Fiber Optic Training Guide

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Introduction

An optical fiber is a long thin strand of impurity-free glass used as a transport medium for data. A typical point-to-point fiber optic communication network consists of a transmitter (laser), a transport medium (optical fiber) and a receiver (photo-diode) as in figure 1.

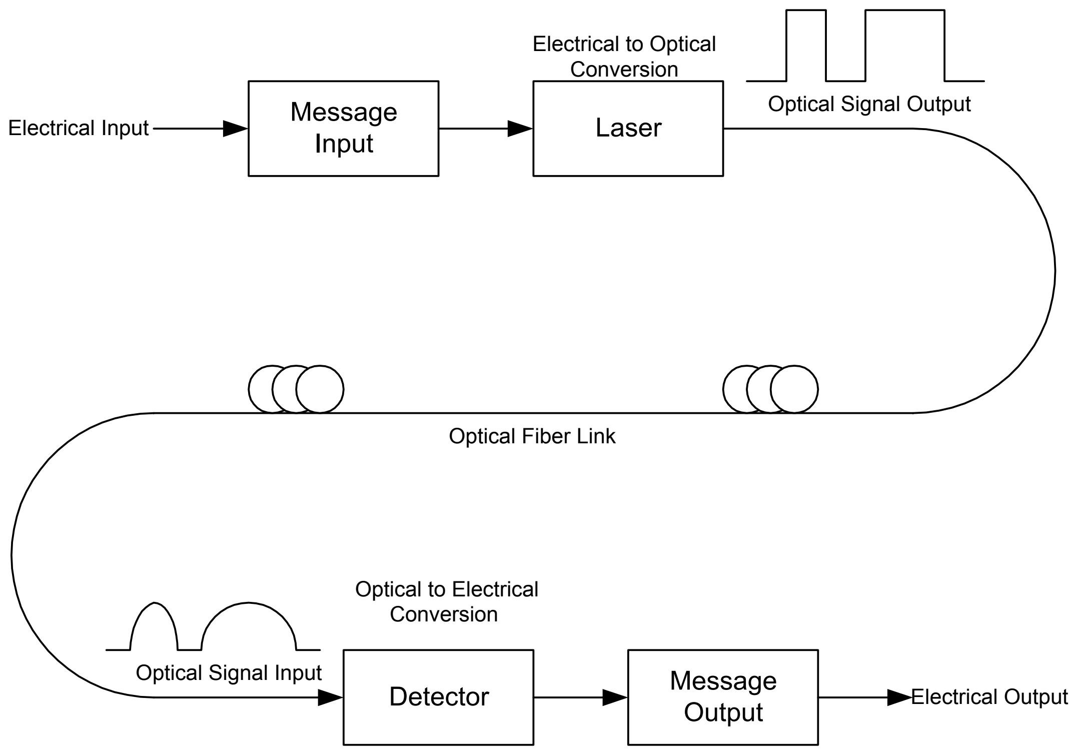


Figure 1: Typical components found in a point-to-point optical communication system

Optical fiber has many advantages over traditional copper cable and free-space microwave networks:

(i) Less signal degradation per meter
(ii) Higher signal carrying capacity / bandwidth
(iii) Less costly per meter
(iv) Lighter and thinner than copper wire
(v) Free from electromagnetic interference (Poor weather does not affect signal)
(vi) Lower transmitter launching power
(vii) Flexible (used in medical and mechanical imaging systems)

Structure of Optical Fiber

The optical fiber is made up of two concentric cylindrical strands of silica surrounded by a plastic coating. The center most silica strand is the cone of the fiber with a refractive index[1] of approximately 1.48. The core of the fiber physically transports most of the optical power. The core is surrounded by another strand of silica called the cladding. The cladding has a slightly lower refractive index, 1.46 and provides the interface that confines the optical signal to the core. The outermost layer of the optical fiber is the buffer coating. This thin plastic covering protects the glass from mechanical and environmental damage. A pictorial representation of the components that makeup an optical fiber is shown in figure 2.

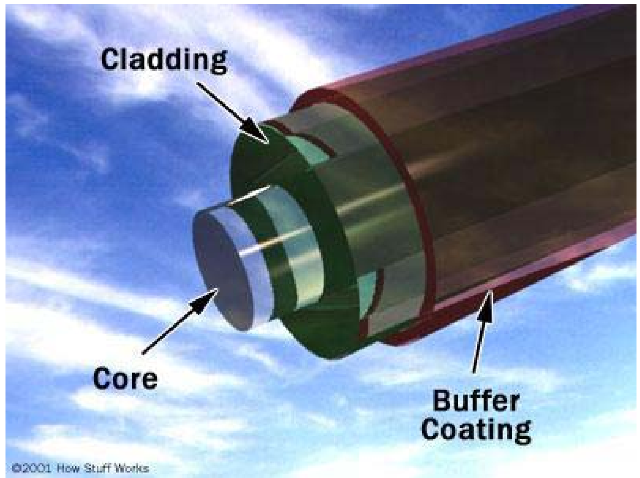


Figure 2: Makeup of an optical fiber

Signal Transport Mechanism

Physics of Total Internal Reflection

Consider a ray of light passing between two media of different refractive indexes n_1 and n_2 as shown in figure 3. If $n_1 > n_2$ the light ray as it passes from one media to the next will bend away from an imaginary line (the normal) perpendicular to the media's mating surface. Conversely if $n_1 < n_2$ then the ray will bend towards the normal. Total internal reflection occurs when $n_1 > n_2$ and the incident ray of light makes an angle, Θ_c, such that it does not enter the adjacent medium but travels along the interface. At angles greater than Θ_c the ray will be reflected back into medium A.

