PRAMANA — journal of physics

Vol. 57, Nos 5 & 6
Nov. & Dec. 2001
pp. 849–869

Optical fiber communication — An overview

M ARUMUGAM
Department of Physics, Anna University, Chennai 600 025, India

Abstract. This paper deals with the historical development of optical communication systems and their failures initially. Then the different generations in optical fiber communication along with their features are discussed. Some aspects of total internal reflection, different types of fibers along with their size and refractive index profile, dispersion and loss mechanisms are also mentioned. Finally the general system of optical fiber communication is briefly mentioned along with its advantages and limitations. Future soliton based optical fiber communication is also highlighted.

Keywords. Bandwidth; optical fiber; group index; group velocity; soliton v-number; dispersion.

PACS Nos 42.65 Tg; 47.81 Dp; 42.79 Sz; 05.45 Yv

1. Introduction

Now we are in the twenty first century, the era of 'Information technology' [1-6]. There is no doubt that information technology has had an exponential growth through the modern telecommunication systems. Particularly, optical fiber communication plays a vital role in the development of high quality and high-speed telecommunication systems. Today, optical fibers are not only used in telecommunication links but also used in the Internet and local area networks (LAN) to achieve high signaling rates.

1.1 *Historical perspective of optical communication*

The use of light for transmitting information from one place to another place is a very old technique. In 800 BC., the Greeks used fire and smoke signals for sending information like victory in a war, alertting against enemy, call for help, etc. Mostly only one type of signal was conveyed. During the second century B.C. optical signals were encoded using signaling lamps so that any message could be sent. There was no development in optical communication till the end of the 18th century. The speed of the optical communication link was limited due to the requirement of line of sight transmission paths, the human eye as the receiver and unreliable nature of transmission paths affected by atmospheric effects such as fog and rain. In 1791, Chappe from France developed the semaphore for telecommunication on land. But that was also with limited information transfer.

In 1835, Samuel Morse invented the telegraph and the era of electrical communications started throughout the world. The use of wire cables for the transmission of Morse coded signals was implemented in 1844. In 1872, Alexander Graham Bell proposed the photo phone with a diaphragm giving speech transmission over a distance of 200 m. But within four years, Graham Bell had changed the photophone into telephone using electrical current for transmission of speech signals. In 1878, the first telephone exchange was installed at New Haven. Meanwhile, Hertz discovered radio waves in 1887. Marconi demonstrated radio communication without using wires in 1895. Using modulation techniques, the signals were transmitted over a long distance using radio waves and microwaves as the carrier.

During the middle of the twentieth century, it was realized that an increase of several orders of magnitude of bit rate distance product would be possible if optical waves were used as the carrier [1].

Table 1 shows the different communication systems and their bit rate distance product. Here the repeater spacing is mentioned as distance. In the old optical communication system, the bit rate distance product is only about 1 (bit/s)-km due to enormous transmission loss (10^5 to 10^7 dB/km). The information carrying capacity of telegraphy is about hundred times lesser than a telephony. Even though the high-speed coaxial systems were evaluated during 1975, they had smaller repeater spacing. Microwaves are used in modern communication systems with the increased bit rate distance product. However, a coherent optical carrier like laser will have more information carrying capacity.

So the communication engineers were interested in optical communication using lasers in an effective manner from 1960 onwards. A new era in optical communication started after the invention of laser in 1960 by Maiman. The light waves from the laser, a coherent source of light waves having high intensity, high monochromaticity and high directionality with less divergence, are used as carrier waves capable of carrying large amount of information compared with radio waves and microwaves. Subsequently H M Patel, an Indian electrical engineer designed and fabricated a CO_2 laser.

1.2 *Unguided optical communication*

The optical communication systems are different from microwave communication systems in many aspects. In the case of optical systems, the carrier frequency is about 100 THz and the bit rate is about 1T bit/s. Further the spreading of optical beams is always in the forward direction due to the short wavelengths. Even though it is not suitable for broadcasting applications, it may be suitable for free space communications above the earth's atmosphere like intersatellite communications. For the terrestrial applications, unguided optical communications are not suitable because of the scattering within the atmosphere, atmospheric turbulence, fog and rain. The unguided optical communication systems played

Table 1. Bit rate distance product.

System	Bit rate distance product (bit/s) - km
Old optical communication	1
Telegraph	10
Telephone	10^3
Coaxial cables	10^5
Microwaves	10^6
Laser light in open air	10^9

an important role in the research between 1960 and 1970. For longer range unguided optical communication systems the neodymium laser (1.06 μm) and the carbon dioxide laser (10.6 μm) were the most favorable sources. Using narrow bandgap compound semiconductors like indium sulphide (for neodymium laser) and cadmium mercury telluride (for CO_2 laser) one can have better detection using heterodyne detection techniques.

2. The birth of fiber optic systems

To guide light in a waveguide, initially metallic and non-metallic wave guides were fabricated. But they have enormous losses. So they were not suitable for telecommunication. Tyndall discovered that through optical fibers, light could be transmitted by the phenomenon of total internal reflection. During 1950s, the optical fibers with large diameters of about 1 or 2 millimetre were used in endoscopes to see the inner parts of the human body.

Optical fibers can provide a much more reliable and versatile optical channel than the atmosphere, Kao and Hockham published a paper about the optical fiber communication system in 1966. But the fibers produced an enormous loss of 1000 dB/km. But in the atmosphere, there is a loss of few dB/km. Immediately Kao and his fellow workers realized that these high losses were a result of impurities in the fiber material. Using a pure silica fiber these losses were reduced to 20 dB/km in 1970 by Kapron, Keck and Maurer. At this attenuation loss, repeater spacing for optical fiber links become comparable to those of copper cable systems. Thus the optical fiber communication system became an engineering reality.

2.1 *Different types of fibers*

We know that the light or the optical signals are guided through the silica glass fibers by total internal reflection. A typical glass fiber consists of a central core glass ($\approx$50 μm) surrounded by a cladding made of a glass of slightly lower refractive index than the core's refractive index. The overall diameter of the fiber is about 125 to 200 μm. Cladding is necessary to provide proper light guidance i.e. to retain the light energy within the core as well as to provide high mechanical strength and safety to the core from scratches.

Based on the refractive index profile we have two types of fibers (a) Step index fiber (b) Graded index fiber.

(a) *Step index fiber*: In the step index fiber, the refractive index of the core is uniform throughout and undergoes an abrupt or step change at the core cladding boundary. The light rays propagating through the fiber are in the form of meridional rays which will cross the fiber axis during every reflection at the core cladding boundary and are propagating in a zig-zag manner as shown in figure 1a.

(b) *Graded index fiber*: In the graded index fiber, the refractive index of the core is made to vary in the parabolic manner such that the maximum value of refractive index is at the centre of the core. The light rays propagating through it are in the form of skew rays or helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner as shown in figure 1b.

