Fiberoptic Communication Systems

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1.0 Introduction

Fiberoptic communication systems have become the backbone of the long distance communications network with their ability to carry data at rates of several Gbits/s. The high bandwidth capability of the fiberoptic systems makes it possible to offer the variety of services we typically associate with information superhighway. Cables consisting of several strands of fibers, each of diameter in the range of a few hundred microns, have been laid across the United States and other countries. The cables are also laid on the bottom floor, completing the network linking several continents, making it possible transmit information instantly from one end of the world to the other.

Information transmission is not the only area in which optical fibers have found a unique place. Optical fibers are also used as sensors to detect and measure various physical, chemical, biochemical and biomedical parameters of interest. These parameters include pressure, temperature, presence and absence of certain chemicals/ biochemicals. The inert nature of the optical fiber allows it possible for use in environments having strong electrical fields, making it an ideal choice within fighter planes, power plants etc. to monitor what is going on. We will, however, limit ourselves to the understanding of optical fibers in communications.

1.1 Light Propagation in Optical Fibers

An optical fiber is a cylindrical structure made up of pure silica. As light is launched into the fiber, the light is confined to the fiber by virtue of the phenomenon of Total Internal Reflection (TIR). To understand TIR, we need to look at the transmission of light through materials having different refractive indices. The refractive index determines the speed of the wave inside the material. The speed of light **v** inside any material is given by the following expression,

$$v = \frac{c}{n} \qquad (1)$$

where **c** is the velocity of light in free space ($3x10^8$ m/s) and **n** is the refractive index. We can now explain the phenomenon of total internal reflection using Figure 1. In Figure 1a, a ray of light is going from a medium of lower index (**rarer**) to one of a higher index (**denser**). As the ray enters the second medium it moves **towards** the normal (the dotted line). In Figure 1b, light goes from a higher index to a lower index and the light moves **away** from the normal. As the angle of incidence θ_i is increased and becomes equal to θ_c, the light in the second medium grazes the interface (Figure 1c). We now have total internal reflection if the angle of incidence goes above θ_c, known as the critical angle. All the light now stays in the medium of higher index.

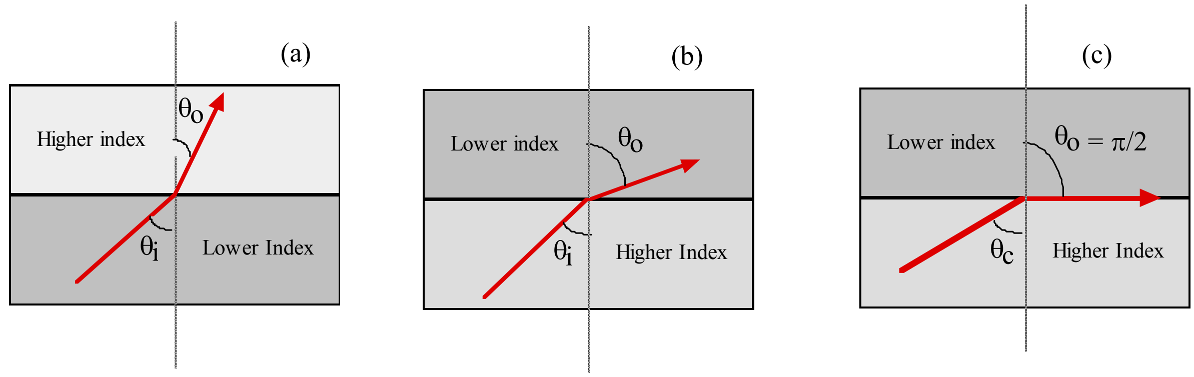

Figure 1 Reflection at an interface (a) Lower index to higher index (b) Higher index to lower index(c) Higher index to lower index at critical angle θ_c.

Condition of TIR allows light to be guided. To understand this, consider a simple experiment as shown in Figure 2. A beaker full of water has a glass tube on the right through which water can flow out freely. A beam of laser light is allowed to enter from the left as shown. If the water is now allowed to flow out, the water will appear red as it flows freely out of the tube. The higher index water (1.33) surrounded by lower index air (1.0) creates TIR conditions, and the light that was present in the beaker is now provided guiding conditions as it comes out because of water being surrounded by air.

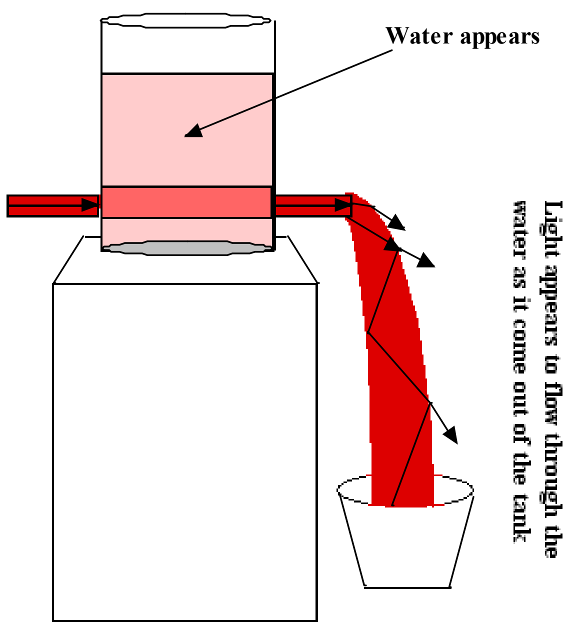

Figure 2 Concept of Total Internal reflection

The conditions of total internal reflection in optical fibers are created by having the fiber with an inner core of high index silica glass surrounded by silica glass of slightly lower index. A number of ways exist for the creation of the required index difference between the core and cladding. Thus there are a number of index profiles that are used in the fabrication of fibers. Some of these are shown in Figure 3.

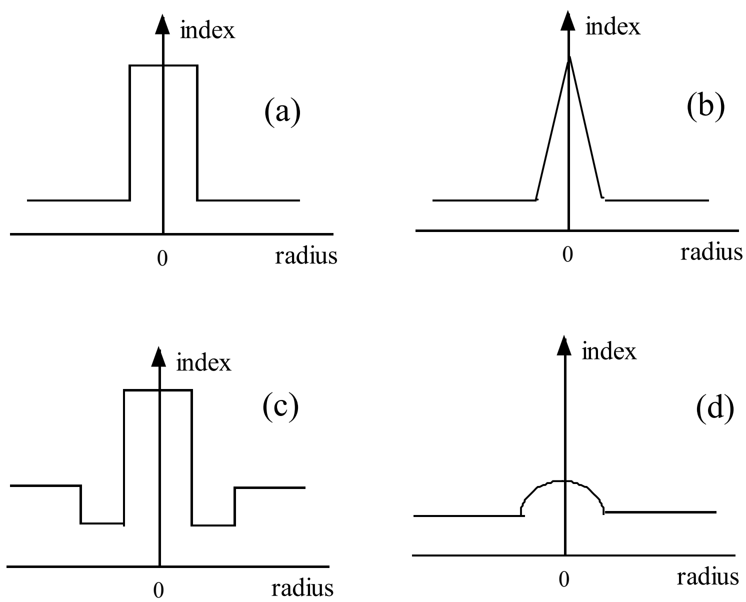

Figure 3 Index profiles
(a) Step Index
(b) Traingular
(c) W-type
(d) Graded Index

We will look at the case of the step index fiber. The structure is shown in Figure 3a. The index of the core is n_c and index of the cladding is n_{cl}. Note that air has refractive index of unity, water has a refractive of 1.33, and ordinary glass has a refractive index of around 1.45. A cut out of the fiber is shown in Figure 4.

Thus, if we have an inner cylinder (core) made up of a higher index, surrounded by material (cladding) of lower index, total internal reflection conditions can be met. Indeed, the material, Silica, is used for the core and cladding. By doping the core with a small percentage of Germanium, the index of the core region can be increased by about 10^{-3} to 10^{-4} above the cladding index (~1.456). We now have three physical parameters that characterize the fiber, the radius of the core (a), the index of the core (n_c), and the index of the cladding (n_{cl}). We will normally assume that the cladding is infinitely thick.