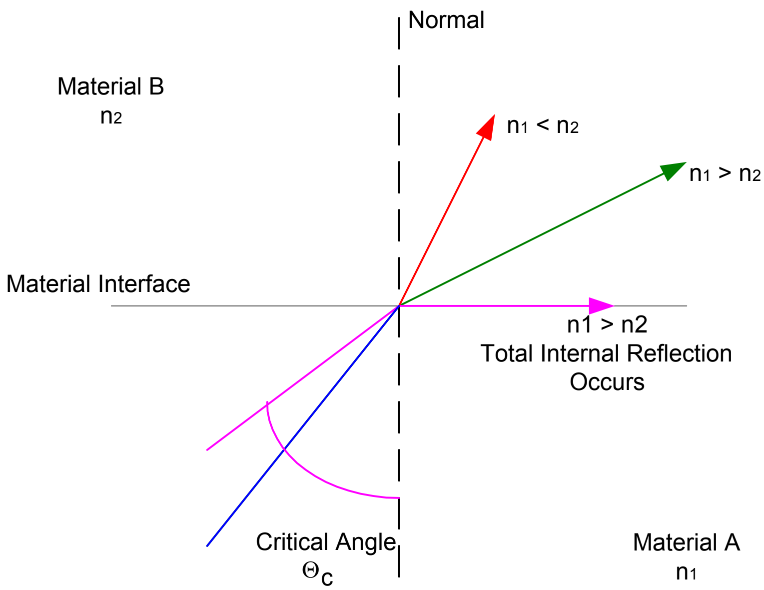


Figure 3: Total Internal Reflection

Ray Theory

Light is confined within the core of the optical fiber through total internal reflection. To understand the phenomenon of total internal reflection and how it is responsible for the confinement of light in an optical fiber consider a ray of light incident on the fiber core as shown in figure 4.

Light enters the core of the optical fiber and strikes the core/cladding interface at an angle Θ. If this angle is greater than the critical angle (i.e. $\Theta \geq \Theta_c$ where $\Theta_c = \arcsin(n_2/n_1)$) then the ray will reflect back into the core thus experiencing total internal reflection. This ray of light will continue to experience total internal reflection as it encounters core/cladding interfaces while propagating down the fiber.

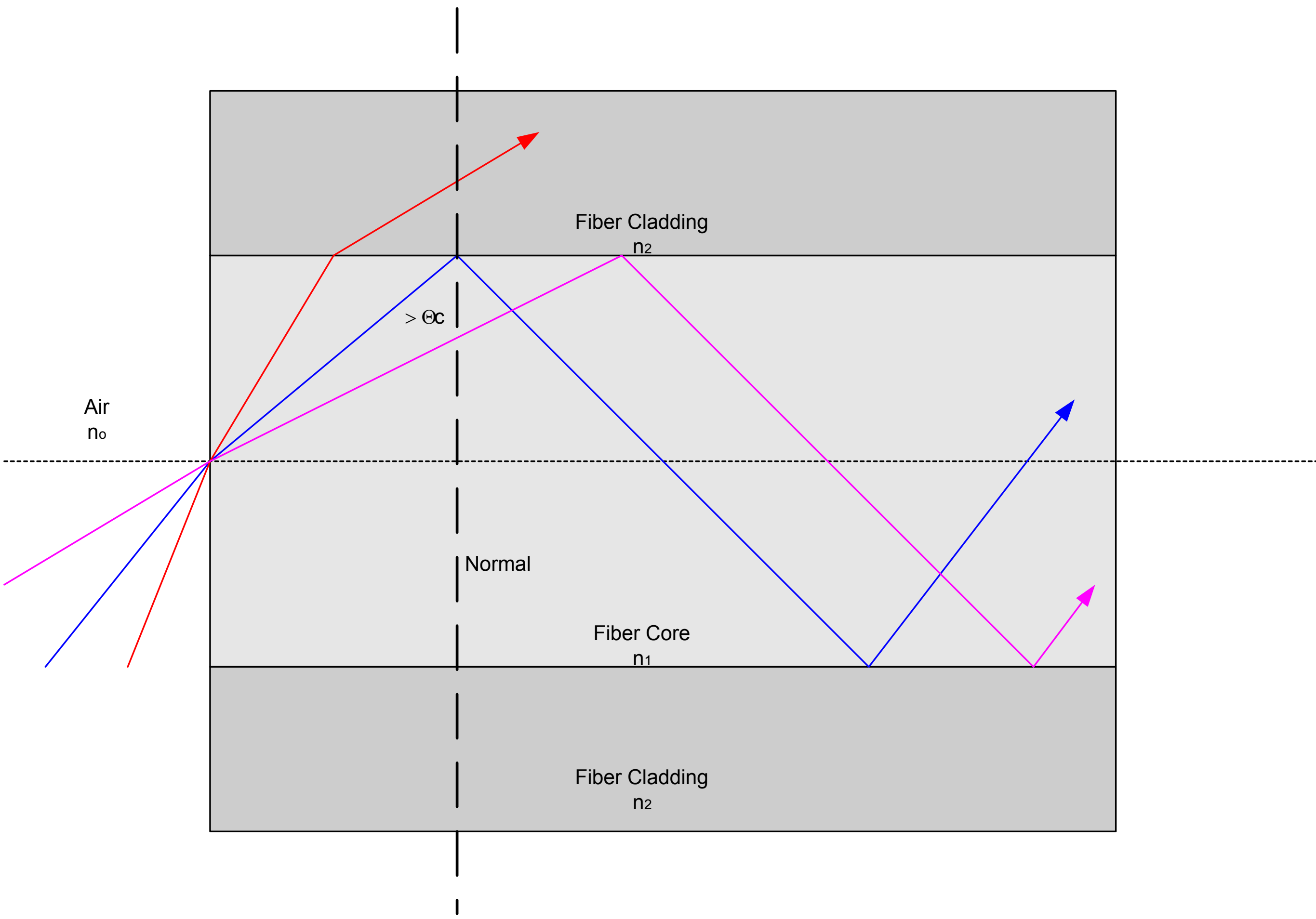


Figure 4: Light propagates through a fiber due to total internal reflection

Fiber Types

Multi-Mode Fiber

Multi-mode fiber is so named by its large core. On the order of 50μm and 65μm, multi-mode fiber allows multiple rays/modes to couple and propagate simultaneously down the fiber as demonstrated in figure 5. Large core fiber is attractive due to the ease in which light form a source can be coupled into the fiber, significantly reducing the cost of transmitter design and packaging. As will be discussed later, multimode fiber is very sensitive to dispersion, which tends to limit the distance and bandwidth of an optical system.