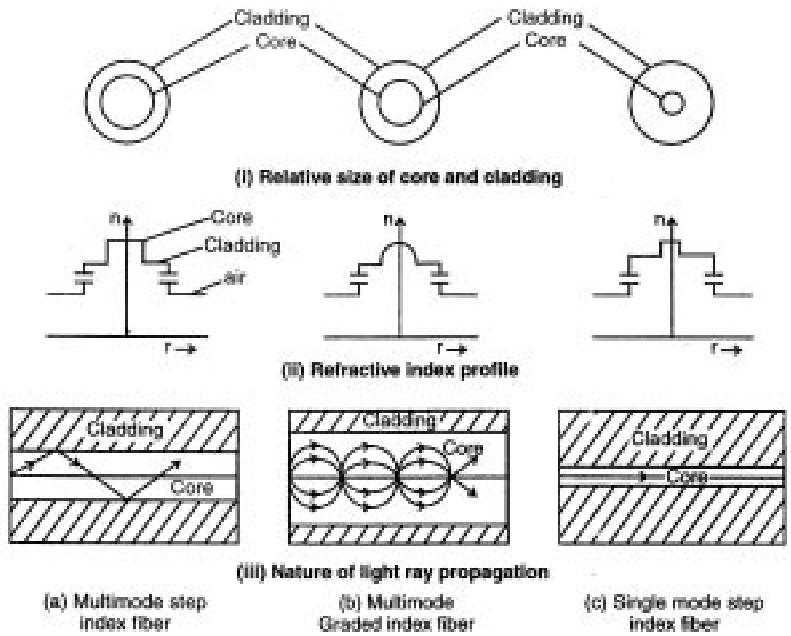

Figure 1. Different types of fibers.

Based on the number of modes propagating through the fiber, there are multimode fibers and single mode fibers. Mode is the mathematical concept of describing the nature of propagation of electromagnetic waves in a waveguide. Mode means the nature of the electromagnetic field pattern (or) configuration along the light path inside the fiber. In metallic wave-guides there are transverse electric (TE) modes for which $E_z = 0$ but $H_z \neq 0$ and transverse magnetic (TM) modes for which $H_z = 0$ but $E_z \neq 0$ when the propagation of microwaves is along the z-axis. In optical fibers, along with TE and TM modes, there are also hybrid modes which have both axial electric and magnetic fields E_z and H_z. The hybrid modes are further classified into EH and HE modes. In EH modes, the axial magnetic field H_z is relatively strong whereas in HE modes, the axial electric field E_z is relatively strong. Based on the linearly polarized nature of light, today these modes are designated as linearly polarized (LP) modes. For example LP_{01} mode corresponds to HE_{11} mode. LP_{11} mode is the combination of HE_{21}, TE_{01} and TM_{01} modes.

(c) *Single mode fibers*: In a single mode fiber, only one mode (LP_{01} mode) can propagate through the fiber (figure 1c). Normally the number of modes propagating through the fiber is proportional to its V-number where

$$\text{V-number} = \frac{2\pi}{\lambda} n_1 a \sqrt{2\Delta}$$

Here a = radius of the core of the fiber; n_1 = refractive index of the core, λ = wavelength of light propagating through the fiber; Δ = relative refractive index difference = $\frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1}$, where n_2 = refractive index of cladding.

In the case of single mode fiber, V-number ≤ 2.405. The single mode fiber has a smaller core diameter (10 μm) and the difference between the refractive indices of the core and the cladding is very small. Fabrication of single mode fibers is very difficult and so the fiber is expensive. Further the launching of light into single mode fibers is also difficult. Generally in the single mode fibers, the transmission loss and dispersion or degradation of the signal are very small. So the single mode fibers are very useful in long distance communication.

(d) *Multimode fibers*: Multimode fibers allow a large number of modes for the light rays traveling through it. Here the V-number is greater than 2.405. Total number of modes 'N' propagating through a given multimode step index fiber is given by [7]

$$N = \frac{V^2}{2} = 4.9\left(\frac{dn_1\sqrt{2\Delta}}{\lambda}\right)^2$$

where d is the diameter of the core of the fiber. For a multimode graded index fiber having parabolic refractive index profile core,

$$N = \frac{V^2}{4}$$

which is half the number supported by a multimode step index fiber.

Generally in multimode fibers, the core diameter and the relative refractive index difference are larger than in the single mode fiber. In the case of multimode graded index fiber, signal distortion is very low because of self-focusing effects. Here the light rays travel at different speeds in different paths of the fiber because of the parabolic variation of refractive index of the core. As a result, light rays near the outer edge travel faster than the light rays near the centre of the core. In effect, light rays are continuously refocused as they travel down the fiber and almost all the rays reach the exit end of the fiber at the same time due to the helical path of the light propagation. Launching of light into the fiber and fabrication of the fiber are easy. These fibers are generally used in local area networks.

2.2 *Basic optical fiber communication system*

Figure 2 shows the basic components in the optical fiber communication system. The input electrical signal modulates the intensity of light from the optical source. The optical carrier can be modulated internally or externally using an electro-optic modulator (or) acousto-optic modulator. Nowadays electro-optic modulators (KDP, $LiNbO_3$ or beta barium borate) are widely used as external modulators which modulate the light by changing its refractive index through the given input electrical signal.

In the digital optical fiber communication system, the input electrical signal is in the form of coded digital pulses from the encoder and these electric pulses modulate the intensity of the light from the laser diode or LED and convert them into optical pulses. In the receiver stage, the photo detector like avalanche photodiode (APD) or positive-intrinsic-negative (PIN) diode converts the optical pulses into electrical pulses. A decoder converts the electrical pulses into the original electric signal.

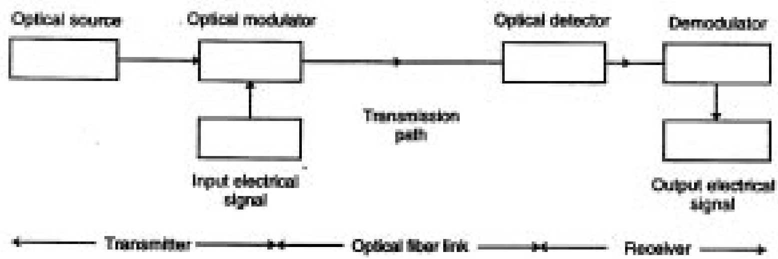

Figure 2. Basic analog optical fiber communication system.

Table 2. Different generations of optical fiber communication systems.

Generation	Wavelength of optical source (μm)	Bit rate (Mb/s)	Repeater spacing (km)	Loss (dB/km)	Existed up to
I	0.8	4.5	10	1	1980
II	1.3	1.7×10^2	50	<1	1987
III	1.55	1.0×10^4	70	<0.2	1990
IV	1.55	1.0×10^5	100	<0.002	2000
V (soliton based)	1.55	$> 1.0 \times 10^9$	>100	<0.002	

2.3 *Different generations of optical fiber communication*

Table 2 shows the different generations of optical fiber communication. In generation I, mostly GaAs based LEDs and laser diodes having emission wavelength 0.8 μm were used. From 1974 to 1978, graded index multimode fibers were used. From 1978 onwards, only single mode fibers are used for long distance communication.