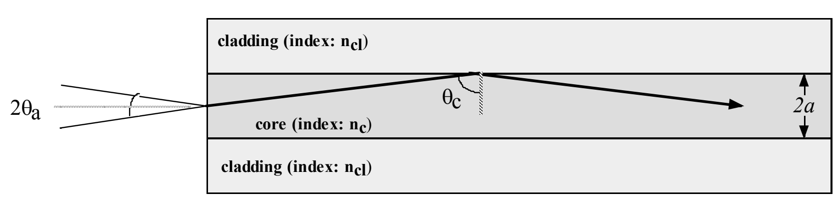

Figure 4 The critical angle at the interface of the core/cladding is θ_c. This determines the maximum angle (θ_a) for accepting light into the fiber. Light beyond the cone of $2\theta_a$ will be lost.

The acceptance angle θ_a is determined by the indices of the core and cladding and is given by

$$\theta_a = \sqrt{n_c^2 - n_{cl}^2}\ rad\ . \qquad (2)$$

The acceptance angle expressed in radians is also known as the **Numerical Aperture** (NA) of the fiber. Higher values of numerical apertures point to better light gathering capacity of the fibers. Note that NA does not depend on the radius of the fiber.

Example: A fiber has a core index of 1.458 and a cladding index of 1.451. What is the acceptance angle?

Answer: Acceptance angle $= \sqrt{1.458^2 - 1.451^2} = 0.1427 rad\ or\ 8\ deg$.

1.2 Modes in Fibers

An optical mode refers to a particular solution to the equation governing the propagation of light inside the fiber, subject to the boundary conditions existing from the physical properties of the fiber such as the core diameter, index of the core, index of the cladding and the operating wavelength. The mode has the property that its spatial distribution does not change with length or distance. The only effect of propagation is a change in the instantaneous phase or a change in amplitude induced due to losses. No change in shape of the spatial distribution (i.e., in a direction at right angle to the propagation) takes place. A fiber can support many modes. We can also fabricate a fiber that only supports a single mode. Such a fiber is known as single mode fiber. If we take a multimode fiber and reduce the radius of the fiber, the number of modes supported in the fiber goes down, and, it is possible to reach a point when only a single mode can be supported. Before we look at the simple equations governing the number of modes supported by the fiber, let us try to understand the concept of modes using a simple analogy of a 'highly flexible vertical rod' in a long box. Let us look at Figure 5. If the box is small in height (box *aa*), then the rod that can be fitted in the box can only take one possible shape (mode 1). If we increase the height now to *bb*, it can fit mode 1 and another shape (mode 2). For the box of height *cc*, the rod can also take another shape (mode 3). Thus, the transverse dimensions determine how many different 'shapes' can be present in the box. These shapes can be identified as the modes in an optical waveguide.

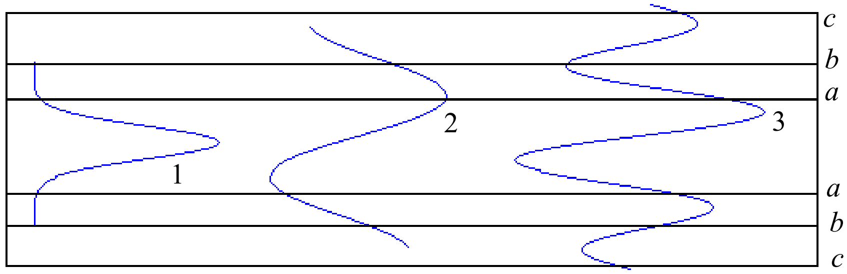

Figure 5 Concept of modes

The number of modes and their shapes will be determined by the cross sectional geometry of the fiber.

The parameter that determines whether a fiber is single mode or multimode is referred to as the V parameter of the fiber given by

$$V = \frac{2\pi}{\lambda} a \sqrt{n_c^2 - n_{cl}^2} \,. \tag{3}$$

Making an approximation that the indices are very close,

$$V = \frac{2\pi}{\lambda} a\, n_c \sqrt{2\Delta} \quad , \tag{4}$$

where Δ is the index difference defined as

$$\Delta = \frac{n_c^2 - n_{cl}^2}{2n_c} \,. \tag{5}$$

If the V value is less than 2.405, the fiber is considered to be a single mode fiber. The number of modes, N, supported in a step index fiber is given by

$$N = \frac{V^2}{2} \,. \tag{6}$$

It might appear that for V=2.405, N~2. This is **not** a mistake. It simply reflects the fact that the single mode contains two polarizations, which are indistinguishable from each other because of circular symmetry of the optical fiber. In other words, a single mode fiber contains two modes that are together and cannot be separated. One way to separate them is to use an elliptical fiber. An elliptical fiber cross section is shown Figure 5 which has the capability of separating the two modes of a single mode fiber. These fibers are also known as polarization preserving single mode fibers. Such fibers are used in coherent fiber communications and in fiber sensors.

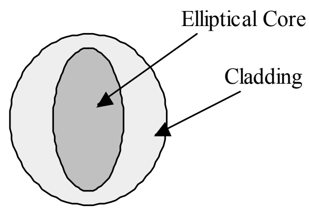

Figure 5 A typical elliptical fiber cross section. It allows the LP01 modes to become two separate modes, LP_{01}^{x} and LP_{01}^{y}.

A few modes of an optical fiber are shown in Figure 6. As the mode order increases, the patterns become more and more complex. The lowest order mode has almost a Gaussianfield pattern as shown in Figure 7.

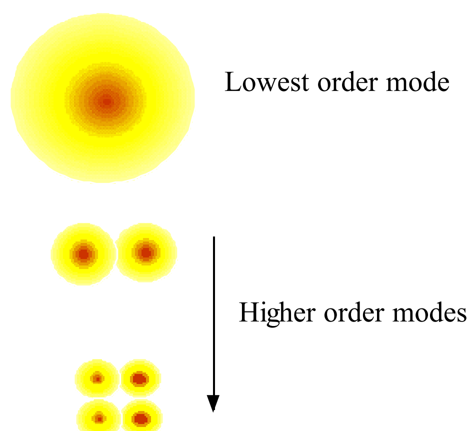

Figure 6 Modes in an optical fiber

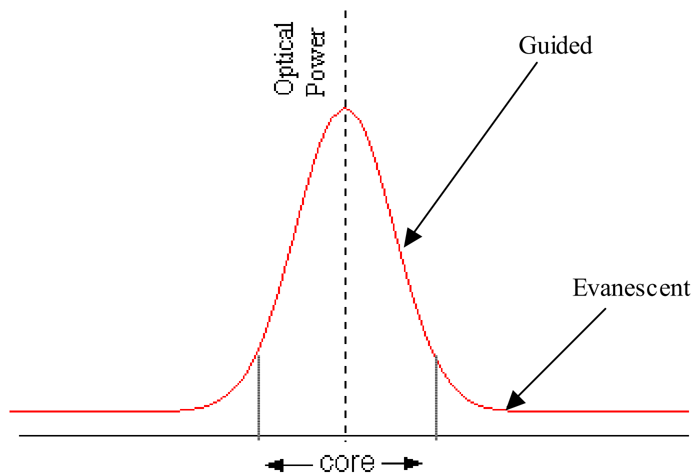

Figure 7 Intensity (power) profile of the fundamental mode

The pattern of the lowest order shows a 'guided' part of the mode inside the core and an 'evanescent' part in the cladding which has an exponential decay in the radial direction. The lowest order mode intensity profile can be approximated to a Gaussian pattern. As the V –value increases, the fundamental mode becomes 'tighter and tighter' and all most all the power in the lowest order power stays within the core. In the case of a single mode fiber of a step index fiber (V<2.405), about 85% of the power travels through the core and the rest travels through the cladding.

Example:
A step index fiber has a core radius of 8 microns. The core and cladding indices are 1.458 and 1.44 respectively. What is the V value of the fiber if the operating wavelength is

1300 nm? How many will be supported in the fiber? If a fiber must be operated as a single mode fiber at 1500 nm with the indices as given, what must be the radius of the fiber?

Answer: $V = 2\pi \frac{a}{\lambda}\sqrt{\left(n_c^2 - n_{cl}^2\right)} = 8.83.$

Number of modes supported $N = \frac{V^2}{2} = 39$.

For single mode operation V=2. 405

$$a = \frac{2.405\lambda}{2\pi\sqrt{\left(n_c^2 - n_{cl}^2\right)}} = 2.5\mu\text{m}.$$

The fiber should not have a radius larger than 2.5 µm for single mode operation at 1500 nm.