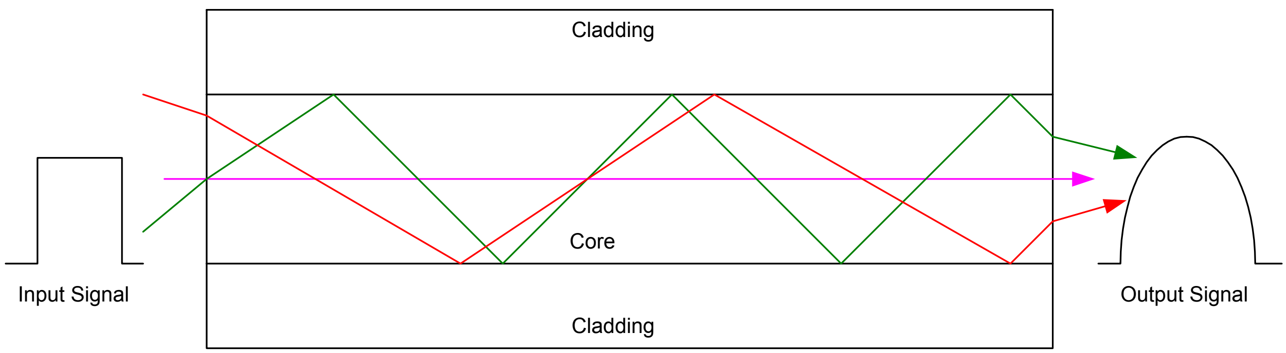


Figure 5: An input pulse is made up of multiple Modes/Rays. Each of the three rays takes different paths propagating through the core of the multi-mode fiber. As a result the three light rays shown arrive at different times causing broadening of the input pulse. This is known as dispersion and can lead to inter-symbol interference

Single-Mode Fiber

As the name implies, a single mode fiber only allows one ray/mode to propagate through the fiber core. This is accomplished by shrinking the core of the fiber to dimensions comparable to that of the wavelength being transmitted. Single mode fiber has a core dimension of ~9μm making transmitter coupling much more difficult. Consequentially single mode fiber systems employ higher costing lasers. However, single mode fiber has an advantage of higher capacity/bandwidth and is also much less sensitive to the effects of dispersion than multi-mode fiber. It is also possible to incorporate wavelength division multiplexing techniques to further increase the transmission capacity of a single-mode fiber

Evertz optical platform is compatible with both multi-mode and single-mode fiber. Our uni-directional optical cards can transmit and receiver on both multi-mode and single-mode fibers. Any bi-directional card can transmit and receive simultaneously on one single mode fiber. For WDM and multimode applications bi-directional cards require two fibers, one for transmission and the other for reception.

Optical Sources

The most commonly used optical source is the *LASER* diode (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation). Physically, a laser converts electrical current to light, which is in turn coupled into an optical fiber. An important characteristic of a laser is its threshold current. A typical current Vs optical output power is shown in figure 6.

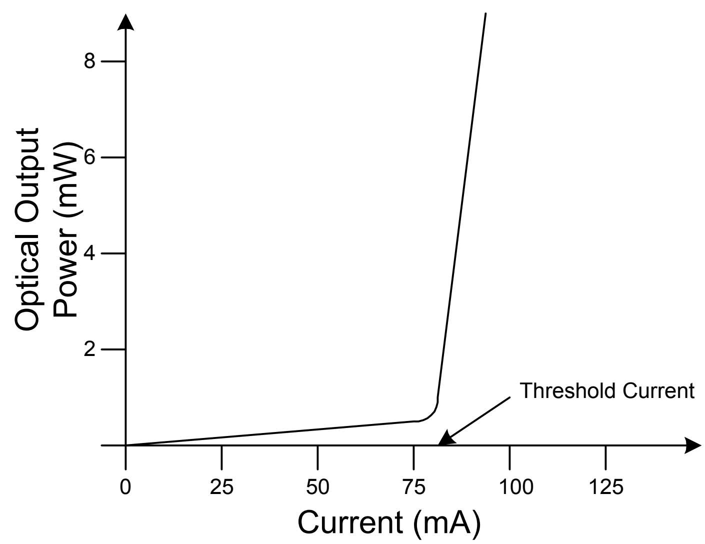


Figure 6: Typical laser response plot

Below the threshold current the optical output power of the laser is essentially zero, any photon emissions are due to spontaneous transitions in the laser's semi-conducing material. Once the applied current crosses the threshold value the output power rises considerably. The slope of the current Vs power curve above the threshold is a measure of how good the laser is at converting electrical power to optical power otherwise known as the external quantum efficiency.

Laser Modulation

Fiber communication systems typically employ some form of digital communication technique that requires the laser to be switched *ON* to transmit a digital *1* and switched *OFF* to transmit a digital *0*. To transmit a digital *0* the laser is biased slightly above the threshold where the optical output power will be low. Conversely, to generate a digital *1*, a current pulse is applied to the laser so that its optical output power will jump significantly as shown in figure 7.

