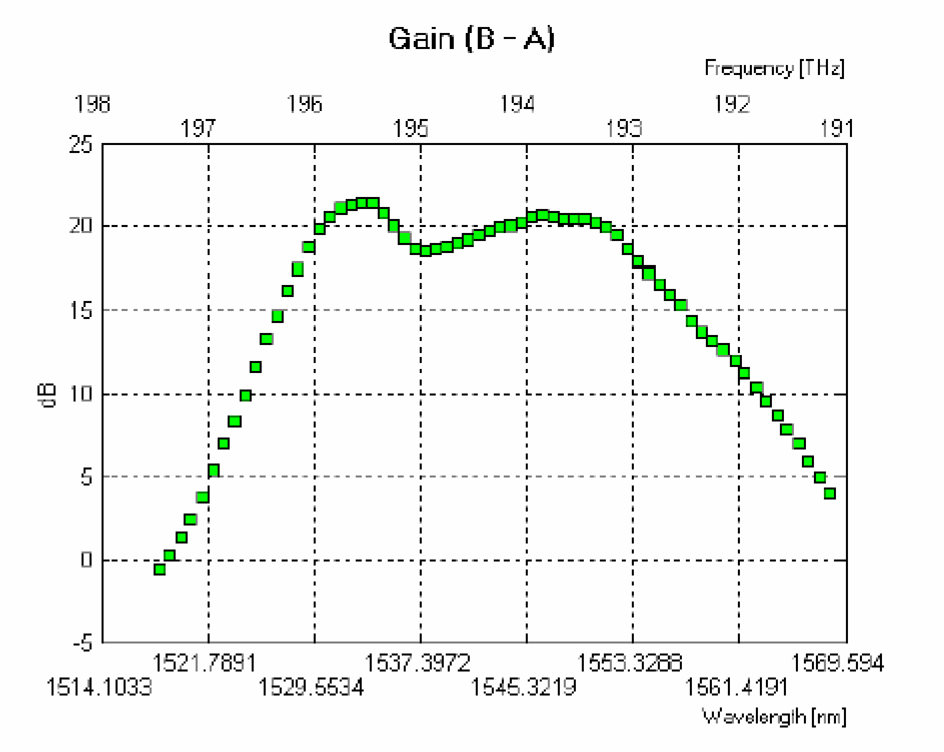
Noise Figure

Select the **Noise Figure** option in **Plot Type**. The diagram shows for each channel the noise figure value measured between the output of the 64 channels WDM transmitter (power spectrum A) and the output of the ideal EDFA second span (power spectrum B).



Gain

Select the **Gain** option in **Plot Type**. The diagram shows for each channel the linear gain value measured between the output of the 64 channels WDM transmitter (power spectrum A) and the output of the ideal EDFA second span (power spectrum B).



The Gain Diagram

Click on the **Min** button in **Calculations**, to obtain the minimum gain value. Click on the **Max** button in **Calculations**, to obtain the maximum gain value.

About OptSim 4.0

OptSim is an advanced optical communication system simulation package designed for professional engineering and cutting-edge research of WDM, DWDM, TDM, optical LAN, parallel optical bus, and other emerging optical systems in telecom, datacom, and other applications. It can be used to design optical communication systems and simulate them to determine their performance given various component parameters. *OptSim* is designed to combined the greatest accuracy and modeling power with ease of use on both Windows and UNIX platforms. It includes the most advanced component models and simulation algorithms, validated and used for research documented in numerous peer-reviewed professional publications, to guarantee the highest possible accuracy and real-world results.

OptSim represents an optical communication system as an interconnected set of blocks, with each block representing a component or subsystem in the communication system. As physical signals are passed between components in a realworld communication system, "signal" data is passed between component models in the *OptSim* simulation. Each block is simulated independently using the parameters specified by the user for that block and the signal information passed into it from other blocks. This is known as a block-oriented simulation methodology. These blocks are graphically represented as icons in *OptSim*. Internally, they are represented as data structures and sophisticated numerical algorithms.