1.3 Power Loss in Fibers

As the light travels through the fiber, power is attenuated mainly because of scattering and absorption. These two phenomena are wavelength dependent, resulting in strong attenuation peaks around 1250 nm and 1400 nm. These peaks arise from the presence of water (OH) content during the fabrication. Attenuation lows exist around 1300 nm and 1500 nm. Most of the fiber communication systems operate around these two wavelengths. The attenuation is around 0.22 dB/Km in the 1500 nm region and 0.5 dB/Km in the 1300 nm (See the Appendix for definition of dB). The attenuation characteristics are shown in Figure 8.

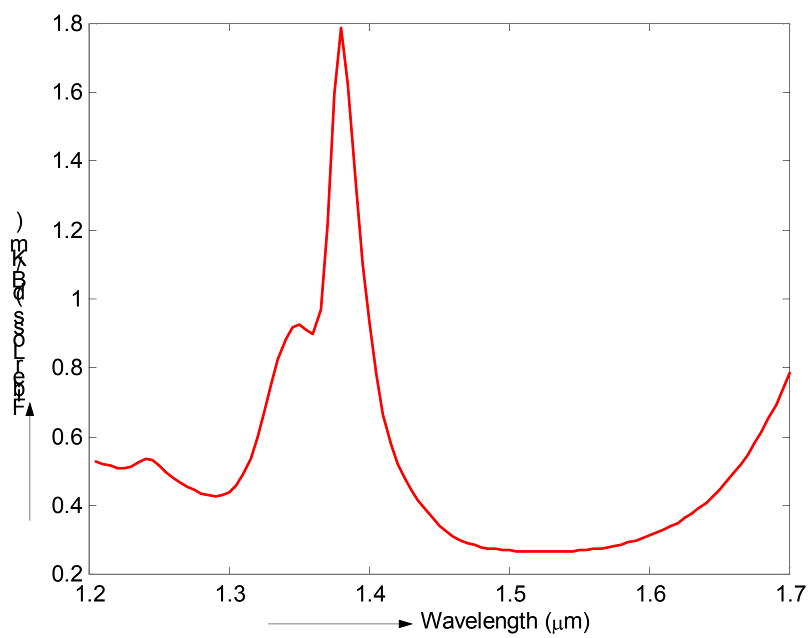

Figure 8 Power loss in optical fibers. Two low loss windows, around 1.3 µm and 1.5 µm can be seen.

1.4 Dispersion in Fibers

One of the major limitations of fiber communication systems is the pulse broadening introduced by dispersion. Dispersion is present in both single mode and multimode fibers. If a fiber is multimode, it supports a number of modes. Each of these modes will travel down the fiber at different speeds, resulting in a significant difference in times of arrival of the modes at the output end. Consider now the launch of a single pulse of light as shown in Figure 9. As soon as the pulse enters the fiber, replicas of the pulse will be created corresponding to each of the modes. Since these replicas will arrive at the receiver at different times, the resultant pulse will be broader (dark line envelope of the replicas at the output). The broadening of the pulse is the result of differential time delays and is said to come from the multimode dispersion in the fiber.

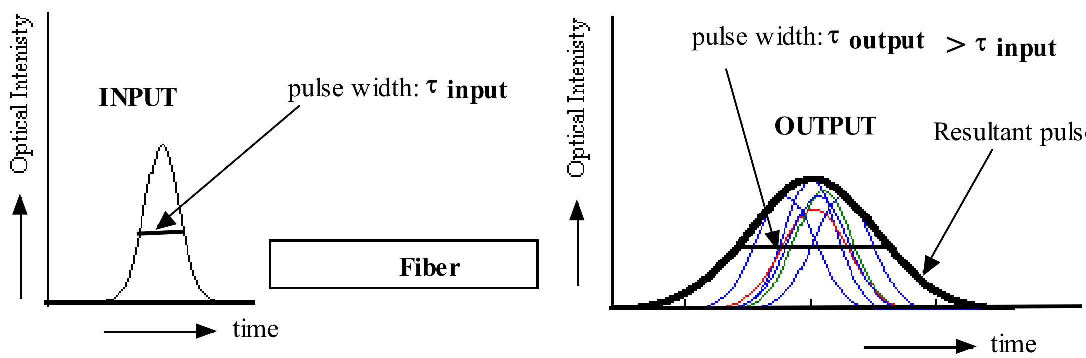

Figure 9 Pulse broadening in fibers is shown. The output pulse is an envelope of all the replicas and is thus, broader than the input pulse.

The dispersion in multimode fibers limits the data rate of transmission. As the transmission distance increases, two adjoining pulses transmitted through the fiber broaden and it becomes difficult to separate the pulses. For a multimode fiber, the upper limit of the distance-bit-rate product *BL* is given by

$$BL < \frac{8c}{n_c \Delta^2} \text{ bits/s.Km.} \tag{7}$$

Dispersion also is present in single mode fibers. The primary cause of dispersion in single mode fiber is the dispersive nature of the refractive index of glass. A material is considered to be dispersive if the speed depends on the wavelength. The refractive index of glass indeed is a function of wavelength, i.e., $n \equiv n(\lambda)$. Since all the optical sources have a finite spectral width, the dispersive nature of the index in conjunction with the finite spectral width of the source leads to dispersion in single mode fibers. We can go back to Figure and visualize that each of the replicas of the pulses now correspond to the individual wavelengths that constitute the spectrum of the source, the output pulse will certainly be broadened. The pulse broadening in single mode fibers will be much smaller than the corresponding value in multimode fibers.

There are two components to the dispersion in single mode fibers. One is the *material dispersion*, determined purely by the material properties. The other one, *waveguide dispersion* is dependent on the waveguide parameters such as the V-value, the index profile and the core diameter. This also means that while material dispersion remains a constant for a given material, the waveguide dispersion can be tailored by the choice of an appropriate index profile and diameter. The material and waveguide dispersion are interdependent. The total dispersion is the sum of these two and is shown in Figure along with the material and waveguide dispersion. The point at which the dispersion value is zero gives the operating wavelength for minimum dispersion. If the waveguide dispersion is not tailored, the fiber operated around this wavelength is referred to as a *zero dispersion* fiber (typically around 1300 nm). If the waveguide dispersion is tailored, the zero dispersion point can be moved and fibers operated at such a wavelength is identified as a *dispersion shifted* fiber (around 1500 nm). By having negligible dispersion around a band wavelengths we can have a *dispersion flattened* fiber (around 1500 nm). The dispersion characteristics of a typical single mode fiber are shown in Figure 10 and Figure 11. The unit of dispersion (D) is ps/nm.Km. Figure 10 shows the two components of the dispersion in single mode fibers. Since they are interdependent, the total dispersion in single mode fibers is given by

$$\delta\tau_{total} = \delta\tau_{mat} + \delta\tau_{waveguide}. \tag{8}$$

If we have a multimode fiber, the total dispersion in a multimode fiber sill be given by

$$\Delta\tau_{total} = \sqrt{\delta\tau_{total}^2 + \delta\tau_{mod\,al}^2}, \tag{9}$$

where the first term is the contribution from the material and waveguide dispersion while the second term is arising from the multimodes.

Figure 11 compares the dispersion characteristics of the three single mode fiber types. The dispersion flattened fiber has very low dispersion over a broad range of wavelengths. These fibers will find applications in wavelength division multiplex fiberoptic systems.

The ‘nm’ (nanometer) refers to the spectral width of the source and the ‘Km’ refers to the transmission distance in kilometers. The pulse broadening is given by

$$\Delta\tau = |D| L \sigma_{\lambda} \text{ ps}, \tag{10}$$

where D is given in Figure 11.

