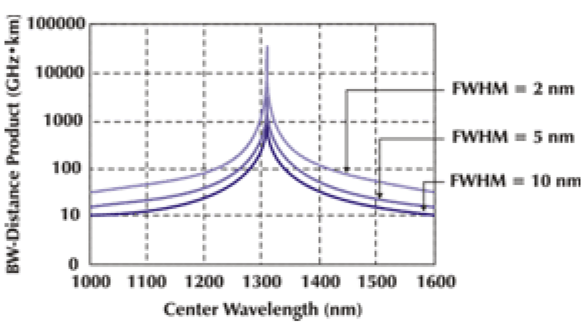
Fiber Dispersion

Once upon a time, the world assumed that fiber possessed infinite bandwidth and would meet mankind's communication needs into the foreseeable future. As the need arose to send information over longer and longer distances, the fiber optic community developed additional wavelength "windows" that allowed longer transmission. The 1550 nm region, with a loss of only 0.2 dB/km, seemed like the answer. Millions of kilometers of fiber were installed around the world creating a high-speed communication network. However, as the data rates increased and fiber lengths increased, limitations due to dispersion in the fiber became impossible to avoid. Dispersion was initially a problem when the first optical fibers, multimode step-index fiber, were introduced. Multimode graded-index fiber improved the situation a bit, but it was single-mode fiber that eliminated severe multimode fiber related dispersion and left only chromatic dispersion and polarization mode dispersion to be dealt with by engineers. This article describes the sources of dispersion in optical fiber and the strategies for getting around this limitation.

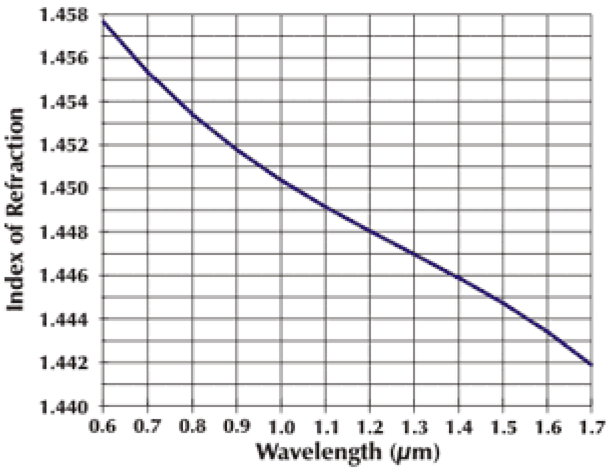
Chromatic Dispersion

Figure 1 - Chromatic Dispersion



Chromatic dispersion represents the fact that different colors or wavelengths travel at different speeds, even within the same mode. Chromatic dispersion is the result ofmaterial dispersion, waveguide dispersion, or profile dispersion. Figure 1 below shows chromatic dispersion along with key component waveguide dispersion and material dispersion. The example shows chromatic dispersion going to zero at the wavelength near 1550 nm. This is characteristic of bandwidth dispersion-shifted fiber. Standard fiber, single-mode, and multimode has zero dispersion at a wavelength of 1310 nm.

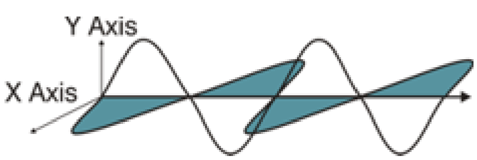
Figure 2 - Refractive Index of Fused Silica



Every laser has a range of optical wavelengths, and the speed of light in fused silica (fiber) varies with the wavelength of the light. Figure 2 illustrates the refractive index of fused silica as it changes with wavelength. Since a pulse of light from the laser usually contains several wavelengths, these wavelengths tend to get spread out in time after traveling some distance in the fiber. The refractive index of fiber decreases as wavelength increases, so longer wavelengths travel faster. The net result is that the received pulse is wider than the transmitted one, or more precisely, is a superposition of the variously delayed pulses at the different wavelengths. A further complication is that lasers, when they are being turned on, have a tendency to shift slightly in wavelength, effectively adding someFrequency Modulation (FM) to the signal. This effect, called "chirp," causes the laser to have an even wider optical line width. The effect on transmission is most significant at 1550 nm using non-dispersion-shifted fiber because that fiber has the highest dispersion usually encountered in any real-world installation.