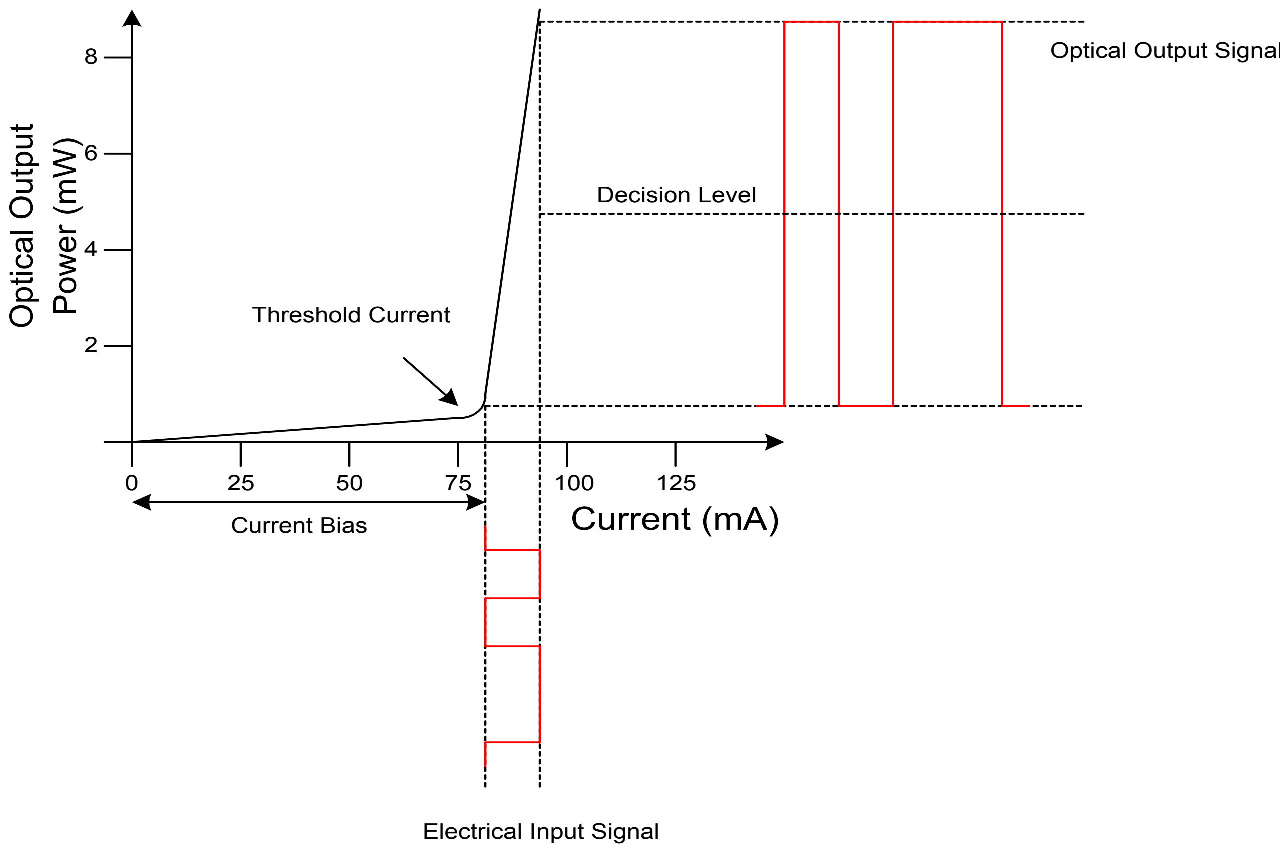


Figure 7: Laser modulation graphical representation

The amplitude of the signal can be adjusted as not to exceed the maximum current rating of the laser but high enough so that the difference in optical power representing a *1* and that representing a *0* is easily distinguished by the optical receiver. The decision level of the receiver is usually set halfway between the minimum and maximum transmitted power. The ratio between the high power state (*1*) and the low power state (*0*) is called the extinction ratio. Maximizing the extinction ratio while not over driving the laser transmitter results in better noise immunity and better sensitivity at the receiver.

Laser Spectrum

Two laser types are commonly used in optical communication systems, the Fabry Perot laser (FP) and the Distributed Feed Back laser (DFB). An FP laser is also known as a multi-longitudinal laser because its laser cavity resonates at multiple regularly spaced wavelengths, $\Delta\lambda=\lambda^2/c$. Figure 8a presents an FP laser's spectral output, notice the discrete regularly spaced wavelengths emitted from the laser. The spectral width of an FP laser is measured at the –3dB point or the FWHM and is typically around 4nm. The FP laser's greatest advantage is it's relatively low cost and is used for multimode, point-to-point direct links and low bandwidth networks

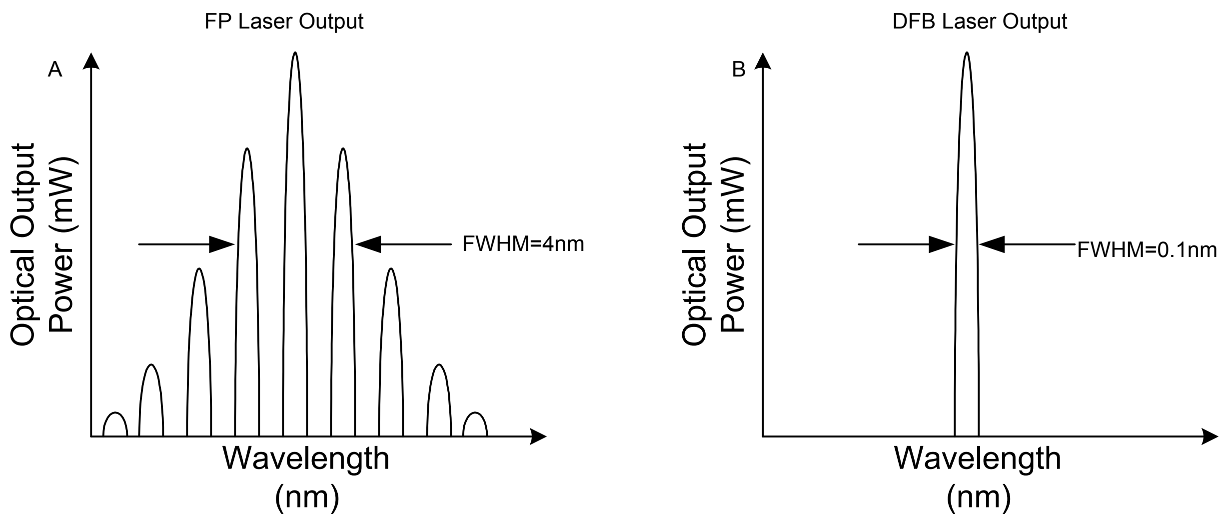


Figure 8a: A typical Fabry Perot laser's output spectrum. The full width at half maximum (FWHM) is 4nm
Figure 8b: A typical DFB laser's output spectrum. The full width at half maximum (FWHM) is 0.1nm

Figure 8b is the spectral output of a DFB laser. Immediately it is obvious that a DFB laser's output is spectrally narrower than its FP counterpart. Periodic changes in the laser's refractive index makes it highly reflective at certain wavelengths. Reflections provide feedback to the laser creating high losses at all but one wavelength so that the laser oscillates at one frequency only, making the DFB essentially a monochromatic source.

Evertz utilizes DFB lasers for all of its high bandwidth WDM systems. The spectral width of these lasers is 0.1nm at FWHM making DFB systems less susceptible to dispersion effects than those systems employing FP laser transmitters. The complex make up of DFB lasers increase the cost of the transmitters and should only be used when necessary.

Laser Back Reflection

All lasers are susceptible to back reflection. Back reflection or as it is sometimes called, optical return loss (ORL) is a peculiar phenomenon where by a fraction of the transmitted optical power will reflect back toward the source upon encountering variations in refractive index. Splices, patches and defects in the fiber all can cause back reflections. Fiber with more than 20dB of back reflection are considered quite high and optical isolators should be used on laser sources. For example the back reflection of an air-glass interface, as one would see in a broken fiber is -15 dB. If a laser with –5dBm output power was launched into this broken fiber, then the laser would have –20dBm optical power reflecting back into the laser cavity disrupting the standing optical wave generating noise in the output optical signal.

A laser's susceptibility to back reflection is determined by its coupling efficiency. For example a laser that couples only 25% of its output power into the fiber then only 25% of the total reflected power would be coupled back into the laser cavity. Likewise, a laser with 80% coupling efficiency would have 80% of the reflected power couple into the laser cavity making it very sensitive to back reflections.

To combat the negative effects of back reflection Evertz laser transmitters are equipped with optical isolators limiting the amount of optical power allowed to re-enter the laser cavity. In systems with multiple fiber patches and splices reflections becomes a major concern for single fiber bi-directional transceivers. Using a two-fiber module with the transmitter of one card connected to the receiver of the other card will eliminate reflection issues allowing a much larger link budget.