During the second generation the operating wavelength is shifted to 1.3 μm to overcome loss and dispersion. Further InGaAsP hetero-junction laser diodes are used as optical sources. In the third generation the operating wavelength is further shifted to 1.55 μm and the dispersion-shifted fibers are used. Further single mode direct detection is adopted. In the fourth generation erbium doped optical (fiber) amplifiers are fabricated and the whole transmission and reception are performed only in the optical domain. Wavelength Division Multiplexing (WDM) is introduced to increase the bit rate. In the proposed next generation (V generation), soliton based lossless and dispersionless optical fiber communication will become a reality. At that time, the data rate may increase beyond 1000 Tb/s.

2.4 *Advantages of optical fiber communication*

1. *Wider bandwidth*: The information carrying capacity of a transmission system is directly proportional to the carrier frequency of the transmitted signals. The optical carrier frequency is in the range 10^{13} to 10^{15} Hz while the radio wave frequency is about 10^6 Hz and

the microwave frequency is about 10^{10} Hz. Thus the optical fiber yields greater transmission bandwidth than the conventional communication systems and the data rate or number of bits per second is increased to a greater extent in the optical fiber communication system. Further the wavelength division multiplexing operation by the data rate or information carrying capacity of optical fibers is enhanced to many orders of magnitude.

2. *Low transmission loss*: Due to the usage of the ultra low loss fibers and the erbium doped silica fibers as optical amplifiers, one can achieve almost lossless transmission. In the modern optical fiber telecommunication systems, the fibers having a transmission loss of 0.002 dB/km are used. Further, using erbium doped silica fibers over a short length in the transmission path at selective points, appropriate optical amplification can be achieved. Thus the repeater spacing is more than 100 km. Since the amplification is done in the optical domain itself, the distortion produced during the strengthening of the signal is almost negligible.

3. *Dielectric waveguide*: Optical fibers are made from silica which is an electrical insulator. Therefore they do not pickup any electromagnetic wave or any high current lightning. It is also suitable in explosive environments. Further the optical fibers are not affected by any interference originating from power cables, railway power lines and radio waves. There is no cross talk between the fibers even though there are so many fibers in a cable because of the absence of optical interference between the fibers.

4. *Signal security*: The transmitted signal through the fibers does not radiate. Further the signal cannot be tapped from a fiber in an easy manner. Therefore optical fiber communication provides hundred per cent signal security.

5. *Small size and weight*: Fiber optic cables are developed with small radii, and they are flexible, compact and lightweight. The fiber cables can be bent or twisted without damage. Further, the optical fiber cables are superior to the copper cables in terms of storage, handling, installation and transportation, maintaining comparable strength and durability.

2.5 *Dispersion and losses in fibers*

Dispersion in the fiber means the broadening of the signal pulse width due to dependence of the refractive index of the material of the fiber on the wavelength of the carrier. If we send digitized signal pulses in the form of square pulses, they are converted into broadened gaussian pulses due to dispersion. The dispersion leads to the distortian (or) degradation of the signal quality at the output end due to overlapping of the pulses. There are two kinds of dispersion mechanisms in the fiber: (i) Intramodal dispersion and (ii) Intermodal dispersion.

The dispersion effects can be explained on the basis of behavior of group velocities of the guided modes in the optical fiber. Group velocity is the velocity at which the energy in a particular mode travels along the fiber.

The propagation constant $\beta = n_1 \frac{2\pi}{\lambda} = \frac{n_1 \omega}{C}$, therefore

$$\text{Group velocity } v_g = \frac{\mathrm{d}\omega}{\mathrm{d}\beta} = \frac{\mathrm{d}\lambda}{\mathrm{d}\beta}\frac{\mathrm{d}\omega}{\mathrm{d}\lambda}.$$

Since $\beta = n_1 \frac{2\pi}{\lambda}$,

$$\frac{\mathrm{d}\beta}{\mathrm{d}\lambda} = \frac{2\pi}{\lambda} \cdot \frac{\mathrm{d}n_1}{\mathrm{d}\lambda} - n_1 \frac{2\pi}{\lambda^2}$$

Using $\omega = \frac{2\pi C}{\lambda}$,

$$\frac{\mathrm{d}\omega}{\mathrm{d}\lambda} = -\frac{2\pi C}{\lambda^2}.$$

Therefore

$$v_g = \frac{\mathrm{d}\lambda}{\mathrm{d}\beta} \cdot \frac{\mathrm{d}\omega}{\mathrm{d}\lambda} = -\frac{\frac{2\pi C}{\lambda^2}}{\left(\frac{2\pi}{\lambda}\frac{\mathrm{d}n_1}{\mathrm{d}\lambda} - n_1 \frac{2\pi}{\lambda^2}\right)} = \frac{C}{\left(n_1 - \lambda \frac{\mathrm{d}n_1}{\mathrm{d}\lambda}\right)} = \frac{C}{N_g}$$

where $N_g = n_1 - \lambda \frac{\mathrm{d}n_1}{\mathrm{d}\lambda}$ is called the group index of the fiber. Thus the group velocity and phase velocity $(v_p = (C/n_1))$ are different in the optical fiber. Otherwise an optical fiber is a dispersive medium.

Intramodal dispersion arises due to the dependence of group velocity on the wavelength. Further it increases with the increase in spectral width of the optical source. This spectral width is the range of wavelengths emitted by the optical source. For example in the case of LED, it has a large spectral width about 40 nm since it emits wavelengths from 830–870 nm with the peak emission wavelength at 850 nm. In the case of laser diode which has a very narrow spectral width, the spectral width is about 1 or 2 nm only. Thus the intramodal dispersion can be reduced in an optical fiber using single mode laser diode as an optical source. Intramodal dispersion arises due to the dispersive properties of the optical fiber material (material dispersion) and the guidance effects of the optical fiber (waveguide dispersion).

(a) *Material dispersion* (*or*) *chromatic dispersion*: This dispersion arises due to the variation of the refractive index of the core material with the wavelength or frequency of light. It is directly proportional to the frequency bandwidth of the transmitted pulse. A material exhibits material dispersion when $\mathrm{d}^2 n_1/\mathrm{d}\,\lambda^2 \neq 0$. For pure silica, the material dispersion tends to zero at the wavelength of 1.3 μm. Further by using an optical source with a narrow spectral width, the material dispersion can be reduced. For shorter wavelengths around 0.6 μm to 0.8 μm, the material dispersion exponentially rises to a higher value.

(b) *Waveguide dispersion*: This dispersion arises due to the finite frequency bandwidth and the dependence of the mode group velocity on the frequency of light. Higher the frequency bandwidth of the transmitted pulse, higher will be the waveguide dispersion. The amount of waveguide dispersion depends on the fiber design like core radius, since the propagation constant 'β' is a function of a/λ. In the case of single mode fibers, waveguide dispersion arises when $\mathrm{d}^2\beta/\mathrm{d}\lambda^2 \neq 0$. In the case of multimode fibers, most of the modes propagate far from the cutoff value. Therefore then all are almost free from waveguide dispersion.