Polarization Mode Dispersion

Figure 3 - Polarization Mode Dispersion



Polarization mode dispersion (PMD) is another complex optical effect that can occur in single-mode optical fibers. Single-mode fibers support two perpendicular polarizations of the original transmitted signal. If a were perfectly round and free from all stresses, both polarization modes would propagate at exactly the same speed, resulting in zero PMD. However, practical fibers are not perfect, thus, the two perpendicular polarizations may travel at different speeds and, consequently, arrive at the end of the fiber at different times. Figure 3 illustrates this condition. The fiber is said to have a fast axis, and a slow axis. The difference in arrival times, normalized with length, is known as PMD ($ps/km^{0.5}$). Excessive levels of PMD, combined with laser chirp and chromatic dispersion, can produce time-varying composite second order (CSO) distortion in amplitude modulated (AM) video systems. This results in a picture that may show a rolling or intermittent diagonal line across the television screen. Like chromatic dispersion, PMD causes digital transmitted pulses to spread out as the polarization modes arrive at their destination at different times. For digital high bit rate transmission, this can lead to bit errors at the receiver or limit receiver sensitivity.

Calculating Dispersion

Computing PMD is quite difficult unless specific measurements are made on the particular fiber span of interest. Because of this difficulty, and because PMD is generally a much smaller effect at any given data rate, we will not go into details of PMD computation. We will focus on computing the effects of chromatic dispersion. Let's first consider non dispersion-shifted single-mode fiber, such as Corning SMF-28 CPC3 single-mode fiber. This fiber type makes up the largest percentage of the installed fiber base. Its zero-dispersion wavelength lies between 1301 nm and 1321 nm. At the zero-dispersion wavelength, the fiber bandwidth is very high. However, the fiber attenuation in this range is about 0.5 dB/km. This attenuation limits transmission distances to perhaps 60 km. It would be more desirable to operate in the 1550 nm band where attenuation is about 0.2 dB/km. This attenuation would allow transmission to about 150 km as long as dispersion does not limit performance. Equation 1 can be used to compute the dispersion of Corning SMF-28 single-mode fiber.

$$D_\lambda = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$

Where:

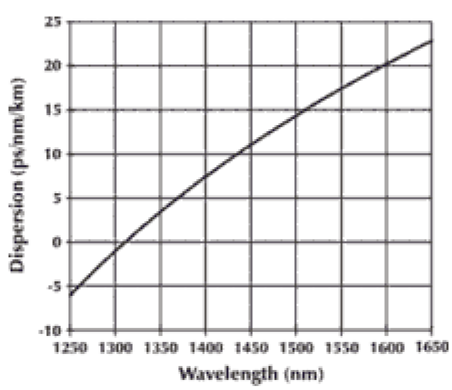
S_0 = 0.092 ps/(nm^2 • km)

λ_0 = 1311 nm (Corning specifies a range of 1302-1322 nm. This number is the average.)

D_λ = Dispersion (ps/nm/km)

Figure 4 shows the behavior of Equation 1 over the wavelength range from 1250 nm to 1650 nm. As expected, the dispersion goes to zero at a wavelength of 1311 nm. At the window of greatest interest, near 1550 nm, the dispersion is about 17 ps/nm/km. If a laser has a spectral width of 1 nm, then the dispersion will be 17 ps/km/nm.

Figure 4 - SM Fiber Dispersion



Dispersion Power Penalty

Now that we know the dispersion of the fiber, we can compute the effect on our transmission link. When a fiber optic transmitter is connected to a fiber optic receiver through a short length of fiber and an optical attenuator, the attenuation can be increased to determine the receiver sensitivity. Usually the receiver sensitivity limit is defined at a given bit error rate (BER). Usually a BER of 10^{-9} or 10^{-12} is used. Figures 5 and 6 illustrate test setup for receiver sensitivity with and without fiber dispersion.