Signal Degradation in Fiber

Attenuation and dispersion are the two critical characteristics that determine the maximum distance an optical signal can be transmitted before the receiver is unable to detect it.

Attenuation

Compared to conventional transmission media the most attractive feature of fiber optic cable is its extremely low signal attenuation. The attenuation profile of a fiber is wavelength dependant; standard non-dispersion compensated fiber (i.e. corning SMF28) has an attenuation profile shown below in figure 9.

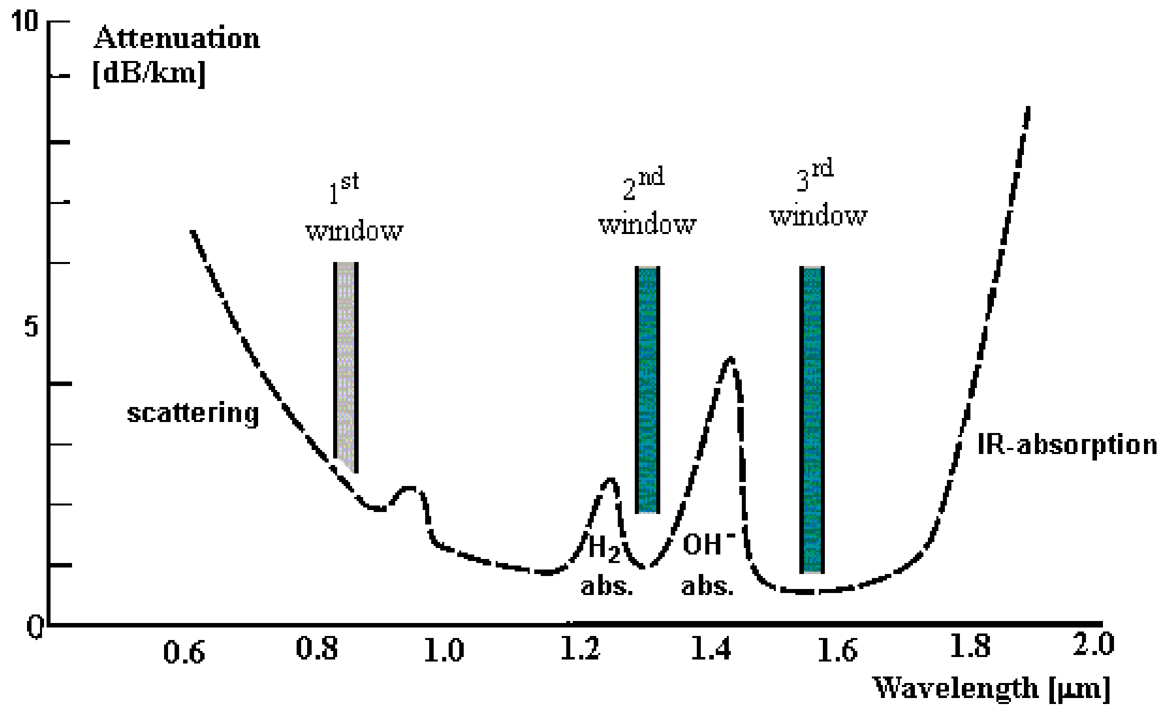


Figure 9: Attenuation profile of Corning single mode SMF28 optical cable

Typically systems are designed centered around 1310nm and 1550nm having attenuation values of 0.4dB/km and 0.3dB/km respectively. Comparatively standard Belden 1694 coaxial cable transmitting SDI video at 270MB/s has an attenuation of 100dB/km; the attractiveness of fiber becomes obvious.

Dispersion

To send information over a fiber bits of information are successively encoded and represented digitally by pulses of light. The more rapidly a laser pulses on and off the higher the bit rate and the closer encoded bits of information are spaced temporally. As these pulses of light propagate through a fiber, figure 10, they tend to lose their shape and spread out eventually over lapping each other causing inter-symbol interference. The higher the data rate of the channel the more sensitive the overall system is to the effects of dispersion. Hence dispersion limits the information carrying capacity of a fiber.

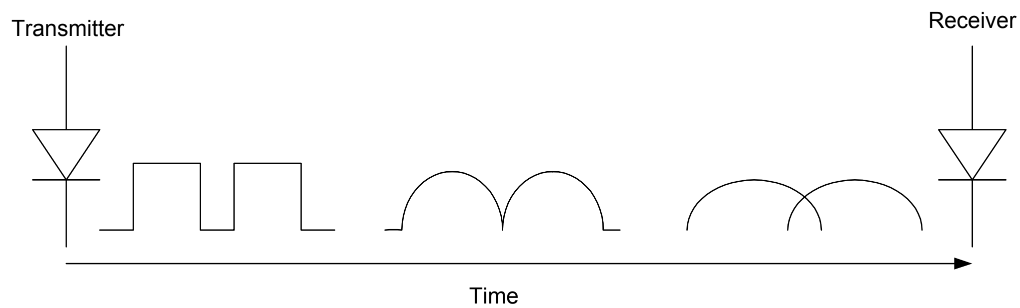


Figure 10: A square pulse of light spreads as it travels through an optical fiber eventually two adjacent pulses will overlap one another. This is known as dispersion

Multimode fiber is much more sensitive to dispersion than single mode fiber because of its large core, as shown in figure 5 different rays making up a bit of data take different paths as they propagate. These rays arrive at the receiver at slightly different times resulting in the broadening of the optical pulse. To compensate for pulse broadening the multimode fiber core has a graded refractive index profile shown in figure 11. The refractive index of the fiber is greatest in the center of the core and decrease rapidly until it becomes constant near the core/cladding interface. The refractive index value effects the speed of light, the greater the refractive index the slower light propagates making the ray passing directly through the center of the core travel slower than rays near the outside. Rays arrive at the receiver with less temporal distortion reducing the dispersion of the fiber.

Figure 8 illustrates the spectral output of a laser is not monochromatic but has a finite spectral width made up of many different wavelengths. Each of these wavelengths propagates through a fiber at slightly different speeds leading to pulse broadening. Although this type of dispersion is far less apparent than that experienced in multimode fiber it still affects the transmission distance of high data rate single mode systems.