OptSim includes an extensive component model library of the most commonly used components for the engineering of electro-optical systems. This component library is continuously being expanded through ongoing research and collaboration with world-renowned simulation specialists at major optical technology centers throughout the world. *OptSim* 4.0 includes models and algorithms developed by and in collaboration with the Polytechnic University of Turin, University of California at Santa Barbara, and University of Illinois at Urbana-Champaign. It incorporates the capabilities of iFROST (illinois FibeR-optic Link Demonstrator) from the University of Illinois at Urbana-Champaign which was licensed by RSoft Design Group, FOLD (Fiber Optic Link Demonstrator) from the University of California at Santa Barbara which was licensed by RSoft, *LinkSIM*™ which was developed by RSoft Design Group, and *OptSim*™ version 3.5 which was acquired from ARTIS by RSoft. The GUI and some aspects of the simulation engine are derived from the Ptolemy II and Ptolemy Classic software projects at the University of California at Berkeley. *OptSim* also includes a large selection of predefined component parameter sets representing a wide array of commercially available components. These can easily be selected in the component model parameter editing window.

In addition to the extensive component library, *OptSim* 4.0 includes a new sophisticated yet easy-to-use graphical user interface (GUI), plus twin simulation engines, and powerful simulation result analysis and post-processing tools. The user interface provides a hierarchical object-oriented CAD environment for schematic development and system design. It is described in further detail in this documentation.

Twin Simulation Engines

The twin simulation engines support two complementary simulation approaches. The block mode simulation engine performs simulations in which the signal data passed between components represents the entire simulated time in one block of data. The advantage of this approach is that component models and algorithms can easily work with the entire signal, transforming it back and forth between the time and frequency domains to operate on the data in the domain most convenient for the simulation algorithm. Nonlinear fiber is simulated using the Split Step Fourier technique in this mode [1]. This simulation approach was used by the *LinkSIM*, iFROST, and FOLD tools, for example. The sample mode simulation engine performs simulations in which the signal data passed between components represents a single sample or time step at a time. Unlike the block mode simulation approach where one component model may only pass data to another component model once during the course of the simulation, covering the entire simulated time in one block of data, in the sample mode simulation approach a component model will pass new sample data to another component model at each time step in the simulation. One advantage of this approach is that simulations can be performed over an unlimited amount of simulated time covering an unlimited transmitted sequence length. In this mode, signal processing is done completely in the time domain. Nonlinear fiber is simulated using the Time Domain Split Step technique in this mode [2]. The sample mode also provides two types of simulations: a Spectral Propagation Technique (SPT) that performs quick simulations of the optical spectrum including ASE noise, optical amplifications, and optical filtering; and Variable Bandwidth Simulation (VBS) which performs the full time-domain waveform simulation with options to include all effects with or without noise, in a linear or nonlinear simulation. Note that through the flexible user model capabilities provided with *OptSim*, users can create models that operate on signal data a sample at a time or in large blocks, in either the time domain or frequency domain, for both the block mode and sample mode simulation engines.

OptSim 4.0 also introduces new capabilities for simulation of power transients due to adding and dropping of channels in optical amplifier chains and all-optical gain control techniques. These capabilities make use of new features for Wavelength Domain Simulation [3] and true simulation iterations enabling simulations of feedback paths and fast simulation of large time windows (on the order of seconds) which were not computationally feasible with previous simulation technologies.

Results Analysis and Post Processing

Simulation results that are produced by *OptSim* include signal waveform plots and eye diagrams at any point within the optical communication system, and bit error rate (BER) plots vs. various parameters within the system such as the received optical power. Other simulation results are also available, including signal spectra, frequency chirp, power and dispersion maps, and more. Simulation results may also be plotted against one another and correlated with scanned parameter values. *OptSim* performs analyses of the effects of noise, crosstalk, jitter, skew, and variations in component parameters using Monte Carlo and quasianalytical methodologies. Several post-processing and simulation results analysis tools are provided including the WinPlot™ and RPlot™ simulation result plotting tools as well as the VirLab™ post-processing and simulation results analysis tool. These tools make it easy to interactively work with the simulation results to present them in the manner desired and analyze them further.