Figure 5 - Receiver Sensitivity with no Fiber Dispersion

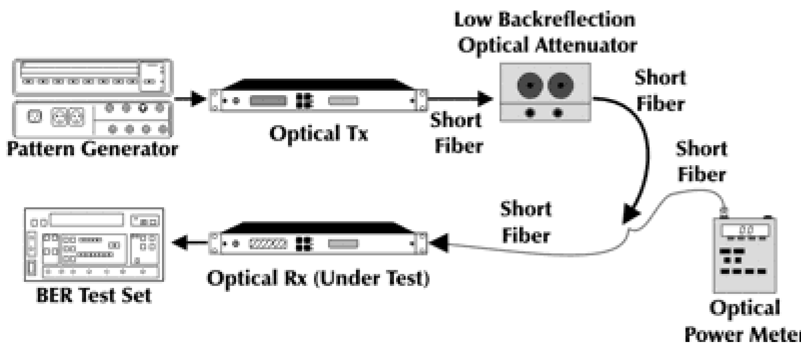
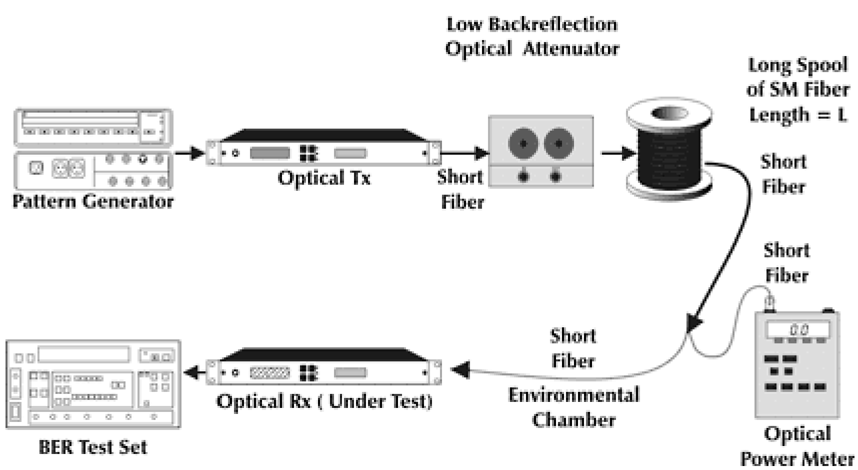


Figure 6 - Receiver Sensitivity with Fiber Dispersion



The expected power penalty due to dispersion is given by a parabolic function of the ratio of symbol rate to dispersion limited bandwidth times a coefficient, "c," which relates to the roll-off of a raised cosine receiver response. If we wish to examine this in terms of dispersion power penalty versus total dispersion. First we need to know the spectral width of the laser. Formultilongitudinal mode (MLM) laser, usually Fabry-Perot (FP) type, the spectral width is the root-mean-square spectral width, and for single-longitudinal mode (SLM) lasers, usually distributed feedback (DFB) lasers, the spectral width is the width at the 20 dB down points divided by 6.07. This is the Gaussian spectral width at the 20 dB down point. Figure 7 shows the typical optical output spectrum of an MLM laser and the corresponding RMS spectral width.

Figure 7 - MLM Laser Spectral Output

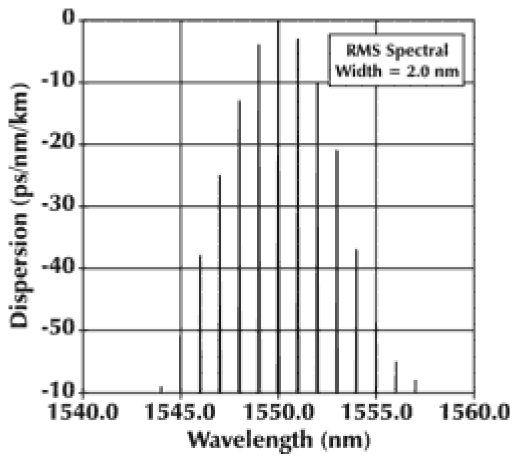
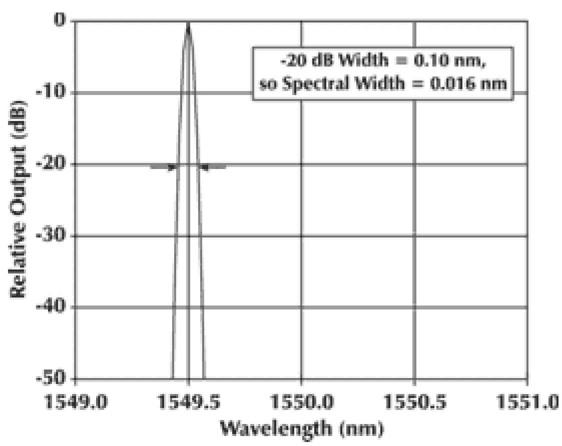


Figure 8 shows the typical optical output spectrum of an SLM laser and the spectral width.