(c) *Intermodal dispersion* (*or*) *multimode dispersion*: Intermodal dispersion or multimode dispersion arises due to the variation of group velocity for each mode at a single frequency. Different modes arrive at the exit end of the fiber at different times. So there is multimode dispersion and hence there is broadening of the signal pulses.

Dispersion in different fibers:

Among the three dispersions,
multimode dispersion > material dispersion > waveguide dispersion.

Based on the dispersion effects, one can get the following results:

(i) The multimode step index fibers exhibit a large value of dispersion due to the enormous amount of multimode dispersion which gives the greatest pulse broadening. At the same time the multimode graded index fiber exhibits an overall dispersion which is 100 times lesser than the multimode step index fiber's dispersion. This is due to the shaping of the refractive index profile in a parabolic manner.

(ii) In the case of single mode step index fibers, they have only intramodal dispersion. Further among the intramodal dispersions, the waveguide dispersion is the dominant one. The material dispersion in them is almost negligible due to axial ray propagation and small core radius. When we compare it with the dispersion in the multimode graded index fiber, the dispersion in the single mode fiber is negligible. That is why single mode fibers are highly useful in long distance communication systems.

2.6 *Dispersion-shifted single mode fibers*

Generally in single mode fibers, zero dispersion is obtained at a wavelength of about 1.3 μm. Since there is a finite loss in the silica fiber at 1.3 μm, today the fibers are designed such that there is zero dispersion at 1.55 μm with a minimum loss. At 1.55 μm, the material dispersion in single mode fiber is positive and large, while the waveguide dispersion is negative and small. So to increase the waveguide dispersion equal to that of material dispersion, the relative refractive index difference 'Δ' may be slightly increased by adding more Ge O_2 in the core (which increases the refractive index of the core) or adding more fluorine in the cladding (which decreases the refractive index of the cladding) or instead of parabolic refractive index profile, a triangular refractive index profile can be designed. Thus the dispersion-shifted fibers have minimum loss and zero dispersion at 1.55 μm.

2.7 *Dispersion compensating fibers*

At present the installed fiber optic links are operating at the wavelength of 1.3 μm using conventional single mode fibers. Instead of 1.3 μm wavelength if one wants to use 1.55 μm wavelength to reduce the transmission loss, then the whole fiber optic link should be replaced with the new dispersion-shifted fibers. This will require an enormous expenditure. The avoid this huge expenditure and to use the old fiber optic links dispersion compensating fibers were evolved. These fibers have a large negative dispersion at 1.55 μm, while the conventional single mode fibers operating at 1.3 μm have positive dispersion at 1.55 μm.

By suitably replacing 1 km length of conventional single mode fiber in the fiber optic link with the dispersion compensating fiber for every 100 km length of conventional single mode fiber optic link, one can achieve minimum loss and zero dispersion also.

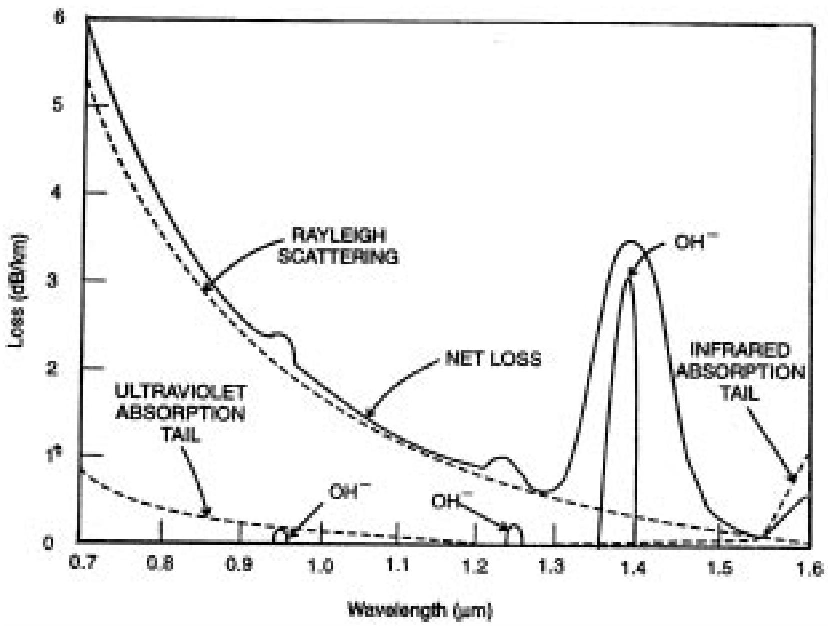

Figure 3. Different intrinsic losses in a pure silica fiber.

2.8 *Transmission losses in fibers*

The transmission loss or attenuation of the signal in an optical fiber is a very important quantity to consider in optical fiber communication. The attenuation of the signal transmitting through the fiber results from absorption and scattering and is measured in decibel/km and is a function of wavelength as shown in figure 3. The optical communication wavelengths are 0.8, 1.3 and 1.55 μm.

Attenuation can be classified into two types:
(i) Intrinsic losses and (ii) Extrinsic losses.

Mechanisms generating intrinsic losses

1. Tail of infrared absorption by Si-O coupling—it is present at higher wavelengths around 1.4 μm to 1.6 μm.
2. Tail of ultraviolet absorption due to electron transition—it is present at lower wavelengths near 0.8 μm. This will produce a loss of 0.3 dB/km.
3. Rayleigh scattering due to spatial fluctuation of refractive index and is inversely proportional to λ^4—it produces a maximum loss in the ultraviolet region only. In the wavelength region around 0.8 μm to1 μm, it gives a loss of 0.6 dB/km.
4. Absorption by molecular vibration of OH impurity—fundamental absorption due to hydroxyl (OH) ions is present at $\lambda = 2.8$ μm. But its harmonics occur at wavelengths 1.38 μm and 0.95 μm respectively. This kind of absorption is almost eliminated

by the modified chemical vapor deposition process adopted for the fiber preform production reducing the water content in the fiber to below 10 parts per billion.

5. Absorption by transition metal impurities like Cr, V, Fe, Mn and Ni—this absorption produces a loss at wavelengths greater than 0.8 μm. In ultra low loss fibers, this absorption is practically negligible.
6. Thus it is found that in the case of pure silica fibers the transmission losses are reduced to a minimum value at 1.55 μm wavelength. At 1.3 μm also, the transmission losses are minimum but the net attenuation is slightly greater with respect to the wavelength 1.55 μm.

Mechanisms generating extrinsic losses:

1. Geometrical non-uniformity at the core-cladding boundary.
2. Imperfect connection or alignment between fibers.
3. Microbending.
4. Radiation of leaky modes.