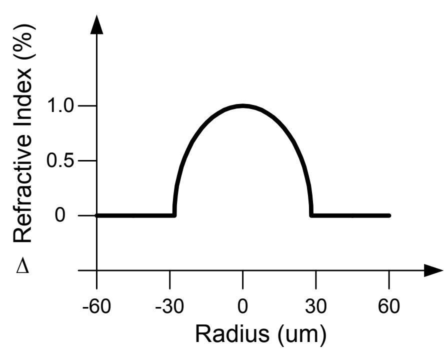


Figure 11: A standard core index profile of a multimode fiber. The graded index reduces the amount of dispersion introduced in the fiber

Bending loss

As the title implies, bending loss is introduced in a fiber when there is a sharp bend in the optical cable. Bends introduce an interruption in the path of light causing some of the optical power to leak into the cladding where it is lost. Evertz recommends a minimum-bending radius of 5cm on any fiber pigtail and when bundling fibers together with tie wraps or twist ties avoid tying these fibers too tight as to not introduce micro bending into the fiber, which will further introduce loss into your system

Signal Multiplexing

Multiplexing is defined as the process of combing multiple signals together in order to share a transportation medium. Two popular multiplexing techniques for fiber optic communication systems are Time Domain Multiplexing (TDM) and Wavelength Division Multiplexing (WDM). Multiplexing saves the number of fibers needed to transmit signals.

TDM

Time domain multiplexing; Figure 12, is accomplished in the electrical domain. Multiple parallel signals are simultaneously applied to a multiplexor that will only allow each input signal to transmit through the communication link at certain times. Since multiplexing is done in the time domain, TDM can be used with multimode fiber. Since the output bit rate is an addition of all the input signals plus some overhead, the output data rate quickly becomes large. Timing and latency issues are to be considered when using a TDM network.

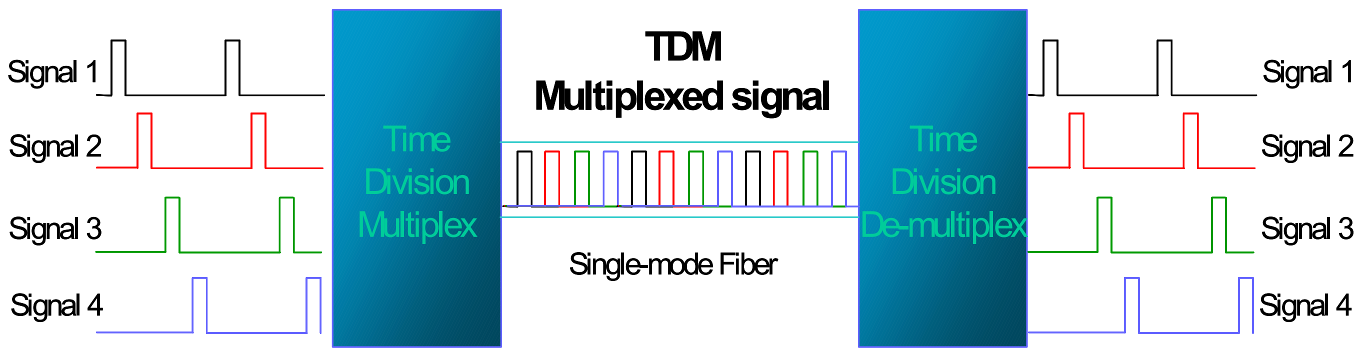


Figure 12: Time domain multiplexing block diagram. Multiple input signals are sequentially transmitted. Multiplexing is accomplished in the electrical domain

WDM

Wavelength Division Multiplexing, figure 13 is done entirely in the optical domain. Input electrical signals are each assigned a wavelength, which are combined on one fiber for transmission and separated before being received. Each electrical input signal can operate at an independent bit rate and will not interfere with any of the other input signals. Wavelength division multiplexing is available in multiple channels. Evertz offers an economical 1310nm/1550nm WDM solution consisting of two wavelengths only. Also available are 4, 8, 12 and 16 channel CWDM systems that have a 20nm channel spacing. 8, 16, 24, 32, and 40 channel dense wavelength division multiplexing systems are also now available for high signal capacity networks.

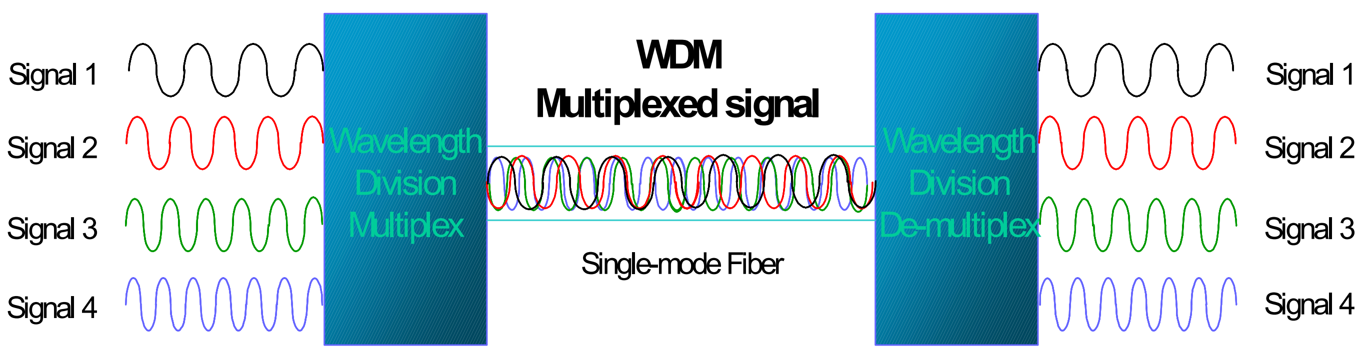


Figure 13: A 4 Channel Wavelength Division Multiplexing Block Diagram. Multiple input signals are combined optically, each signal having its own bit rate.

Optical Network Components

There are many different active and passive components that make up an optical network. A solid understanding of the function of these components is vital when designing a cost-effective optical network that will meet the bandwidth needs for many years to come.

The Coupler

The optical coupler is often called a splitter and is depicted in Figure 14. It is a passive optical component (requires no power to operate) that can divide or combine light power between multiple fibers. There are many types of couplers available; the most commonly used are the 50/50, 80/20 and the 90/10. The numbers designate the percentage of light power divided between the outputs. Other coupler types split incoming optical signals among multiple outputs. Couplers are bi-directional and can combine multiple optical signals on to a single fiber, however this will introduce some loss in the system. Evertz's passive optical couplers are available in many commonly used splitter types to meet the requirements for many optical systems.