Figure 8 - SLM Laser Spectral Output



Equation 2 describes the calculations for dispersion power penalties in fiber optic systems.

$\tau = \omega \bullet D_\lambda$	ps/km	Where:
$f = 1n(4)/(\tau \bullet \pi)$	Hz•km	ω = laser spectral width (nm)
$F_F = f/L$	Hz	τ = product of ω and D_λ (see equation 1 above)
$\eta_L = c \bullet (F_R/F_F)^2$		c = 0.5
$dB_L = 10 \bullet \mathrm{Log}\,(1+\eta_L)$	dB	L = fiber length (km)
		F_R = receiver data rate (b/s)
		F_L = fiber bandwidth-distance product (Hz•km)
		f = fiber bandwidth (Hz)
		dB_L = dispersion power penalty (dB)

Figure 9 - Dispersion with a Normal DFB Laser

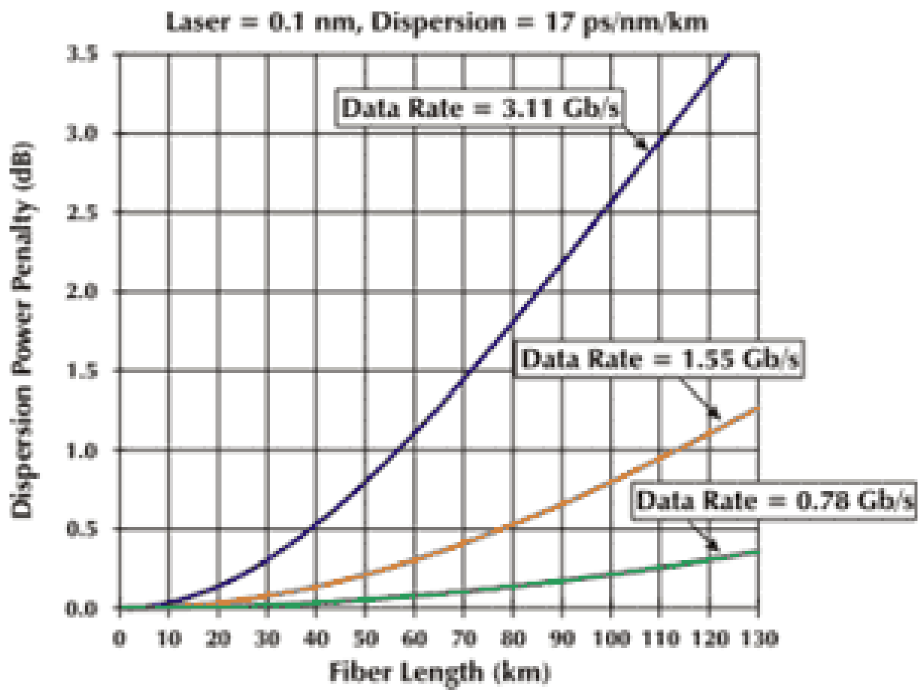
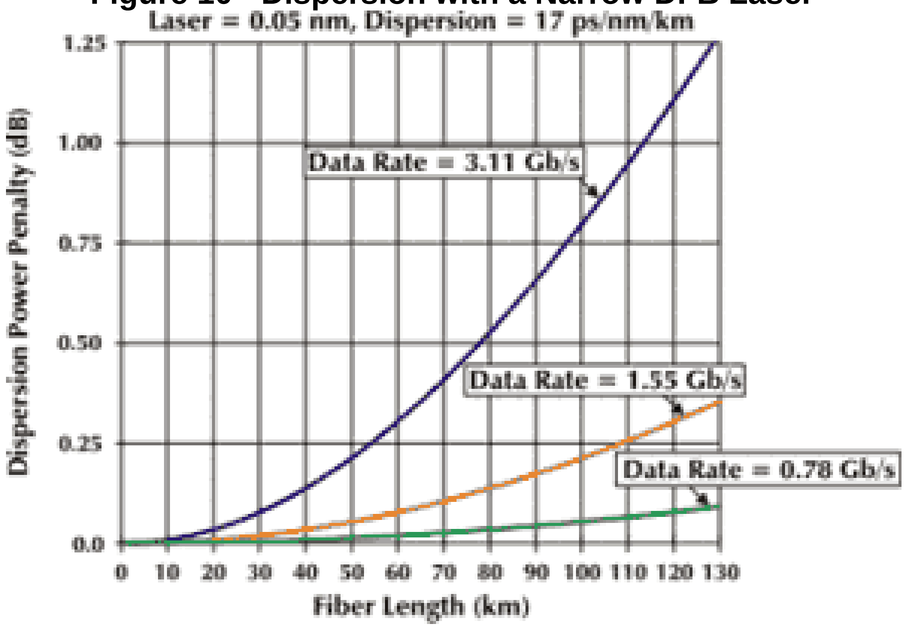