Best Fit Laser Toolkit and SPICE Model Generator™

OptSim is also the only tool that provides the Best Fit Laser Toolkit™ for quickly and easily producing accurate rate equation laser models that are well-fitted to real-world laser performance characteristics as determined through measurements or data sheets provided by the manufacturer. Accompanying this capability is the SPICE interface that bridges the gap between the electronic circuit and optical system simulation domains. This includes the unique SPICE Model Generator™ that automatically generates a SPICE model deck based on *OptSim*'s rate equation laser models for use in SPICE simulations. Using this capability, the laser's true driving conditions can be accurately modeled in SPICE simulations of the laser driver. Then the laser driver's accurate output waveform can be used to drive the laser model in *OptSim* to produce the most accurate simulations of the system performance. Because the laser model used in the SPICE simulation of the laser driver and *OptSim*'s system simulation of the optical channel, the results are much more accurate than when the laser's driving conditions are estimated in SPICE simulations with a simple RC circuit, as has been frequently the case. This is an effective aid in the laser driver design optimization as it enables the simulation of the true driving conditions of the laser and enable the designer to explore the effects of different driver design parameters on the laser and system performance. The driver's design directly influences the pulse distortion induced by the laser output due to chromatic dispersion in the fiber. Through this capability, the system impacts of signal integrity and electromagnetic interference in the laser driver can also be investigated.

ModeSYS™ Multimode Simulation Platform

OptSim can be fully integrated with ModeSYS™, RSoft's multimode simulation platform, for accurate simulation of multimode optical communication systems. With a primary focus on data communication applications, ModeSYS allows users to evaluate both temporal and spatial attributes of optical signal propagation. This capability enables the systemlevel analysis of standardized communication technologies such as 1 Gb and 10 Gb Ethernet and Fibre Channel, as well as the study of proprietary data communication platforms. ModeSYS is the first commercial tool to address this challenge. Spatially-dependent models included with ModeSYS enable the accurate analysis of a transverse electromagnetic spatial field starting with its generation by an optical source, continuing with its propagation through spatially-dependent components in a multimode optical link such as multimode fiber and connectors, and through to its detection at a photoreceiver. The wide range of multimode analyses that can be performed with ModeSYS include differential mode delay (DMD), encircled flux (EF), effective modal bandwidth (EMB), launch conditions, modal coupling, transverse optical field profiles, and transient analyses. In addition, eye diagrams, signal waveforms, frequency spectra, BER curves, etc. are also provided. ModeSYS performs device-level modeling within a system simulation infrastructure, so extremely detailed spatial field calculations are implemented in a manner that allows a very straightforward system-level analysis. The platform shields the user from much of the complex optical physics that are necessary to analyze multimode systems, making it not only powerful, but easy to use.

Extending OptSim

OptSim also provides powerful capabilities for creating user models in both the block mode and sample mode simulation engines. User models may be written in a programming language such as C++ or FORTRAN and linked into the simulation tool utilizing application programming interface (API) provided with *OptSim*. In addition, *OptSim* supports MATLAB® interfaces that enable users to write their user models in MATLAB for full co-simulation with *OptSim* as well as use MATLAB for post-processing analysis of *OptSim* simulation results. *OptSim* also provides interfaces to various device-level simulation tools including RSoft's BeamPROP™, GratingMOD™, and LaserMOD™, as well as third-party tools such as Thin Film Center's Essential MacLeod thin film design software. Also, *OptSim* provides interfaces to leading laboratory test equipment including Agilent's 86146B-DPC Optical Spectrum Analyzer and Time Resolved Chirp measurement solution and 81910A Photonic All-parameter Analyzer, and Luna Techologies' Optical Vector Analyzer (OVAe).