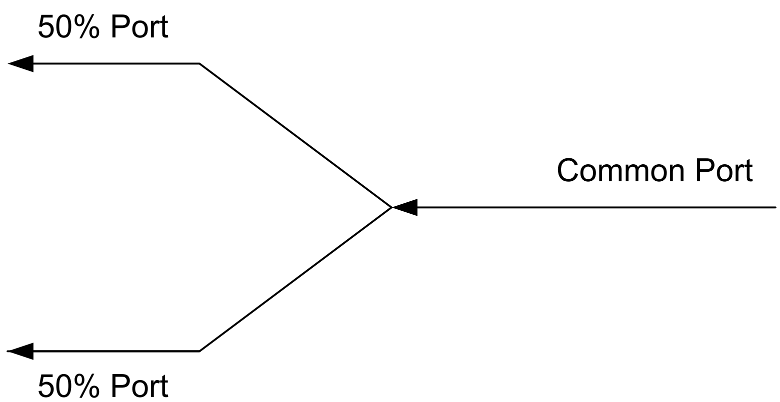


Figure 14: A 50/50 passive optical coupler evenly distributes an incoming optical signal applied to its common port between its two output ports

Optical Switch

The optical switch is an important component as it allows a network supervisor to selectively choose the input fiber. Intelligent switches are now being manufactured so that channel selection is automatic based on input optical strength. The optical switch will automatically change to input channels if the signal strength drops below a user set acceptable level. Optical signals can be lost should a fiber be damaged or disconnected. Evertz 7707BPX is an intelligent switch that can be set to automatically return to the original input if the optical link is restored.

Wavelength Division Multiplexors and Demultiplexors

Wavelength division multiplexing is used to combine/separate multiple wavelengths onto one fiber with minimum insertion loss. The internal make up of a WDM is shown in Figure 15 and is essentially a group of cascaded dichroic filters of different wavelengths. A dichroic filter is based on interferometric technology that reflects all light it does not transmit. Note the filter orders are reversed in the mux and demux to keep the insertion loss constant across all wavelengths.

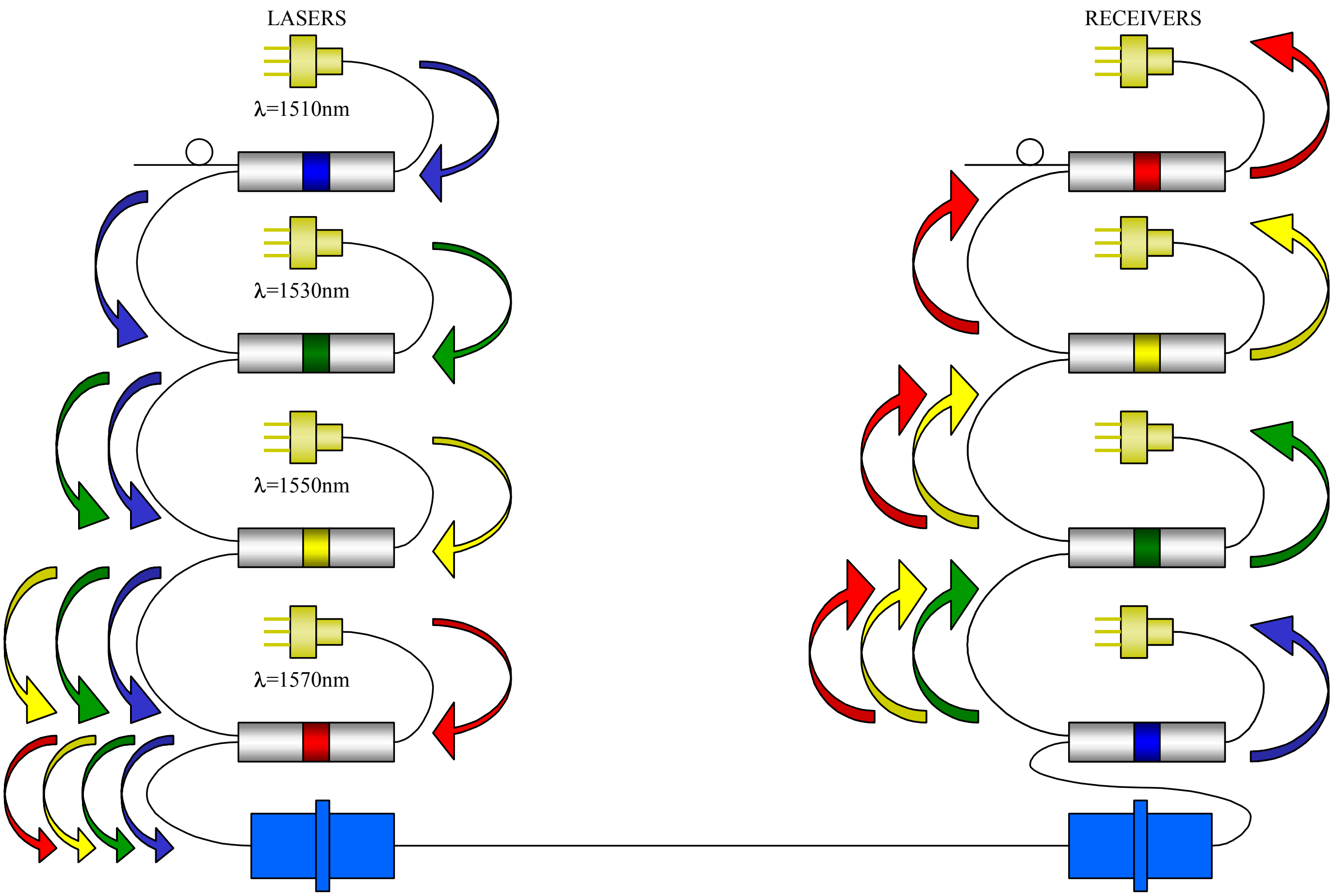


Figure 15: Internal structure of a 4 Channel CWDM Mux and Demux. Notice how the filters on the Mux side are in the opposite order of the Demux side. This keeps insertion loss constant across all wavelengths

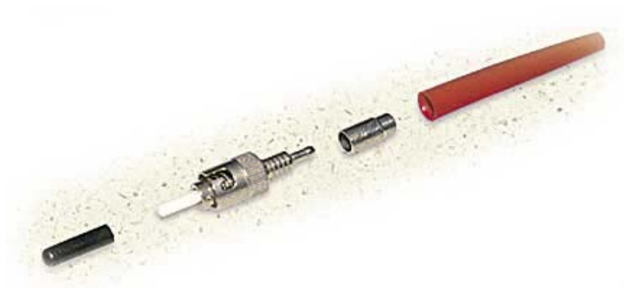
Fiber Connectors

Many different styles of fiber connectors are available to the consumer; three popular connector types available on all Evertz products are the FC/PC, SC/PC and ST/PC.