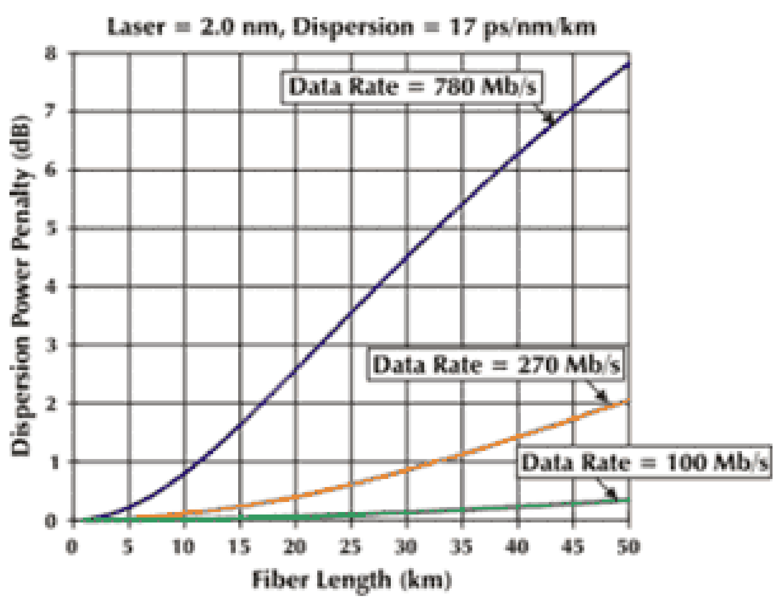
Figure 9 shows the dispersion penalty for a data link operating at three data rates. The laser is 0.1 nm wide with a center wavelength of 1550 nm and a fiber dispersion of 17 ps/nm/km. The maximum acceptable dispersion penalty is usually 2 dB, though it is possible for a system to tolerate a larger dispersion penalty if the optical attenuation is low. For the example shown in Figure 9, the maximum usable fiber length at a data rate of 3.11 Gb/s would be 85 km. At a wavelength of 1550 nm, the optical attenuation would be about 20 dB for that distance, much less than the 30 dB loss budget provided by many high-speed links. In this case, the fiber optic link would be considered dispersion-limited. Figure 10 shows a second example with a much more narrow line width laser. In this case, all conditions are the same except the laser spectral width is 0.05 nm.

Figure 10 - Dispersion with a Narrow DFB Laser



The dispersion penalty has dropped more than a factor of two compared to Figure 9. In this case, the dispersion penalty at a data rate of 3.11 Gb/s never reaches 2 dB, even at 130 km. The fiber optic link will, however, reach its optical attenuation limit near this distance. In this case, the fiber optic link is said to be attenuation-limited. To show that severe impact a laser spectral width has on the dispersion power penalty, Figure 11 shows the dispersion power penalty of a FP MQW laser with a spectral width of 2 nm. The fiber dispersion is still 17 ps/nm/km and the operating wavelength is 1550 nm.