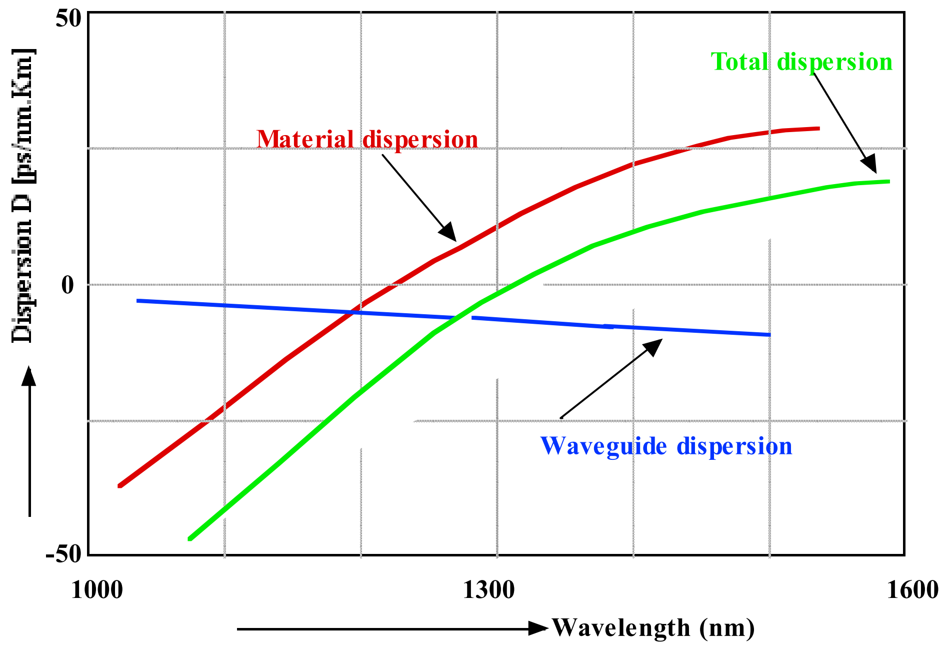

Figure 10 The material and waveguide dispersion are shown. The total dispersion is the sum of the two.

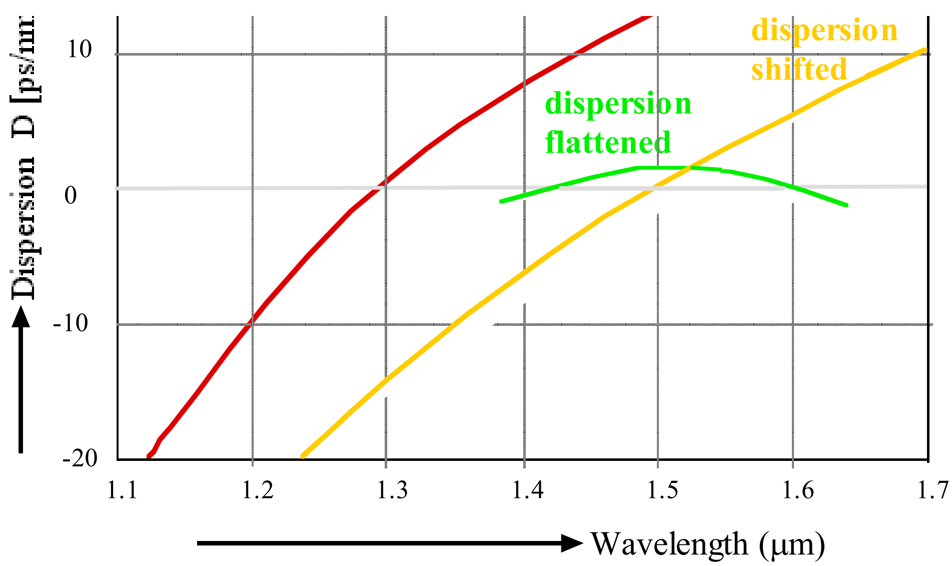

Figure 11 Dispersion in single mode fibers

Dispersion limits the ability to transmit data at high rates over long distances. As the data rate-distance product increases, we will be dealing with a weaker signal as the transmission distance increases. We also will be facing increased dispersion leading overlapping of the adjoining bits resulting in intersymbol interference as shown in Figure 11. The ISI will increase the likelihood of errors in the detection of 0's and 1's. The weaker signal also increases the likelihood of increased errors because the signal-to-noise ratio may fall below the threshold value required for acceptable performance. This means that the optical signal needs to be detected, pulses reshaped, and retransmitted. This is accomplished by using a repeater. Repeater is a receiver/transmitter combination. Before we look at a repeater

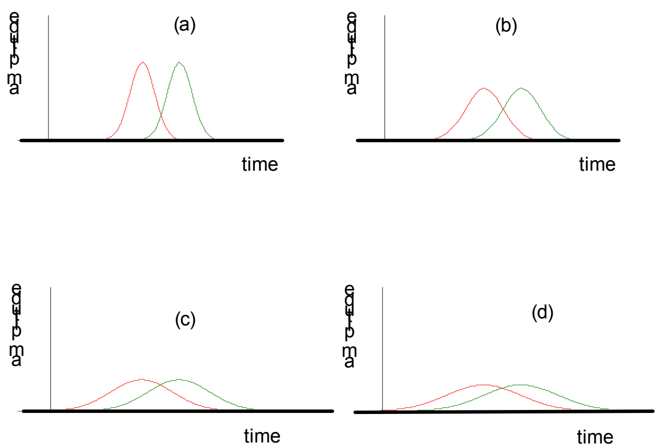

Figure 12 Two pulses are injected into the fiber. Pulses broaden as they travel down the fiber
(a) Closest to the input end
(b) away from the input end
(c) further away
(d) farthest from the input end.

Figure 12 shows the problems arising out of dispersion. As the pulses travel down the fiber, they broaden and start overlapping. It becomes difficult to separate the two adjoining pulses, increasing the error at the receiver. Reducing the data-rate-distance product will help alleviate the problem. However, this reduces our ability to transmit data at higher rates over long distances. We will see that we can either use a repeater or a soliton based communication system to overcome the limitations imposed by dispersion.

1.5 Data Transmission

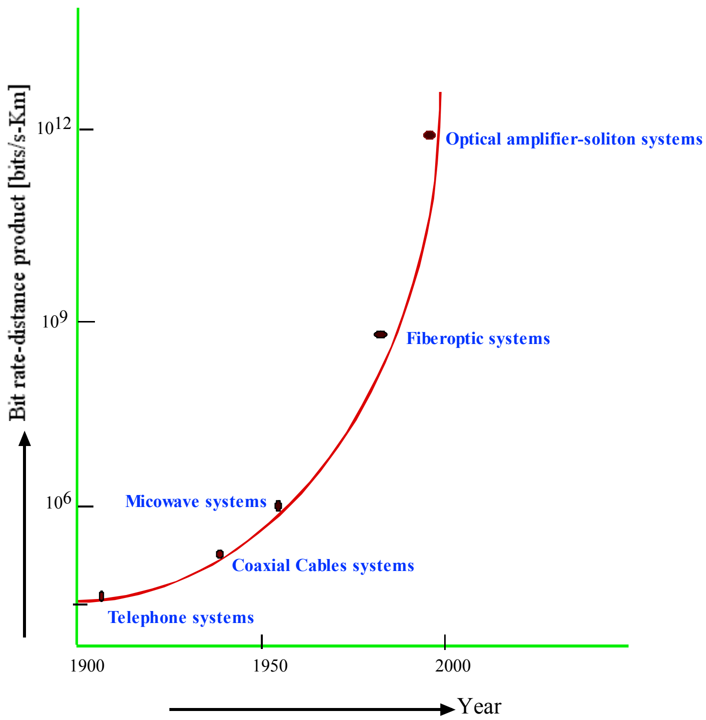

Figure 13 Transmission capabilities of different types of communication systems

Fiberoptic communication systems allow us to transmit data at rates higher than coaxial or microwave systems. A sketch of the transmission capabilities of the systems in terms of the roadmap of time is shown in Figure 13. The ability of traditional fiberoptic communication systems has been extended multifold using soliton based systems. We will briefly look at a generic fiberoptic communication systems before we look at the enhancements that will increase the capacity from a few hundred Mbits/s –Km to Gbits/s-Km.

A standard fiberoptic communication system is shown in Figure 14. It consists of a source (typically a laser diode) that can be directly modulated in accordance with the data to be transmitted, fiber, and photodiode which demodulates and converts the data back to electrical/electronic form. The laser diodes are modulated directly by applying the data signals to the bias circuit of the laser diode.

When the signal strength becomes weak and pulses broaden, there is a need to amplify the signals, ‘put the pulses back in shape’ or equalize and retransmit. This is accomplished using a repeater as shown in Figure 13b. A repeater is of regenerative type, it detects the signal, generates the electrical pulses, equalizes them to correct for the pulses distorted from dispersion. These amplified and equalized pulses are applied to the laser diode (transmitter).