Extrinsic losses are very small when compared to intrinsic losses and can be minimized by proper care during the manufacturing and installation of the fibers.

3. Different components used in the optic fiber communication systems

3.1 *Optical sources*

Heterojunction LEDs and lasers are mostly used as the optical sources in optical fiber communication. Heterojunction means that a *p-n* junction is formed by a single crystal such that the material on one side of the junction differs from that on the other side of the junction. In the modern GaAs diode lasers, a hetero junction is formed between GaAs and GaAlAs. This type of *p-n* junction diode laser or LED is used at 0.8 μm wavelength. At longer wavelengths, InP-InGaAsP heterojunction laser diodes are used.

Heterojunction lasers or LEDs are superior to conventional homojunction lasers or LEDs. Generally heterojunction lasers and LEDs have minimum threshold current density (10 A/mm^2), high output power (10 mW) even with low operating current ($<$500 mA), high coherence and high monochromaticity, high stability and longer life.

For example in the case of a double hetero structure stripe laser, the active junction region is few microns. So the threshold current density is drastically reduced. The stripe geometry provides stability with longer lifetime for the diode. Thus it gives high power output, continuous wave operation, high efficiency, high coherence and high directionality. By means of the heterojunction formed by two different materials, both the carriers and the optical field are confined in the central active layer. The bandgap differences of adjacent layers confine the charge carriers while the step change in the indices of refraction of adjoining layers confines the optical field to the central active layer and provides an efficient waveguide structure. This dual confinement leads to both high efficiency and high power output.

3.2 *Optical detectors*

Semiconductor based photodiodes are used as optical detectors in the optical fiber communication systems. They have small size, high sensitivity and fast response. There are two types of photodiodes:

(i) p-i-n photodiodes and (ii) Avalanche photodiodes (APD)

(i) *p-i-n photodiodes*: A positive-intrinsic-negative (p-i-n) photodiode consists of p and n regions separated by a very lightly n doped intrinsic region. Silicon p-i-n photodiodes are used at 0.8 μm wavelength and InGaAs p-i-n photodiodes are used at 1.3 μm and 1.55 μm wavelengths. In normal operation, the p-i-n photodiode is under high reverse bias voltage. So the intrinsic region of the diode is fully depleted of carriers. When an incident photon has energy greater than or equal to the bandgap energy of the photodiode material, the electron-hole pair is created due to the absorption of photon. Such photon-generated carriers in the depleted intrinsic region where most of the incident light photons are absorbed, are separated by the high electric field present in the depletion region and collected across the reverse biased junction. This gives rise to a photocurrent flow in the external circuit. The p-i-n photodiode acts as a linear device such that

$$I = RP$$

where $I =$ photo current; $P =$ incident optical power; $R =$ responsivity of the photodiode $= \frac{\eta q}{h\nu}$.

Here $\eta =$ quantum efficiency of the diode; $h\nu =$ energy of the incident photon; $q =$ charge of electron.

The responsivity of the photodiode depends on the bandgap of the material, operating wavelength, the doping and the thickness of the p, i and n regions of the diode. For example to get high quantum efficiency and hence the maximum sensitivity, the thickness of the depletion layer should be increased so that the absorption of photons will be maximum. But it reduces the response speed of the photodiode. In the wavelength 1.33 μm and 1.55 μm, InGaAs p-i-n photodiodes have high quantum efficiency and high responsivity.

(ii) *Avalanche photodiodes* (*APDs*): It consists of four regions $p^+ - i - p - n^+$ in order to develop a very high electric field in the intrinsic region as well as to impart more energy to photoelectrons to produce new electron-hole pairs by impact ionization. This impact ionization leads to avalanche breakdown in the reverse biased diode. So the APDs have high sensitivity and high responsivity over p-i-n diodes due to the avalanche multiplication. The responsivity of APD is given by

$$R = \frac{\eta q}{h\nu} M$$

where M is called avalanche multiplication which is greater than 50. APDs are made from silicon or germanium having operating wavelength 0.8 μm and from InGaAs having operating wavelength 1.55 μm.

3.3 *Optical amplifiers*

In the long distance optical fiber communication systems, the repeaters are situated at an equal distance of 100 km. These are used to receive and amplify the transmitted signal to its original intensity and then it is passed on to the main fiber. Previously it was done by conversion of optical energy into electrical energy and amplification by electrical amplifiers and then reconversion of electrical energy into optical energy. Such methods not only increase the cost and complexity of the optical communication system but also reduce the operational bandwidth of the system. But today it is done by erbium doped optical fiber amplifiers in an elegant manner by inserting a length of 10 m fiber amplifier for every 100 km length of main fiber. By this, the signal to noise ratio is greatly improved due to optical domain operation only [8,9].

Further there is a large reduction in the cost of laying and maintaining the optical amplifier, due to its simple design which is in the form of fiber coupler, and easy fabrication. It is found that optical amplifiers can simultaneously amplify multiple wavelength division multiplexed optical signals.

Initially optical amplifiers were designed utilizing stimulated Raman scattering and Brillouin scattering. By injecting a high power laser beam as a pumping radiation into an undoped relatively long length fiber ($\approx$ 10 km) or a doped short length fiber ($\approx$ 10 m), the laser action is achieved through the nonlinear effects produced within the fiber and can provide optical amplification. Generally Raman gain is very small. It is found that higher Raman gain is achieved in large length fibers, ultra low loss fibers and small diameter fibers. For high-speed communications, the narrow gain-bandwidth of Raman amplifiers or Brillouin amplifiers are not suitable. Further there is no possibility to increase the bandwidth or gain in these amplifiers.

Meanwhile Mollenauer designed an erbium doped silica fiber laser amplifier. It has high gain even in a short length fiber. In erbium doped silica fiber, the erbium ions concentration is about 10^{25} ions/m^3. For an optical signal amplification at wavelength of 1.55 μm, InGaAsP laser diode operating at a wavelength of 1.48 μm is used as a pumping source. The erbium ions in the ground level 'E_1' absorb this radiation and get excited to the broadened upper level E_2. The energy level E_2 is broadened into a band due to the electric field of adjacent ions (i.e. energy level splitting by Stark effect) and due to the amorphous nature of silica glass.

In erbium doped silica fiber, only the transition between E_2 and E_1 is 100% radiative and all other transitions are non-radiative. Due to the rapid thermalization of E_r^{3+} ions in the energy band E_2, even though the absorption wavelength is at 1.48 μm, the emission wavelength is at 1.55 μm from the bottom of the energy band E_2. For low pump powers even though the erbium ions are excited to the E_2 level, population inversion is not there due to predominant spontaneous emission. In such a case the optical signal at 1.55 μm will get attenuation. As the pump power increases, the rate of excitation increases. Hence at some threshold pump power level, population inversion may exist. Stimulation of the erbium ions in the energy level E_2 by the incoming signal photons gives laser action such that the emitted photon and stimulating photon are having the same energy and same phase.