Figure 11 - Dispersion with an FP Laser



In Figure 11, we have chosen three lower data rates. Even so, the FP laser hits the dispersion penalty limit of 2 dB at a distance of 17 km at 780 Mb/s and 50 km at a data rate of 270 Mb/s. At both of these data rates, the data link is dispersion-limited. At a data rate of 100 Mb/s, the link is likely attenuation-limited.

Fiber Types

Thus far, we have only considered the most prevalent fiber type, nondispersion-shifted SM fiber. There are a number of more modern fiber designs available. All offer lower dispersion than the first example, but that may make little difference if the fiber is already in the ground.

Figure 12 - Dispersion of SM Fiber Types

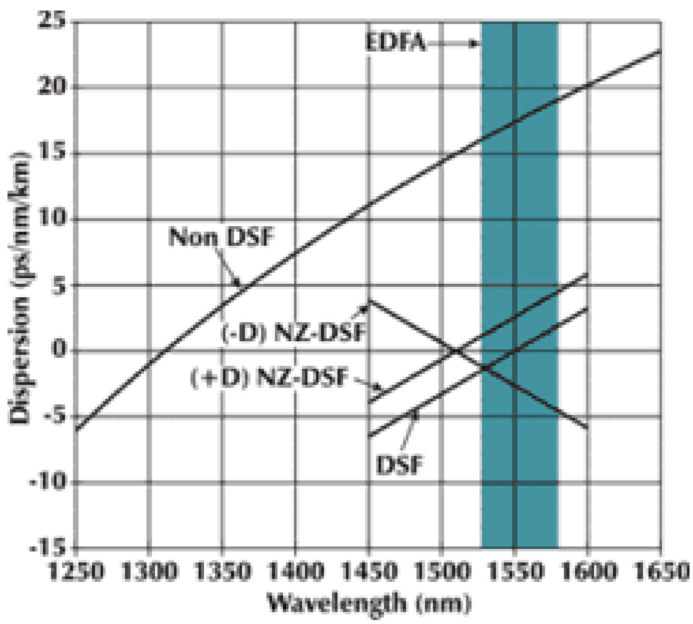


Figure 12 shows the dispersion characteristics of the four key types of optical fiber being deployed at this time in the 1550 nm window. The shaded area, known as the <u>Erbium-Doped Fiber Amplifier</u> (EDFA) window, represents the wavelengths used in DWDM (dense wavelength-division multiplexing) systems. Non-DSF: Nondispersion-shifted fiber has zero dispersion near 1310 nm. DSF: Dispersion-shifted fiber works well in single channel 1550 nm systems, but in DWDM systems, fiber nonlinearities near to the zero-dispersion wavelength cause problems. (+D) NZ-DSF: Similar to DSF, except that the zero-dispersion wavelength is intentionally placed outside of the 1550 nm window. The fiber has a positive dispersion slope versus wavelength. (-D) NZ-DSF: Almost identical to the (+D) NZ-DSF type, except that the dispersion slope is negative versus wavelength.