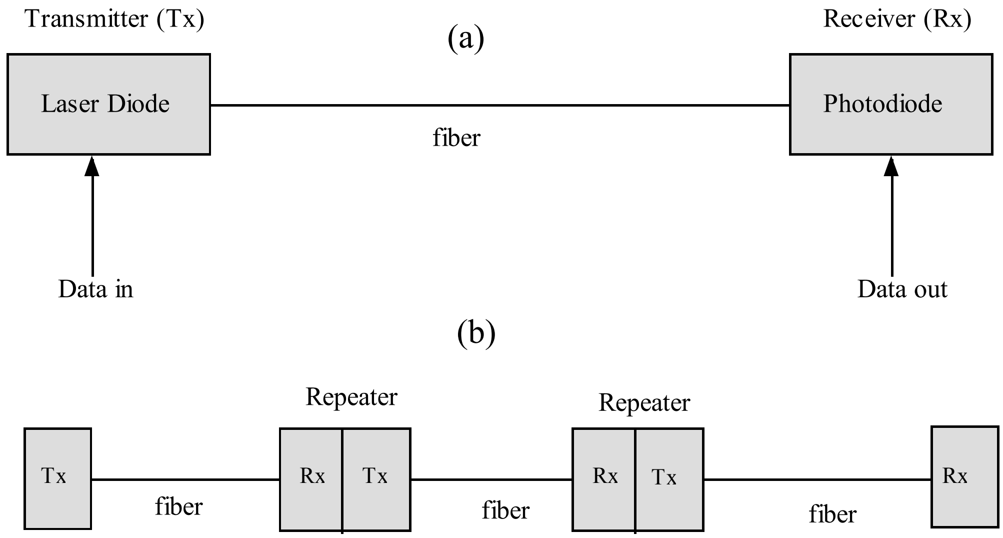

Figure 14 (a) A generic fiberoptic communication system (b) A long distance fiberoptic communication system showing repeaters

The laser diodes must have very narrow spectral widths to reduce dispersion, since the dispersion goes up with the spectral width of the source. A few typical laser diode intensity profiles are shown in Figure 15.

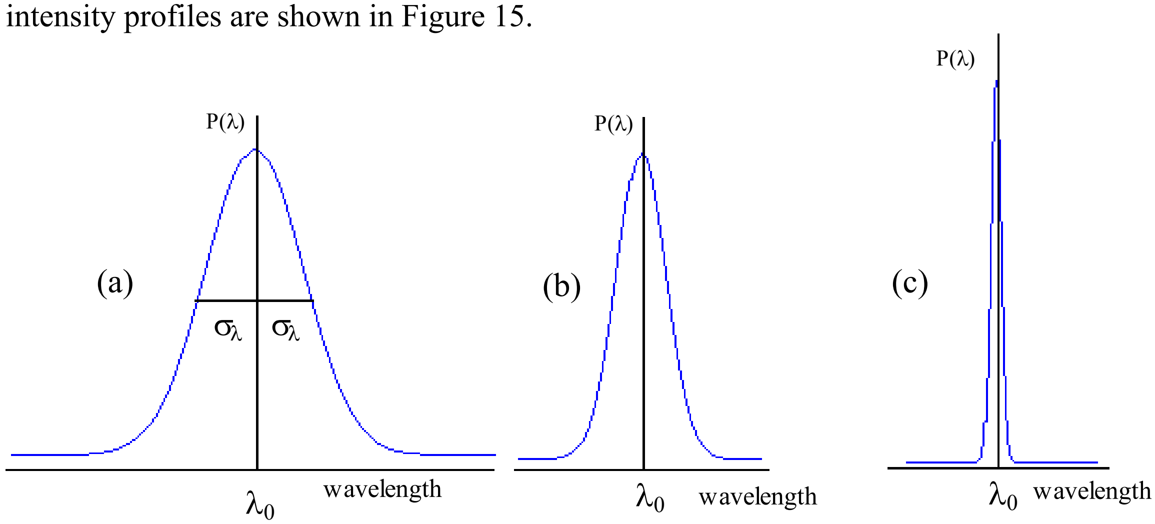

Figure 15 Intensity (power) profiles of three different types of lasers: $P(\lambda) = \frac{1}{\sqrt{2\pi\sigma_\lambda^2}} exp^{-\left(\frac{\lambda-\lambda_0}{\sigma_\lambda\sqrt{2}}\right)^2}$

λ_0 is the mean wavelength and σ_λ is the standard deviation. (a) Low data rate modulation (b) Higher data rate modulation (c) Highest data rate modulation

As the spectral width of the sources goes down, the modulation capability of the source goes up. Spectral widths of the sources can be as small as 10^{-7} nm, allowing the operation at very high data rates. It is also possible to modulate the laser beam indirectly. We will look at these external modulation systems that when we look at coherent modulation schemes.

Low spectral widths alone would not assure higher data rate capabilities. Fibers must have **low attenuation** and **low dispersion** at the operating wavelength. The photodiode must be able to have sufficient sensitivity at the operating wavelength.

One the first undersea fiberoptic systems to become operational (1988) is the TAT-8 (Transatlantic) system. It connects United States with Europe. The data rate was 280 Mbits/s with a repeater spacing of about 50 Km. Repeater used here were of the regenerative type. The operating wavelength was 1300 nm.

Significant improvements in performance of the fiberoptic systems can be realized through the use of coherent fiber systems.

1.6 Power Budget Calculations

The power budget calculations are undertaken to determine the maximum transmission distance while maintaining acceptable performance. The performance is considered to be acceptable, if the power arriving at the receiver is equal to the sensitivity of the receiver. Sensitivity is defined as the minimum power needed to maintain an acceptable value of the bit error rate. Let us look at the block diagram given in Figure 16.

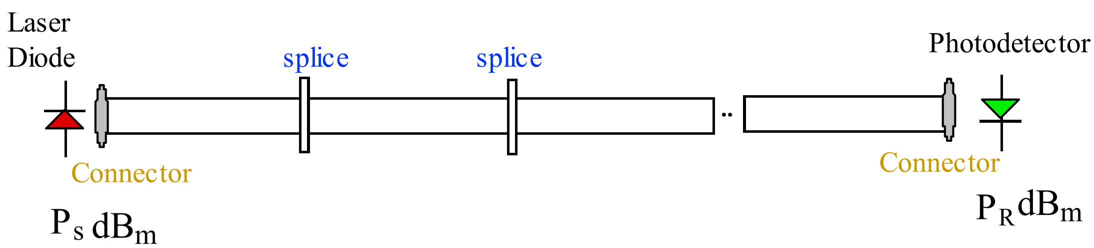

Figure 16 Optical power loss model for power budget calculations

The laser source generates an optical power of Ps dB_m (see the Appendix for the definition of dBm). The receiver sensitivity is P_R dB_m. The power budget is calculated on the basis that there is a certain amount of power equal to (P_s-P_R) dB of power to be expended between the source and the detector.

There are two connectors, one at the source end and the other at the detector end, to properly input the beam into the fiber and output the beam onto the detector respectively. Each connector loses a bit of light. Let α_c be the connector loss in dB. For a long fiber link, fibers are connected using splices and each splice also introduces a loss α_s dB. Attenuation in the fiber also introduces additional losses into the system. Let α_A be the attenuation in dB/Km in the fiber and L be the length of the total link. If there are N splices, the total loss incurred in the system, P_{loss}, is given by

$$P_{loss} = N\alpha_s + 2\alpha_c + \alpha_A L . \qquad (12)$$

We also need to leave a system margin, M dB, to account for any future problems such as degradation in performance of the source, additional splices and compensation for dispersion. Typical value of M is about 6 dB.

The expendable power must therefore be equal to

$$P_s - P_R = N\alpha_s + 2\alpha_c + \alpha_A L + M . \qquad (13)$$

The maximum allowable transmission distance L_{max} is given by

$$L_{max} = \frac{P_s - P_R - N\alpha_s - 2\alpha_c - M}{\alpha_A} \text{ Km.} \qquad (14)$$

As an example, consider a source rated at 0 dB_m. The receiver sensitivity is –42 dB_m.

Assume that there are no splices
Fiber attenuation to be 0.5 dB/km
Connector loss is 3 dB each
L_{max}= [0-(-42)-2x3-6]/0.5= 60 Km.

Note that the sensitivity depends on the data rate.

1.6 Coherent Fiberoptic Communication Systems

The fiberoptic communications systems described in the previous section are often referred to intensity modulated systems. The electrical signal modulates the intensity of the laser beam and the information is contained in the intensity variation of the laser beam. These systems are also examples of non-coherent systems, because the photodetector cannot detect changes in amplitude or phase. However, in conventional digital communication systems, coherent communication systems perform better than the non-coherent systems. Coherent systems use a local source as an integral part of the receiver and such geometries allow phase or frequency modulation of the source.