Thus the signal is amplified. When the signal travels down the optical fiber amplifier, the pump power can be gradually decreased since the signal is amplified and reabsorbed. Thus there is an optimum length for the fiber amplifier to get maximum gain. When the initial pump power is 5 mW, the optimum length of the fiber amplifier is about 7m.

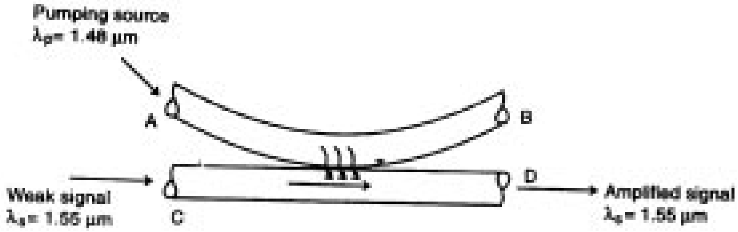

Figure 4. Optical fiber laser amplifier.

Figure 4 shows the optical fiber laser amplifier which is in the form of a T coupler. There are two short fibers whose middle portions are welded together. In this manner the pumping source radiation from 'A' can interact with the weak signal from 'C' through core interaction. The path 'B' is closed. Through 'D' one can get the amplified signal at 1.55 μm.

3.4 *Fiber couplers*

A coupler is a device which distributes light from a main fiber into one or more branch fibers.

There are core interaction type couplers and surface interaction type couplers. In core interaction type couplers, the light energy transfer takes place through the core cross-section by butt jointing the fibers or by using some form of imaging optics between the fibers (i.e. using lensing schemes such as rounded end fiber, a spherical lens used to image the core of one fiber on to the core area of the other fiber and a taper-ended fiber). In the surface interaction type the light energy transfer takes place through the fiber surface and normal to the axis of the fiber by converting the guided core modes to cladding and refracted modes.

Different types of fibers couplers and their functions

(i) *Three and four port couplers*: Figures 5a and 5b show the uses of a three port coupler as splitter and combiner of the signals. Light from the input fiber is coupled to the output fibers as shown in figure 5a or the light from the branch fibers are combined to form a single input to the output fiber. For splitting, a single input fiber core is situated between the cores of two output fibers. This is called the lateral offset method. In this method, the input power can be distributed in a well defined proportion by appropriate control of the amount of lateral offset between the fibers.

Figure 6 shows the directional coupler which is a four port coupler. In this coupler, the fibers are generally twisted together and then spot fused under tension such that the fused section is elongated to form a biconical taper structure. It can act as a three port coupler (or) T coupler if one of the input ends (or) one of the output ends is closed. As shown in figure, each port is meant for different functions.

Figure 5. (**a**) Three port coupler as a splitter. (**b**) Three port coupler as a combiner.

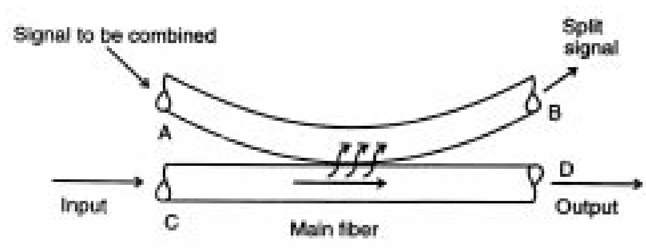

Figure 6. Four port coupler.

Inputs

C - to pass the main signal into the main fiber.
A - to combine the extra signal or data into the main fiber.

Outputs

D - to transmit the combined signal (or) remaining portion of the main signal through the main fiber.
B - to collect the split signal.

This type of coupler is based on the transfer of energy by surface interaction between the fibers. The amount of power taken from the main fiber or given to the main fiber depends on the length of the fused section of the fiber and the distance between the cores of the fused fibers.

This can also act as a wavelength division multiplexer provided that one of the output ends is closed. When D is closed and the signal at λ_1 and the signal at λ_2 are passed through A and C of the coupler respectively, the multiplexed signal $\lambda_1 + \lambda_2$ will come out through B of the coupler. Similarly if the multiplexed signal having wavelength $\lambda_1 + \lambda_2$ is passed through B, then the signal with λ_1 appears at A and the signal with λ_2 appears at C. Thus the demultiplexing action can also be achieved. This can also act as a fiber laser amplifier.

(ii) *A star couplers or multi port coupler*: A star coupler is used to distribute an optical signal from a single input fiber to multiple output fibers. Here many fibers are bundled, twisted, heated and pulled at the twisted area to get fiber fused biconical taper star coupler.

3.5 *Fiber connectors*

Before connecting one fiber with the other fiber in the fiber optic communication link, one must decide whether the joint should be permanent or demountable. Based on this, we have two types of joints. A permanent joint is done by *splice* and a demountable joint is done by *connector*.

Requirements of a good connector

1. At connector joint, it should offer low coupling losses.
2. Connectors of the same type must be compatible from one manufacturer to another.
3. In the fiber link, the connector design should be simple so that it can be easily installed.
4. Connector joint should not be affected by temperature, dust and moisture. That is, it should have low environmental sensitivity.
5. It should be available at a lower cost and have a precision suitable to the application.

The coupling of light energy from one fiber to the other fiber using the connectors is based on either butt-joint alignment mechanism or expanded beam mechanism.

Figure 7 shows the butt-joint alignment type connectors used in both multimode and single mode fiber systems. These are straight sleeve (figure 7a) and the tapered sleeve (or) biconical sleeve connectors (figure 7b). In the straight sleeve connector, there is a metal, ceramic or molded plastic ferrule for each fiber and the ferrule fits into the sleeve. The fiber is epoxied into the drilled hole of the ferrule. In the straight sleeve connector (or) tapered sleeve connector the length of the sleeve and a guide ring on the ferrules determine the end separation of the fibers. In the tapered sleeve connector, the ferrules and sleeves are tapered.

Figure 8 shows the expanded beam connector employing collimating lens at the end of the transmitting fiber and focusing lens at the entrance end of the receiving fiber. The collimating lens converts the light from the fiber into a parallel beam of light and the focusing lens converts the parallel beam of light into a focused beam of light on to the core of the receiving fiber. The fiber-to-lens distance is equal to the focal length of the lens. This expanded beam connector does not depend on lateral alignments and the optical processing elements can be easily inserted into the expanded beam between the fiber ends. The lenses are antireflection coated spherical micro lenses. To avoid losses due to fresnel reflection at the fiber-fiber joint, it is better to use an index matching fluid in the gap between the jointed fibers. When the index matching fluid has the same refractive index as the fiber core, Fresnel reflection losses are completely eliminated. But if there is any angular misalignment between fibers, there is an increased loss for the fibers with index matching fluid than for the fibers with air gap.