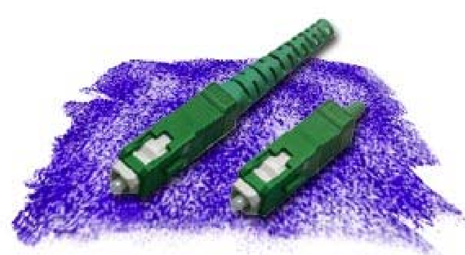
FC/PC - A threaded optical connector that originated in Japan. Good for single-mode or multimode fiber and applications requiring low back reflection. The physical contact (PC) polish produces a slightly curved end face that forces the fibers in the mating connectors into contact. This reduces back reflection to about -40dB.

SC/PC - Abbreviation for subscription channel connector, this push-pull type of optical connector also originated in Japan. Features high packing density, low loss, low back reflection, and low cost. The physical contact (PC) polish produces a slightly curved end face that forces the fibers in the mating connectors into contact. This reduces back reflection to about -40dB.

ST - Abbreviation for straight tip connector originally developed by AT&T. This connector closely resembles a BNC-type coax connector.



SC/APC - Abbreviation for subscription channel connector. The angled physical contact (APC) adds an 8° angle to a flat polish reducing back reflection to -70 dB. Its green colored body signifies Angle PC application. Caution: mating an angle polished connector with a flat polished connector will irreparably damage both connectors, DO NOT do it!



Care for Fiber optic connectors

A properly functioning fiber optic network requires clinical cleanliness of all fiber optic connections. A single particle of dust or fingerprint can scatter enough optical power from the core to take down an entire link. While not in use all fiber connector tips should be covered with dust caps to prevent damage such as scratches and pits from forming on the connector ends. Pits and scratches on the surface of a connector can migrate when mated to another connector consequentially spreading damage and requiring the re-termination on both fibers. To avoid damaging fiber connectors Evertz recommends cleaning both ends of the fiber connection prior to mating using a Cletop Reel as shown in Figure 16.

Figure16: Evertz recommended fiber optic cable cleaner made by Cletop

Network Design Considerations

The goal of any optical system is to deliver virtually error free long distance communication at low cost. There are many criteria to consider when designing an optical communication network, consider the following when contemplating an optical system:

(i) What signals need to be transported? This will determine the types of equipment and the bit rate on the fiber optic cable. For example if SDI video systems need to be transmitted, then Evertz's 7707EO would be adequate and the data rate on the optical fiber would be 270Mb/s.

(ii) What type of fiber is available? As discussed previously the two types of fiber are multimode and single mode. Multimode fibers are very susceptible to dispersion effects and hence do not have the equivalent amount of bandwidth as single mode fiber. It is also important to remember that course and dense wavelength division multiplexing is not done on multimode fiber.

(iii) How many fibers are available? Wavelength division multiplexing can radically increase the price of an optical system. If you are laying your own fiber it is a good idea to lay as many fibers as you can to avoid multiplexing. When designing an optical system every fiber should be lit up in order to avoid multiplexing

(iv) What is the power budget of the system? Wavelengths at or close to 1310nm suffer 0.4dB of attenuation per kilometer while those at or near 1550nm experience 0.3dB of attenuation per kilometer. Bare in mind, fiber links -particularly those that are leased- are often not a single piece of fiber but are commonly made up of many pieces of fiber connected together through patch panels, connectors and splices. Each patch, connector and splice attenuates the signal by approximately 0.5dB as well adding to the total optical return loss of the system. Before designing a system the link budget and if possible the optical return loss should be measured as theoretical attenuation values are often not representative of a real fiber run.

(v) What is the dispersion limit of the system? Dispersion limit is a more subtle consideration than attenuation but is nonetheless ubiquitous in all fiber systems and is usually the limiting factor in multimode fiber and high bandwidth systems. Dispersion shows up at the receiver as *jitter*, too much and the reclocker will not be able to reproduce the signal. Dispersion introduced by fiber is provided by the manufacturer on the accompanying data sheet. For the most common type of single mode fiber Corning's SMF28 the dispersion is given by

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

Zero Dispersion Wavelength, λ_0=1312nm
Zero Dispersion Slope, S_0=0.092ps/(nm^2 km)
λ=operation wavelength
Dispersion at 1310nm, D(λ)=3ps/(nm km)
Dispersion at 1550nm, D(λ)=16ps/(nm km)

The dispersion limit of an Evertz HD fiber system is calculated as follows:

Bit Rate, *f* = 1.485GB/s
Period, f^{1} = 673ps
Jitter Tolerance of Reclocker, J_T = 0.5UI
SMPTE Output Jitter Spec, J_S = 0.2UI

Total Allowable Inserted Link Jitter, J = J_T - J_S=0.3UI=202ps

Expressing the distance as a function of chromatic dispersion,

$$km = \frac{ps}{CD \bullet nm}$$

The distance a 1310nm FP laser operating at a 1.485GB/s bit rate could transmit before dispersion causes bit errors is calculated as

$$L(1310_{FP}) = \frac{202}{3 \bullet 4} = 16.8km$$

Similarly a 1550nm DFB laser could transmit

$$L(1550_{DFB}) = \frac{202}{16 \bullet 0.1} = 126.25km$$

before bit errors caused by dispersion would occur.

Maintenance of Fiber Systems

Fiber optic networks require little maintenance once they are up and running. The most difficult task is setting up the network properly. Things to remember when working with a fiber optic network are

- Proper test equipment. Trouble shooting an optical network is next to impossible without the proper equipment. Make sure you have a properly calibrated optical power meter, fiber cleaners and good optical fiber cables
- Clean all fiber mating surfaces before connection.   Every time a fiber is removed from a mating sleeve it must be cleaned with a proper fiber cleaning apparatus before being replaced
- Never touch the end of a fiber optic. Finger prints interfere with optical signals
- Keep fiber tie wraps loose and keep a minimum bending radius of 5cm on all fiber pigtails
- Never pinch or introduce a sharp bend in the fiber
- Know your network. Make sure you know the attenuation and ORL of your fiber system. Do have enough link budget for the receivers?
- If a link goes down:
  - Verify the transmitter has a valid electrical input signal
  - Verify all jumpers are properly installed and transmitter is configured properly
  - Check the output optical power of the transmitter with a power meter.
  - Verify the optical power at the receiver with an optical meter
  - Verify dispersion limit of system is not violated
  - Verify transmitter and receiver are properly seated in frame
  - Clean all accessible fiber jumpers in the system