Simulation and Analysis

- A powerful nested variable scanning mechanism that allows component parameters to be specified as variables and scanning those variables over user-defined ranges, as well as defining specific variable values for each of a specified number of runs, to see their effect on the link performance are included. Multiple variables may be scanned at the same time, with the scans nested. The scheduling algorithm optimizes the simulation efficiency by only simulating the components in each scan which are affected by the change of the scanned variables, and using previously computed results when possible. This feature permits time efficient analysis of the effects of parameters which use the scanned variables on the overall system performance, and facilitates parametric studies and design optimization. Using this feature, a family of BER curves vs. received optical power can be generated, for example.
- Statistical variations of component parameters is supported. Numerical component parameters may have their probability distribution and standard deviation individually defined. In concert with the nested variable scanning, a specified number of simulation runs with parameters randomized according to their statistics may be performed in each sweep. The multiple simulation runs can be used to determine the range of expected performance for the link given the statistical variations. This information can be used by the designer to center design parameters, perform aging analyses for the links, study the impact of environmental effects on system performance and reliability, determine system yield given known distributions in component parameters, etc. This can also be used to study parallel optical links, where the variations in component parameters between different channels can be the leading performance degradation mechanism.
- Repetition loops allow portions of a link topology to be specified as being repeated *n* times such that the simulation will behave as if there were *n* sets of the groups of component icons within the repetition loop icons attached end to end. Repetition loops may be nested, and may have multiple input and output signals. These are especially useful for defining spans of fibers and amplifiers in long haul systems.
- Network rings may be simulated through initialization and repeated simulations of ring topologies.
- New capabilities are added for simulating power transients due to adding and dropping of channels in optical amplifier chains and all-optical gain control techniques, including simulation of feedback through iterations.
- Measured or externally computed signal waveforms may be used to drive the *OptSim* simulation. This provides flexibility in configuring simulations and allows *OptSim* to be used in conjunction with experimental results as well as other simulation and analysis programs.
- Signals may be saved during the simulation to be used as driving signals for future simulations, or loaded from files to drive the current simulation.
- Signal summary information for signals at all component ports is available from the topology editor after the signals are generated during the simulation as well as after the simulation is completed.

- Users may develop their own component models and incorporate them into the *OptSim* environment.
  These user models can be as sophisticated and powerful as built-in models.
- Users may incorporate optoelectronic components modeled in *BeamPROP™, GratingMOD™, LaserMOD™,* or another device-level tool in an *OptSim* simulation. This unique multi-level simulation capability provides the best accuracy and efficiency in link performance analysis involving complex designs.
- Optional integration with *ModeSYS™,* the industry's only multimode optical communication system simulation solution that takes into account both spatial and temporal effects.
- Best Fit Laser Toolkit™ makes customizing powerful rate-equation laser model parameters to fit desired performance characteristics easy.
- The SPICE Interface, including the SPICE Model Generator™, bridges the gap between electronic circuit and optical communication system simulation. This unique features makes laser driver circuit design and system modeling easier and more accurate than ever before.
- Powerful MATLAB® interface makes it easy to develop user's own models and customize and extend the simulation and analysis capabilities.
- Extensive predefined manufacturer component database makes it easy to model commercially available components.

Measurements

Eye Measures

Sampling Instant: sets the instant of time for the eye measurement. With **Optimum,** the instant is automatically adjusted to obtain the best measurement (higher Q, lower BER, and larger eye opening). With **Marker X1,** the instant is the value selected by the red X1 marker. With **Marker X2,** the instant is the value selected by the blue X2 marker. With **Marker X1 & X2**, the sampling occurs over a range of times specified by the X1 and X2 markers. Over this interval the electrical levels will be averaged.

Decision Threshold: sets the decision threshold level *Vth* for the eye measurements. With **Optimum,** the level is automatically evaluated to obtain the best measurement (higher Q, lower BER). With **Marker Y1,** the level is the value selected by the red Y1 marker. With **Marker Y2,** the level is the value selected by the blue Y2 marker.

Q Factor: evaluates the Q factor of the electrical signal according to the options set for the sampling instant and the decision threshold.

BER: evaluates the BER value of the electrical signal according to the options set for the sampling instant and the decision threshold.

Eye Opening: evaluates the eye opening of the diagram according to the options set for the sampling instant and the decision threshold.

Jitter: evaluates the jitter value of the electrical signal according to the options set for the sampling instant and the decision threshold.

Post-Processing Operations

On this diagram you can:

- evaluate the *Q* factor (optimum or setting the sampling instant and/or the decision threshold)
- estimate the BER value (optimum or setting the sampling instant and/or the decision threshold)
- evaluate the eye opening (optimum or setting the sampling instant and/or the decision threshold)
- evaluate the jitter for RZ signals (optimum or setting the sampling instant and/or the decision threshold)

Q *Factor Estimation*

The Q factor is calculated using mean values and standard deviations of the signal samples using the following expression:

$$Q = \frac{m_1 - m_0}{\sigma_1 + \sigma_0}$$

where $m1$, $m0$, σ1, σ0 are the mean values and standard deviations of the signal samples when a "1" or a "0" is received. This definition of Q factor is not relevant for multilevel digital modulation or for analog modulation; it only makes sense for binary digital modulation.