It is possible to accomplish coherent approaches in fiberoptic communications. A typical geometry is shown in Figure 17.

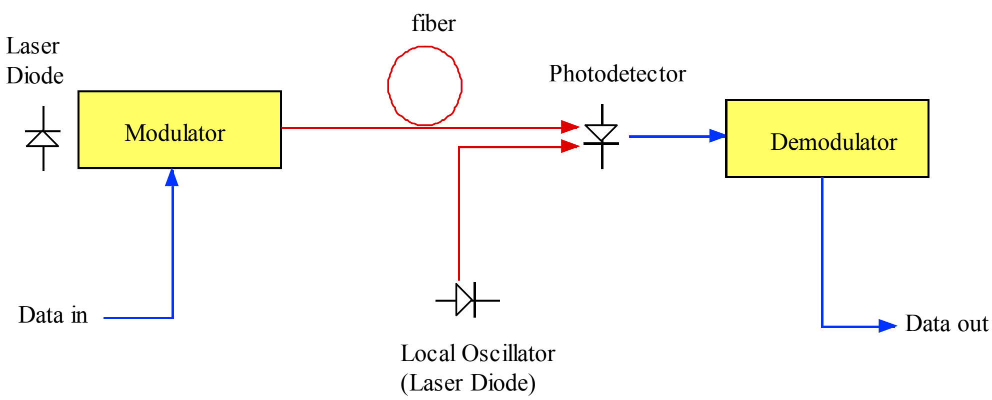

Figure 17 Generic block diagram of a coherent fiberoptic communication system. Note the presence of a laser diode at the receiver side.

The amplitude, phase or frequency of the laser beam is modulated externally. The need for an external modulator arises from two factors: laser diodes are not easily modulated directly at very high data rates and it is very difficult to carry out phase or frequency modulation of laser diodes. Phase modulated schemes lead to the best performance of the communication systems. At the receiver, a local oscillator (another laser diode) is also used. The two beams, the incoming modulated beam and the one from the local oscillator are incident on the photodetector. The photodetector followed by the demodulator can extract the necessary information to recover the data.

There are two forms of coherent fiberoptic communication systems. In the coherent homodyne systems, the frequency of the local oscillator is exactly equal to the frequency of the incoming laser signal ($frequency = \frac{velocity}{wavelength}$). In the heterodyne systems, the frequency of the local oscillator is slightly different from that of the incoming signal. Homodyne systems have the best performance. They are also difficult to implement. A very important requirement for the coherent systems to operate with its full potential is the requirement of polarization match of the incoming and local oscillator signals. A polarization preserving fiber (elliptical fiber) would be ideal in this case. Yet another requirement is the stability of the laser diodes. Their frequency and phase drifts due to changes in ambient temperature should be eliminated. Laser diodes should also have extremely narrow spectral widths ($\sim 10^{-6}$ nm). A few Gbits/s-Km capability can easily be achieved using coherent fiber communication systems.

1.7 Multichannel Lightwave Systems

The low attenuation windows of the fiber attenuation curves are very broad. In fact, those windows can accommodate at least 12 THz (1 THz = 10^{12} Hz) each of frequency content. In a single channel optical communication system described so far, we only use a tiny fraction (a few GHz) of that huge capacity available. With the availability of laser diodes of extremely narrow spectral widths ($<10^{-4}$ nm), it must possible to transmit multiple laser signals, each of which is centered around a different wavelength. For example, if we have 10 laser diodes with center wavelengths of 1510, 1512,… 1528 nm each with a spectral width of 10-5 nm, these signals will undergo almost the same attenuation and same dispersion characteristics. In other words, it should be possible use wavelength division multiplexing (WDM) to take advantage of the huge unused capacity. If each laser source is being modulated at a data rate of 6 Gbit/s, multiplexing of 10 channels (laser diodes) will increase the capacity to 60 Gbit/s over a single fiber. The concept is illustrated in Figure 18.

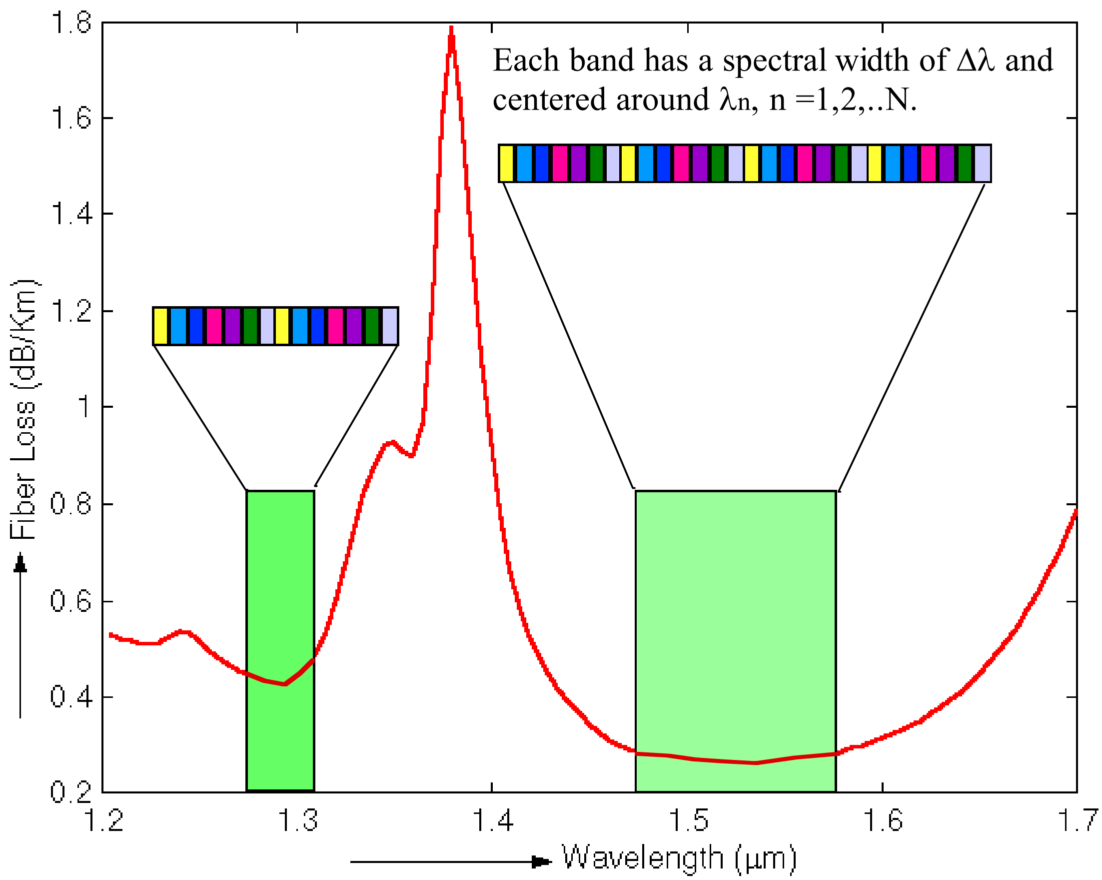

Figure 18 Two low loss windows in the loss curve of a fiber are shown. Each of those windows can accommodate a number of wavelengths.

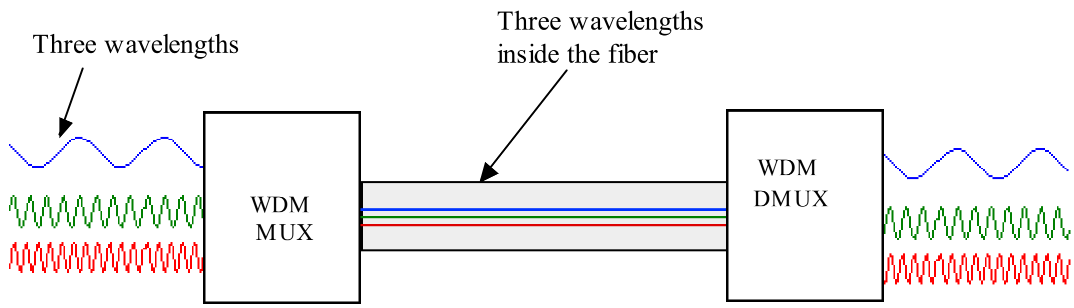

Figure 19 Concept of WDM is shown. Three separate signals are propagating through a single mode fiber.