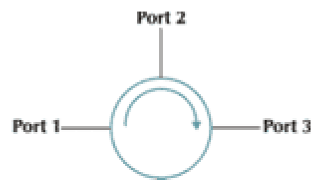
Laser Types

Based on what we saw in Figures 9, 10 and 11, the line width of the laser is critical in limiting the magnitude of the dispersion power penalty. The key laser classes are: Fabry-Perot/MQW: This is the lowest cost laser type available. It also has the worst dispersion power penalty because of its wide optical line width, typically 1-4 nm. (Note that laser line width is often referred to in MHz or GHz, rather than nm. The conversion factor is 1 nm = 125 GHz. So, an FP laser has a line width of 125-500 GHz). Standard DFB: Standard DFB lasers have optical line widths on the order of 0.1 nm, or 12 GHz. At gigabit data rates, this can be a serious limitation for distances over 50 km. Screened DFB: This is basically the same laser design as the standard DFB, however it has been selected for very narrow line width, typically in the 0.01 to 0.05 nm range, 1-5 GHz. This allows the link to reach much longer distances at gigabit data rates. External Modulator/DFB: A very narrow line width laser (1-2 MHz or 0.000008-0.000016 nm) operates in a CW (continuous wave), eliminating any chirp effects that increase the laser line width even further. An external modulator is then used to turn the light on and off. The external modulator acts as an electronic shutter. External modulators are available for digital and analog applications and are capable of data rates to 40 Gb/s and analog bandwidths of 20 GHz or more. The downside of this approach is that very narrow line width sources can stimulate a host of additional fiber nonlinear effects, especially SBS or stimulated brillouin scattering. VCSELs: The vertical cavity surface-emitting laser is the newest laser structure. The VCSELs emit light vertically, as the name suggests, and has a vertical laser cavity. These are typically multi-quantum well (MQW) devices with lasing occurring in layer only 20-30 atoms thick. Bragg-reflectors with as many as 120 mirror layers form the laser reflectors. Because the VCSELs are small and the high efficiency of the mirrors, the threshold current is very low, below 1 mA. VCSELs also exhibit a high efficiency slope. Because of the way they are manufactured, the VCSELs are ideal for applications the require an array of devices.

Countermeasures

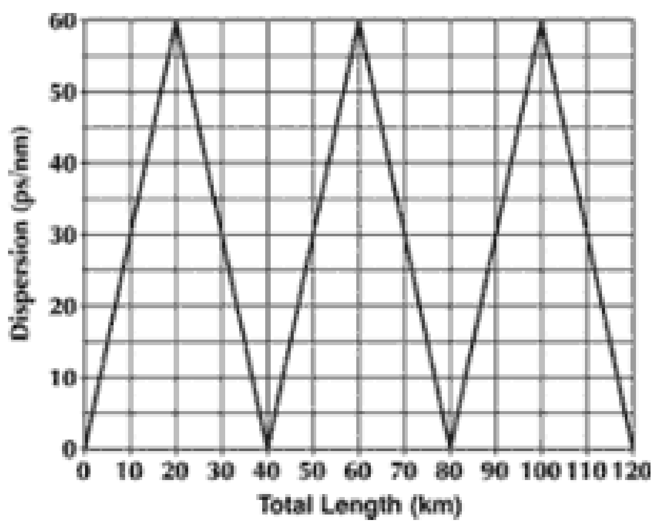
We have now learned about the major types of dispersion in single-mode fiber, the major types of single-mode fiber and techniques for calculating the impact of dispersion on link performance. Now we need to learn about other components that will allow us to minimize the effects of dispersion. There are several passive components that can be used to reduce the effects of dispersion. Generally they consist of introducing an element that has the opposite dispersion of that in the fiber. These are usually referred to as dispersion compensating modules (DCM). They are usually nothing more than a long spool of fiber with the opposite dispersion characteristics. These can be purchased with specified amounts of dispersion, e.g. -1000 ps/nm. There drawback is that they introduce considerable loss in the system, often 8 dB or more. Sometimes, DCMs are used in conjunction with circulators. Circulators are interesting 3-port devices. An example is shown in the Figure 13.

Figure 13 - Use of Circulator to Compensate for Dispersion



In this example light enters the circulator in port 1. Light that enters port 1 is output to port 2 only. Now the light travels through the DCM, reflects off of the reflector and reenters port 2. The light that enters port 2 is output on port 3 only. The net effect is that the light has now traveled through the DCM twice allowing us to use half as much fiber to get the same compensating effect. Circulators are also used in conjunction with devices called Bragg grating reflectors. These devices connect to port 2 of the circulator. They do not require the use of a separate reflector. The Bragg grating reflectors again introduce the opposite dispersion to clean up the signal. Currently they only operate over a very narrow range of wavelengths, perhaps a few nanometers. Thus they can be used to correct for a single channel in a DWDM system, not the entire band. An elegant solution to dispersion compensation consists of alternating lengths of (+D) NZ-DSF and (-D) NZ-DSF fiber types. This would yield very low overall dispersion and could be readily used for DWDM applications. The correction is never perfect over the entire band, but does reduce overall dispersion. The dispersion and transmission distance for alternating lengths of these fiber types is illustrated in Figure 14.

Figure 14 - (+ D) NZ-DSF Fiber and (-D) NZ-DSF Fiber



Source: http://www.fiber-optics.info/articles/fiber_dispersion