The mean values $m1$, $m0$ and the standard deviations σ1, σ0 depend on the sampling instant and on the decision threshold. Therefore the Q may be evaluated by choosing the optimum values of sampling instant and decision threshold (i.e. to obtain the maximum Q), or may be evaluated by specifying values with the X and Y axis markers

To evaluate the optimum Q factor

1. Select the **Optimum** option in the **Sampling Instant** list.
2. Select the **Optimum** option in the **Decision Threshold** list.
3. Click on the **Q Factor** button. In the measurement area will be displayed: the sampling time value, the decision threshold value, the Q factor in linear measurement unit and the Q factor in dB.

To evaluate the Q factor at a given point

1. Select the marker in the **Sampling Instant** list.
2. Select the marker in the **Decision Threshold** list.
3. Position the markers to the desired points.
4. Click on the **Q Factor** button. In the measurement area will be displayed: the value of the sampling time, the value of the decision threshold, the Q factor in linear measurement units and the Q factor in dB units.

BER Estimation

The evaluation of the BER when simulating an optical system is in general a nontrivial task. Direct error counting is usually impractical, since target BER values are typically of the order of 10-9 or less. BER estimation as implemented in OptSim is not relevant for any kind of multilevel digital modulation or for analog modulation; it only makes sense for binary digital modulation. The solution implemented in OptSim is based on fitting a given distribution to the first two moments of the received signal. You should know in advance which kind of probability density function (pdf) is most likely to represent the received signal statistics. As a rule of thumb, in a standard optical system based on binary On-Off modulation and direct detection (IM-DD), the received signal pdf tends to be:

- a Gaussian distribution when the noise mainly comes from the electrical part of the receiver, after the photodetection process
- a $\chi2$ distribution when the noise mainly comes from the optical part of the system, typically from the ASE noise of optical amplifiers. In any event, the Gaussian approximation is very often used in this case.

Good discussions on BER Estimation can be found in the following references: [2] where a detailed theory on $\chi2$ is given, [3] a fundamental paper presenting the theory of BER estimation in optical systems limited by ASE noise, and [4] where a detailed review of BER evaluation in optical systems is given.

The Scope measurement component uses the Gaussian distribution for the pdf of the received signal. In order to use the $\chi2$ distribution you must employ the BER measurement component.

In the Gaussian approximation, the BER is evaluated starting from the received signal mean values *m*1, *m*0 and standard
deviation σ1, σ0 as follows:

$$BER = \frac{1}{4}\left[erfc\left(\frac{m_1 - V_{th}}{\sqrt{2}\sigma_1} \right) + erfc\left(\frac{V_{th} - m_0}{\sqrt{2}\sigma_0} \right) \right]$$

where *Vth* is the decision threshold level between “0” and “1”. The mean values *m*1, *m*0 and the standard deviation σ1, σ0 also depend on the *sampling instant* and on the decision threshold *Vth*. Therefore the BER may be evaluated taking the *optimum* values of *Vth* and sampling instant (i.e. to obtain the minimum BER) or setting a value of *Vth* with the Y axis markers and a value of sampling instant with the X axis markers.

To evaluate the optimum BER

1. Select the **Optimum** option in the **Sampling Instant** list.
2. Select the **Optimum** option in the **Decision Threshold** list.

3. Click on the **BER** button. The sampling time value, the decision threshold value and the estimated BER value will be displayed in the measurement area.

To evaluate the BER at a given point

1. Select the marker in the **Sampling Instant** list.
2. Select the marker in the **Decision Threshold** list.
3. Position the markers at the desired points.
4. Click on the **BER** button. The sampling time value, the decision threshold value and the estimated BER value will be displayed in the measurement area.

Eye Opening

The *eye opening* is the difference between the minimum value of the samples related to a logical “1” and the maximum value of samples related to a logical “0”, measured at the sampling instant. The *average eye opening* is the difference between the mean values of the samples related to a logical “1” and samples related to a logical “0”, measured at the sampling instant.

The *closure* is defined by 10·log10[(average opening)/(opening)]. These three values depend on the *sampling instant* and on the *decision threshold*. Therefore the *eye opening* may be evaluated by using the *optimum* values for *sampling instant* and *decision threshold* (i.e. to obtain the highest Q or the lowest BER), or by specifying values with the X and Y axis markers.