4. Multiplexers

The transmission of multiple optical signals (channels) over the same fiber is a simple way to increase the transmission capacity of the fiber against the fiber dispersion, fiber

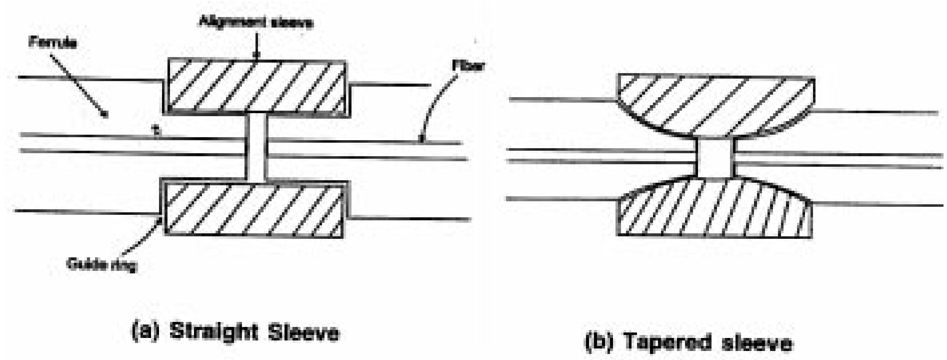

Figure 7. Connectors using butt-joint alignment designs.

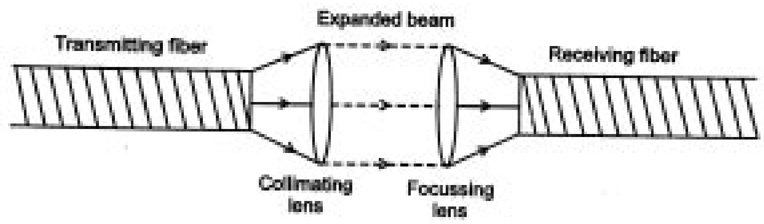

Figure 8. Expanded beam connector.

nonlinearity and speed of electronic components which limit the bit rate. So multiplexing techniques are followed. *Multiplexing* means many signals at a given time [7].

Suppose for each channel the bit rate is 100 Gb/s and by accommodating 100 channels through multiplexing technique the total bit rate through a single fiber can be increased to 10 Tb/s (1 Tera $= 10^{12}$): *Thus the information carrying capacity of a fiber is increased by the multiplexing technique*. There are three types of multiplexing techniques:

(i) TDM – time division multiplexing
(ii) FDM – frequency division multiplexing
(iii) WDM – wavelength division multiplexing

TDM and FDM techniques are operated in the electrical domain and are widely used in the conventional radio wave communication. WDM technique is very useful in the optical domain and by WDM, the bit rate can be increased beyond 10 Tb/s in the optical fiber communication.

Figure 9 shows the basic principle of WDM technique. Here different wavelengths carrying separate signals are multiplexed by the multiplexer and then they are transmitted through a single fiber. At the receiver end, the separate signals at different wavelengths are demultiplexed by the demultiplexer and are given to separate receivers. From the receiver side also the signals can be transmitted in the same manner through the same fiber. Thus

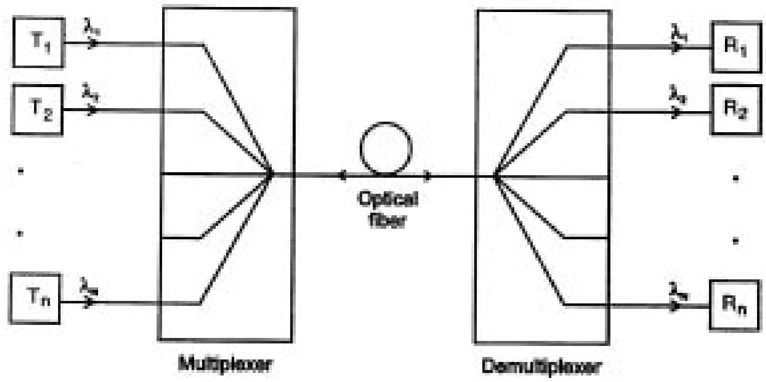

Figure 9. Multichannel point-to-point fiber link. T - transmitter; R - receiver.

instead of handling a single channel with single wavelength and limited bit rate (10 Gb/s), the bit rate is raised to about 10 Tb/s, hence the information capacity of the fiber is increased by WDM technique.

In principle any optical wavelength demultiplexer can be also used as a multiplexer. Thus for simplicity the word ‘multiplexer’ is often used as a general term to refer to both multiplexers and demultiplexers, except when it is necessary to distinguish the two devices or functions.

There are two types of wavelength division multiplexers:

1. Angularly dispensive devices such as prisms or gratings.
2. Interference filter based devices such as multilayer thin film interference filters or single mode integrated optical devices.

(i) *Grating as a multiplexer*: A plane diffraction grating can be taken as a wavelength division multiplexer.

Taking θ as the angle of diffracted beam, the dispersive power of the grating is given by

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} = 2\frac{\tan\theta}{\lambda}$$

The combination of different wavelengths (multiplexing) or separation of different wavelengths (demultiplexing) is directly proportional to the dispersive power of grating i.e. directly proportional to tan θ and inversely proportional to λ.

The different signals carried by different wavelengths $\lambda_1, \lambda_2, \lambda_3, \ldots$ are collimated by a convex lens and then are incident on a reflection grating. The reflected light is a composite light or multiplexed light. The same grating multiplexer can also act as demultiplexer if we change the direction of the light beam.

(ii) *Interference filter as a multiplexer*: There are reflection interference filter type and absorption interference filter type multiplexers. Among these, absorption filter type is not used widely due to their higher absorption of signals. In the reflection type filter, there is a flat glass substrate upon which multiple layers of different dielectric films are deposited for wavelength sensitivity. These filters can be used in series to separate additional wavelength channels.

5. Soliton based optical fiber communication

Solitons are very narrow laser pulses of pulse width 10^{-14} second with high peak powers more than 100 mW. Solitons are mainly used to increase the bit rate or transmission capacity of the fiber by reducing the losses and dispersion effects. Soliton propagation means the propagation of laser pulses through the optical fiber without undergoing any loss or dispersion. That is the pulses are transmitted without change in their shape as they travel down the fiber [2,4,10].

Today soliton fiber lasers are available. Soliton type propagation is achieved by the nonlinear property of the silica fiber when the intensity of the light pulses is more than 15 mW. In the case of single mode silica fiber, when the power level of optical pulses is more than 15 mW, then its refractive index is dependent on intensity such that

$$n = n_0 + n_2 I.$$

If the effective area of the fiber mode is about 50 μm^2 and the power of the optical pulse is about 100 milliwatt, then $n_2 = -6.4 \times 10^{11}$ for silica fiber. So inside the optical fiber, the high intensity portion of the pulse will propagate in a high refractive region of the fiber compared with the lower intensity portion of the pulse. This intensity dependent refractive index leads to a phenomenon called self phase modulation (SPM). Due to this phenomenon the distance traveled by the optical pulse inside the fiber is continuously increased due to lower speed of the high intensity portion of the pulse. Thus there is a generation of additional frequencies and hence the broadening of the spectrum of the pulse while keeping the temporal shape unaltered. Further SPM leads to a chirping of the pulse with lower frequencies in the leading edge and high frequencies in the trailing edge of the pulse. So one can conclude that even though the distance traveled by the high intensity optical pulse is greater than the distance traveled by the low intensity optical pulse inside the fiber having negative nonlinearity, the optical pulse travels down the fiber without any dispersion.