The concept of wavelength division multiplexing is shown in Figure 19. The multiplexer (MUX) combines the multiple laser beams into a single beam so that all of them will enter the fiber. At the output end, the demultiplexer (DMUX) splits the composite signals into the individual wavelength signals. The MUX and DMUX components are dispersive elements. A simple example will be a prism. The prism has the ability to accept white light and break it into the component colors and in reverse, it can take the rainbow colors and create white light. Certainly, a prism will be inadequate in WDM systems, because the prism may only be able to separate colors separated by hundreds of nanometers in wavelength while we need components that can separate colors that differ by 2nm! Fortunately such components are available. These include Fabry-Perot filters (formed by two parallel mirrors), Mach-Zehnder filters formed on an integrated optic device, or gratings.

1.7 Stimulated Raman Systems (SRS)

Fiberoptic communications systems use regenerative repeaters in long haul systems. These repeaters are costly components because each of them contains a receiver and a transmitter. This means that there exists an optical to electrical and electrical to optical conversion taking place at each of the repeaters. Possibility of amplifying the optical signal optically can be accomplished through the use of amplifiers based on Stimulated Raman Scattering.

Stimulated Raman Scattering can be explained with the aid of Figure 20. Consider the propagation of a very strong signal at a wavelength of 1.25 μm as shown. Once this power is more than a certain threshold value, nonlinear effects such as Raman Scattering takes place. Beyond the threshold, the incident energy at the pump signal (λ_p=1.25μm) is absorbed and photons with lower energy are created. These scattered signals correspond to wavelengths (λ_s) longer than the pump signal. As these two signals (pump and scattered ones) travel through the fiber, almost all the energy in the pump is transferred to the scattered wavelengths depleting the pump and providing gain at the scattered wavelengths. The pump signal may be narrow: the scattered spectrum is normally broad as shown because of the non-crystalline nature of silica.

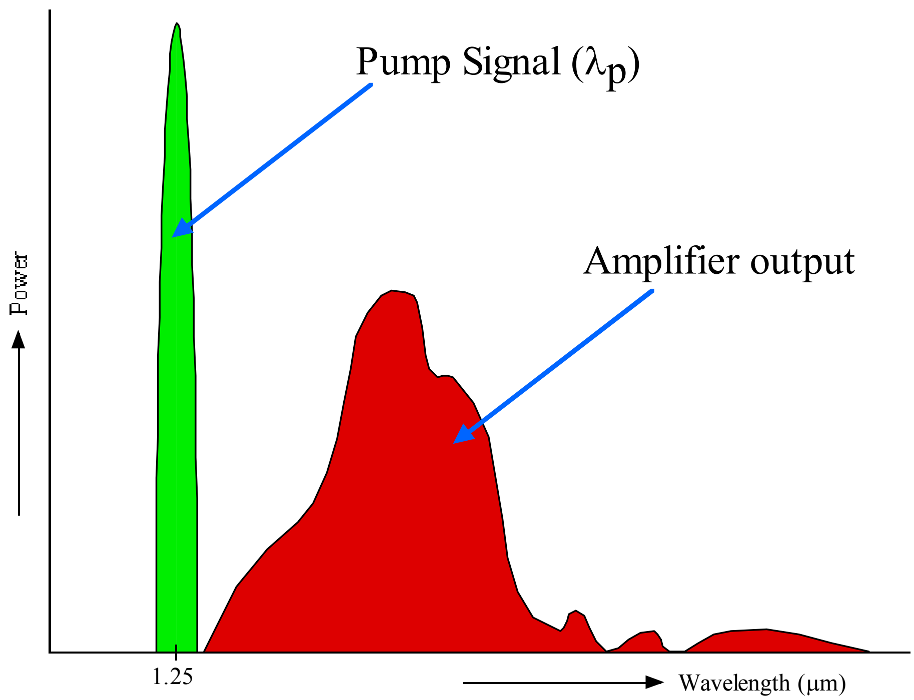

Figure 20 The phenomenon of SRS is shown. The amplified output (scattered signals) have longer wavelengths than the pump signals.

Consider now the following scenario. The information bearing signal is traveling through the fiber, and at some point, if a pump signal of wavelength shorter than the incoming signal is introduced, the incoming signal will be amplified because its wavelength falls in the window of the gain spectrum of the amplifier. The gain can be increased by doping the fiber with Erbium (Er^+) where the interaction is taking place. A schematic of the optical amplifier based system is shown in Figure 21. The pump signal (a few hundred mW) is coupled fiber carrying the incoming signal. The incoming signal gets amplified and the pump signal gets loses most of its energy. The optimum length of the Er^+ doped [or doped with Neodymium (Nd^+) or Praseodymium (Pr^{3+})] fiber region required for an efficient transfer of power can be calculated. These amplifiers can be used in direct detection systems, coherent systems and multichannel WDM systems.

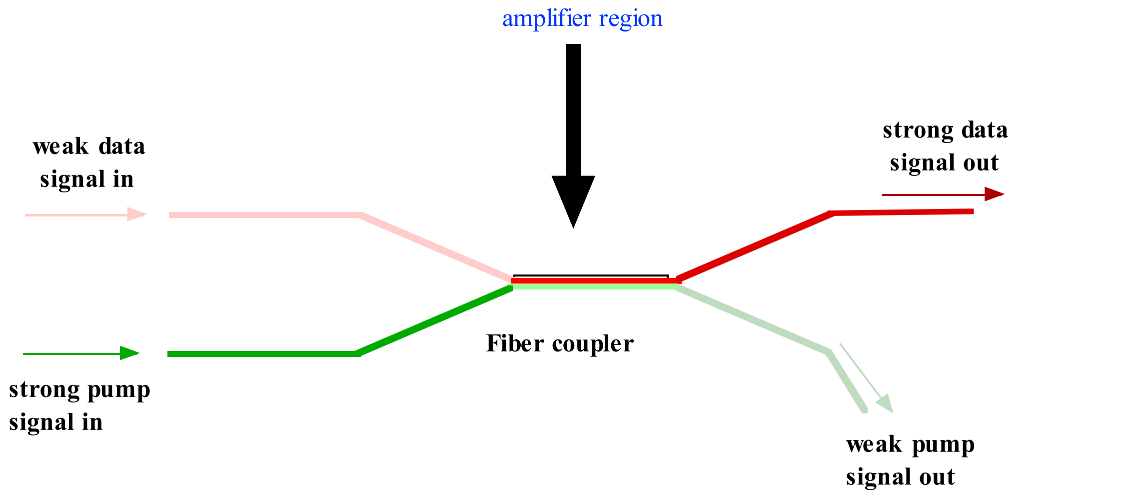

Figure 21 A SRS amplifier is shown. The pump signal is coupled to the incoming fiber.

A concatenated (chain) of amplifiers can be used in long haul systems and replace the repeaters. Note that repeaters will be required if severe dispersion is present. The concept of the concatenated amplifier based fiberoptic communication system is shown in Figure 22. These EDFA (Erbium Doped Fiber Amplifiers) replace the traditional regenerative repeaters.

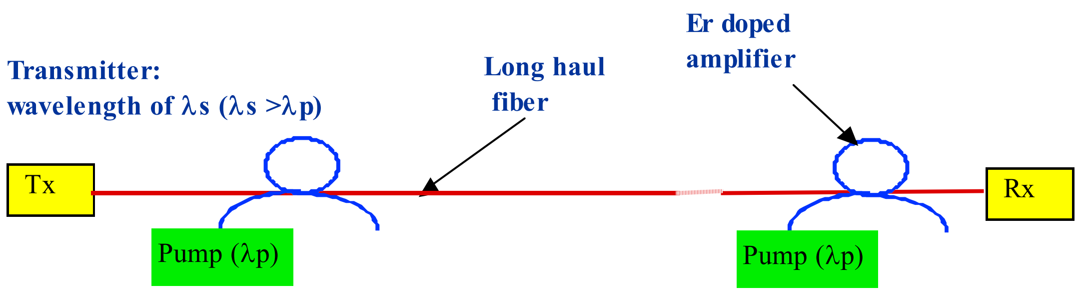

Figure 22 Chain of amplifiers in a long haul fiberoptic system is shown. The pump wavelength is shorter than the wavelength of the information bearing signal.