To evaluate the optimum eye opening

1. Select the **Optimum** option in the **Sampling Instant** list.
2. Select the **Optimum** option in the **Decision Threshold** list.
3. Click on the **Eye Opening** button. The sampling time value, the decision threshold value, the closure value, the opening value and the average opening value will be displayed in the measurement area.

To evaluate the eye opening at a given point

1. Select the marker in the **Sampling Instant** list.
2. Select the marker in the **Decision Threshold** list.
3. Position the markers at the desired points.
4. Click on the **Eye Opening** button. The sampling time value, the decision threshold value, the closure value, the opening value and the average opening value will be displayed in the measurement area.

Jitter

The *jitter* value is the standard deviation of the received RZ signal maximum with respect the specified sampling instant.

The signal maximum depends on the *decision threshold*, therefore the jitter may be evaluated by using *optimum* values of the *sampling instant* and *decision threshold* (i.e. to obtain the highest Q or the lowest BER), or by specifying values with the X and Y axis markers.

The jitter evaluation is suitable for RZ signals with a clearly defined maximum, such as soliton pulses. It is not suitable for NRZ modulation.

To evaluate the optimum jitter

1. Select the **Optimum** option in the **Sampling Instant** list.
2. Select the **Optimum** option in the **Decision Threshold** list.
3. Click on the **Jitter** button. The sampling time value, the decision threshold value and the jitter value will be displayed in the measurement area.

To evaluate the jitter on a given point

1. Select the marker in the **Sampling Instant** list.
2. Select the marker in the **Decision Threshold** list.
3. Position the markers at the desired points.
4. Click on the **Jitter** button. The sampling time value, the decision threshold value and the jitter value will be displayed in the measurement area.

Future Scope

DWDM combines multiple optical signals so that they can be amplified as a group and transported over a single fiber to increase capacity. Each signal carried can be at a different rate(OC-3, -12, -24, etc.) and in a mix of SONET signals at OC-48 (2.5 Gbps) and OC-192 (10 Gbps) over a DWDM infrastructure can achieve capacities of over 40 Gbps. A system with DWDM can achieve all this gracefully while maintaining the same degree of system performance, reliability, and robustness as current transport systems-or even surpassing it. The transmission speed of one Gbps, one thousand books can be transmitted per second.

However today, if one million families decide they want to see video on web sites and sample the new emerging video applications, then network transmission rates of terabits (trillions of bits per second[Tbps]) are required. With a transmission rate of one Tbps, it is possible to transmit 20 million simultaneous 2-way phone calls or transmit the text from 300 years-worth of daily newspapers per second.

Future DWDM terminals will carry up to 80 wavelengths of OC-48, a total of 200 Gbps, or up to 40 wavelengths of OC-192, a total of 400 Gbps-which is enough capacity to transmit 90,000 volumes of an encyclopedia in one second.

A platform that is able to unify and interface with these technologies and position the carrier with the ability to integrate current and next-generation technologies is critical for a carrier’s success. DWDM is that technology that will be sufficiently able to provide this platform.

LIST OF ABBREVIATIONS

DWDM : Dense wavelength division multiplexing.
LED : Light emitting diode
Mbps : Megabits per second
WDM : Wavelength division multiplexing
GHz : Gigahertz
SONET : Synchronous optical network
SDH : Synchronous digital hierarchy
EDFA : Erbedium doped fiber amplifier
NDSF : Non dispersion shifted fiber
DSF : Dispersion shifted fiber
NZDSF : Non-zero dispersion shifted fiber
PMD : Polarization mode dispersion
SM : Single mode
FWM : Four wave mixing
TDM : Time division multiplexing
DFB : Distributed feedback
PIN : Positive intrinsic negative
APD : Avalanche Photo Diode
OA : Optical Amplifier
OEO : Optical-Electrical-Optical
MUX : Multiplexer
DEMUX : Demultiplexer
AWG : Arrayed waveguide gratings
OADM : Optical add drop MUX
ATM : Asynchronous transfer mode
BER : Bit error rate
SPM : Self phase modulation
MI : Modulation instability
XPM : Cross phase modulation
FUT : Fiber under test
CW : Continuous wave
AM : Amplitude modulation
RF : Radio frequency
NRZ : Non-return to zero
RZ : Return to zero
OSNR : Optical signal to noise ratio

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