When the operating wavelength is about 1.3 μm there is zero dispersion. But when the operating wavelength is greater than 1.3 μm, then the fiber has positive group velocity dispersion. So the low frequency components of the pulse will travel at a lower speed than the high frequency components of the pulse. But in the case of self phase modulation, we get the opposite effect. That is due to SPM the low frequency components of the pulse will travel faster than the high frequency components. Thus the broadening of the spectrum by SPM is properly compensated by the compressions of the spectrum by group velocity spectrum, then the pulse will propagate without change in the temperate shape and without broadening of the spectrum of the pulse. Even though there is no dispersion effect, still there is some loss in the fiber due to scattering and absorptions. To compensate this small loss in the transmissions link, for every 100 km or 150 km length, an optical fiber laser amplifier of length 10 m is connected. Due to sufficient amplification at the receiver end one can get the signal without loss of power. Thus during the propagation of the optical pulse through the fiber, there is no change in pulse shape and height and width. Such a propagation is called *soliton propagation*.

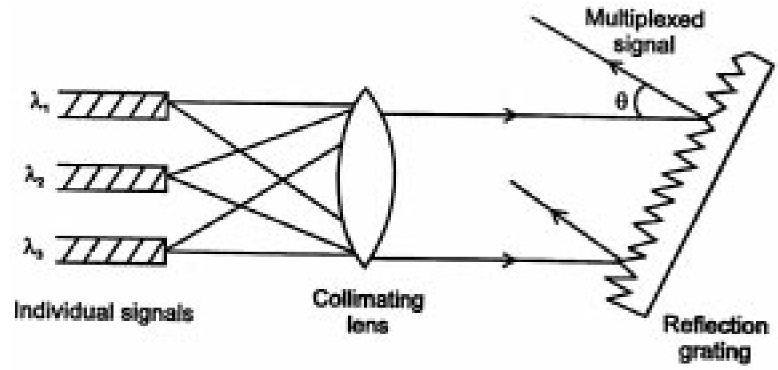

Figure 10. Grating multiplexer.

5.1 *Soliton laser*

Soliton laser is an optical source used to deliver soliton pulses. Since this laser is in the form of number 8, it is also called figure 8 laser (figure 11). It consists of an output fiber loop and nonlinear fiber loop amplifier which are connected by a 50 : 50 coupler. The wavelength division multiplexer which is a T-coupler passes the light from the optical pumping source at a wavelength of 0.98 μm into the nonlinear fiber loop amplifier which is a mode locked single mode fiber laser. The fiber laser is doped with erbium impurity and acts as an optical amplifier. The 50 : 50 coupler is a directional coupler as well as a four-port coupler. This connects the signal at 1.535 μm from the output fiber loop to the nonlinear fiber loop amplifier as well as the amplified signal from the non linear fiber loop amplifier to the output fiber loop. Through the 20 : 80 coupler, the output soliton pulses of 1.535 μm can be obtained. The purpose of the optical isolator in the output fiber loop is to propagate the light in one direction in the output fiber loop. Polarization controllers in both fiber loops are used to maintain the same phase shifts during the propagation of light through the loops. The phase shift between the signal coupled into the non linear fiber loop amplifier and the amplified light in that loop is always an integral multiple of 0 or 2π.

Actually, there are many modes with different frequencies, generated in the erbium doped fiber by the spontaneous emission. But whenever the generated frequency is different from the signal frequency then the time taken by that light (noise) to go around the loop once is different from $\frac{2\pi rn}{C}$ where r is the radius of the loop, n is the refractive index of core of the fiber loop and C is the velocity of light in air or vacuum. Hence its amplitude gradually decreases due to destructive overlap. After few circulations, these noises are completely suppressed. For the signal, the time taken to go around the loop once is exactly $\frac{2\pi rn}{C}$ so that its amplitude gradually increases due to constructive overlap. After few circulations, the amplitude of the signal is increased to a greater extent so that the output light has high power, more than 100 milliwatt, and high coherence.

Further, there is self phase modulation in the nonlinear fiber loop so that the output pulses from the soliton laser cannot undergo any dispersion. Thus the pulses coming out from the soliton laser are behaving as solitary waves having no dispersion and no loss during their transmission through optical fibers.

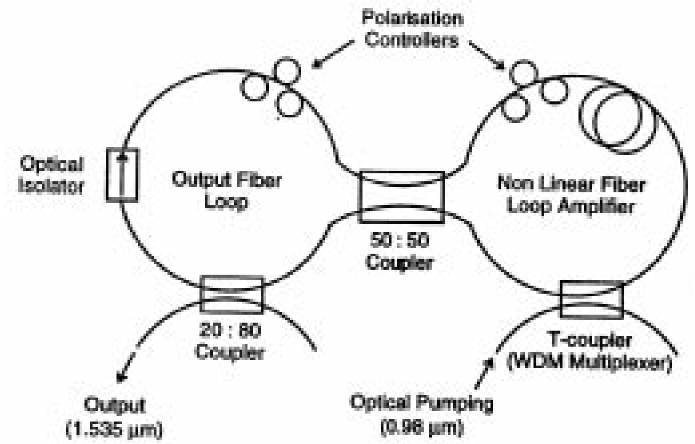

Figure 11. Figure – 8 laser.

6. Conclusion

At present there are many optical fiber communication links throughout the world without using optical solitons. When we introduce optical solitons as light pulses through the fibers, we can achieve high quality telecommunication at a lower cost. We can expect a great revolution in optical fiber communication within a few years by means of solitons.

References

[1] T Okoshi and K Kikuchi, *Coherent optical fiber communication* (Kluwer Academic, Boston, 1988)
[2] A Hasegawa, *Optical solitons in fibers* (Springer Verlag, New York, 1989)
[3] S E Millar and I P Kaminow, eds, *Optical fiber telecommunications - II* (Academic, New York, 1988)
[4] G P Agrawal, *Nonlinear fiber optics* (Academic, New York, 1989)
[5] C Yeh, *Handbook of fiber optics* (Academic, New York, 1990)
[6] G P Agrawal, *Fiber optic communication systems* (John Wiley, Singapore, 1993)
[7] N S Bergano and C R Davidson, Wavelength division multiplexing in long-haul transmission systems, *J. Lightwave Tech.* **14**, 1299 (1996)
[8] E Desurvire, *Erbium doped fiber amplifiers* (John Wiley, New York, 1994)
[9] R J Hoss and E A Lacy, *Fiber optics 2nd edition* (Prentice Hall, New Jersey, 1993)
[10] M Nakazawa, Soliton transmission in telecommunication networks, *IEEE. Communication magazine*, March 24 (1994)