1.8 Soliton Systems

The use of SRS amplifiers only helps in reducing one of the problems of long haul transmission, namely the loss of the signal. The second problem, pulse broadening brought on by dispersion, still remains even with the use of SRS or SBS based amplifiers. Indeed, the fundamental limitation of the fiberoptic communication systems arises from dispersion.

Dispersion can be compensated if it is possible to keep the pulse from expanding or broadening. But, the dispersion in the fiber can only be reduced, not eliminated. However, along with pulse broadening if we can introduce pulse compression, the two counteracting effects, broadening and compression, will ensure that the pulses do not spread in time.

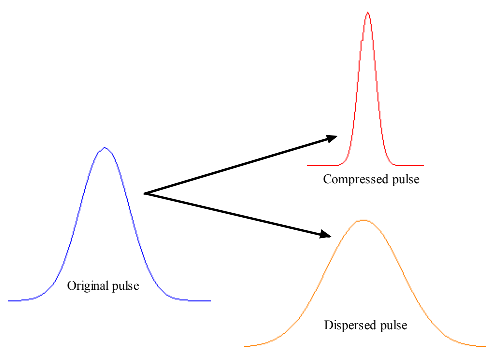

Figure 23 Original pulse, a compressed pulse and a dispersed pulse are shown.

It can be easily seen from Figure 23 that by having pulse a compressed pulse and a dispersed pulse, the pulse can traverse un-dispersed. Pulses that are not dispersed are referred to as solitons or solitary pulses. These pulses must have a certain definite shape and will require a minimum strength. The energy in the pulse introduces intensity induced refractive index change in the material of the fiber. Index changes from intensity variations are a manifestation of the non-linearity of the material. Intensity induced changes leads to pulse compression because such changes are equivalent to self-phase modulation. Phase modulation and frequency modulation increase the frequency content in the pulse. Using the Fourier property of duality (expansion in the frequency domain causes a compression in the frequency domain and vice versa), the pulse must now be narrower. This narrowing of the pulse will be sufficient to compensate for the dispersion in the fiber, keeping the pulse from spreading.

Fiberoptic communication systems based on solitons use SRS or other amplifiers to keep the signal energy back to the minimum value required to produce the nonlinearities needed. Thus, the system shown in Figure 22 where the input pulse is of a specific shape, will provide a fiberoptic communication system that mitigates the twin problems of attenuation and dispersion.

1.9 Concluding Remarks

Fiberoptic communications opened the way for fast, high data rate long haul data transmission systems. Optical fiber switches and routers aid the fast switching, splitting, and routing of information. Indeed, the future of telecommunications is already here, ushered in by signals passing through a micron size glass tube.

Appendix

Decibels

In electrical engineering, it is often necessary to calculate the loss incurred in the transmission link. Knowing the transmitted power and received power, we can obtain the fraction of power lost in transit. This computation becomes easy, if we use the concept of decibels to express the loss. This is particularly useful when power in Watts is transmitted and power received is in microwatts.

Let P_t (W) be the power transmitted and P_r (W) be the power received. The loss in decibels is expressed as the ratio

$$loss = 10 \log_{10}\left(\frac{P_t}{P_r}\right) \text{dB}.$$

1. For example, let us transmit 15 milliwatts (mW) of power. If it is given that there is a loss of 20 dB in transit, how much is the received power in milliwatts?

Answer:

$$20 = 10 \log_{10}\left(\frac{15}{P_r}\right)$$

or

$$P_r = \frac{P_t}{100} = 0.15\, mW .$$

Verify: $loss = 10 \log_{10}\left(\frac{15}{0.15}\right) = 20\, dB$.

2. Transmitted power is 23 mW. The received power is 1 microwatt **(1 mW=1000μW)**. How much is the loss in decibels?

Answer:

$$loss = 10\,log_{10}\left(\frac{23}{1e-3}\right) = 43.6\ dB$$

It can easily be seen that a 3 dB loss mean that the received power will be 50% of the transmitted power. A 10 dB loss means that the received power will be 10% of the transmitted power.

Another quantity that is often used in communication systems, particularly in fiberoptic communication systems is, the dB_m. While dB is a ratio of two powers, dB_m is the power with reference to 1mW. In other words, dB_m can provide a means to express the power in exact terms.

For example, a laser diode is rated at 15 mW. We can express this power in dB_m.

$$Power\left(dB_m\right) = 10\,log_{10}\left(\frac{P}{1mW}\right) = 10\,log_{10}\left(\frac{15mW}{1mW}\right) = 11.77\ dB_m$$

If a laser diode is rated at 0 dB_m, it emits a power of 1mW. If the received power is 1 μW, we can express it as –30 dB_m.

Example:

If a laser diode transmits at a power of 25 mW and the loss in the fiberoptic link is 55 dB, calculate the received power?

Answer:

Transmitted power is $10log_{10}(25)$ dB_m or 14 dB_m. Loss is 55 dB.
The received power = 14-55 = - 41 dBm or $10^{-4.1}$ mW = $80*10^{-6}$ mW.

Exercises

1. Explain why the index of the core must be larger than that of the cladding in a step index fiber. (2-3 sentences)
2. What is meant by Total Internal Reflection?
3. A beam of light is incident at an interface of glass and water. Light enters the water through glass. What is the critical angle at the interface?
4. A step index fiber has a core index of 1.5 and cladding index of 1.456. What is the acceptance angle of the fiber?
5. For the fiber in Exercise 4, the core diameter is 8 microns. A source of wavelength 1300 nm will be used to transmit information through this fiber? What is the V parameter of the fiber? How many modes can be supported in this fiber?
6. It has been decided to take make a single mode fiber with the indices of refraction in exercise 4. Plot a curve of a vs λ to achieve single mode operation. If the operating wavelength is 1200 nm, what must be the core radius for single mode operation?
7. Explain the term evanescent field (or wave). Can you think of any practical uses to which such fields are put to use?
8. It is known that it is possible to 'signals' going through copper wires. Do you think it is possible to 'tap into' the signal in the fiber without cutting it? Explain your answer.
9. It is said that optical fibers are immune from electromagnetic interference. Can you explain the reasons for this view?
10. Explain the concept of a mode.
11. In a multimode fiber there are many modes. Do you think that they mix? Explain your answer?
12. Suppose you have a fiber with two or three modes. The output end of the fiber is held close to a screen. Explain what you are likely to observe on the screen.
13. You have two sources for use in data transmission. One of them has a spectral width of 0.005 nm and the second one has spectral width of 0.006 nm. Both of them have an operating wavelength of 1300 nm. If you are planning to use a single mode fiber, which one will lead to higher dispersion and Why?
14. You have two sources for use in data transmission. One of them has a spectral width of 0.003 nm and an operating wavelength of 1350 nm and the second one has spectral width of 0.006 nm and an operating wavelength of 1301 nm. The fiber is a **standard zero dispersion** fiber. If you are planning to use a single mode fiber, which one will lead to higher dispersion and why?
15. Explain how you can create a dispersion shifted single mode fiber.
16. Explain how you can create a dispersion flattened fiber.
17. Explain why a single mode fiber **really is not** a single mode fiber.
18. Based on what you have read in this writeup, can you explain what is meant by attenuation limited fiberoptic systems and dispersion limited fiberoptic systems.
19. Explain why a pulse broadens as it travels through a (a) multimode fiber and (b) a single mode fiber?

20. You are asked to design a fiberoptic link. Based on the information, you have concluded that the system is attenuation limited. The fiber has an attenuation of 0.5 dB/km and splice loss is 2dB/splice. The connector loss is 3dB/connector. The laser diode will be operated at 20 mW. If the receiver sensitivity is –50 dBm and fiber comes in lengths of 6 Km, calculate the maximum transmission distance.
21. A laser is transmitting 10 mW of power. The loss in the link is 60 dB. How much power in mW will be reach the receiver?
22. Explain the operation of a WDM system.
23. If you are planning to use a WDM system with 20 channels and each channel has a capacity of 2Gbits/s.Km, what is the maximum capacity of the WDM system?
24. Explain the operation of multiplexer using a prism as the multiplexing element.
25. Explain what is ‘coherent’ about coherent fiber systems?
26. Explain the need for a local oscillator in coherent fiber systems.
27. Explain the operation of an optical amplifier based on SRS systems.
28. Can you operate the SRS based amplifier if the pump signal is at 1200 nm and the information bearing signal is at 1150 nm. Explain your answer.
29. Explain the differences between a regenerative repeater and an SRS based amplifier.
30. Explain the concept of a soliton. How can they be used in fiberoptic communication systems?