1.a) State and explain the Fabry Perot resonator cavity of the laser.

Ans .

Light amplification in the laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more. Continuation of this process effectively creates avalanche multiplication, and when the electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained. To achieve this laser action it is necessary to contain photons within the laser medium and maintain the conditions for coherence.

This is accomplished by placing or forming mirrors (plane or curved) at either end of the amplifying medium.

The optical cavity formed is more analogous to an oscillator than an amplifier as it provides positive feedback of the photons by reflection at the mirrors at either end of the cavity.

Hence the optical signal is fed back many times while receiving amplification as it passes through the medium. The structure therefore acts as a Fabry– Pérot resonator. Optical Spacing between the mirror-

$$L = \frac{\lambda q}{2n}$$

where λ is the emission wavelength, n is the refractive index of the amplifying medium and q is an integer. Alternatively, discrete emission frequencies f are defined by:

$$f = \frac{qc}{2nL}$$

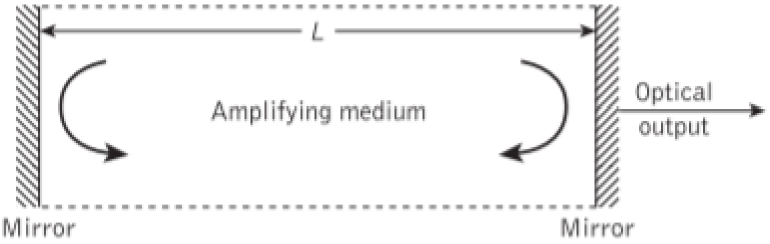


Fig- Fabry Perot Resonator

1. b) The quantum efficiency for an APD is 90%. Find the responsivity at 1600nm.

   Sol. Responsivity= $\frac{n_q}{h_v}$ = (0.9x1.6x10^{-19} x1600x10^{-9})/(6.626x10^{-34} x 3x10^{8})

   = 1.16

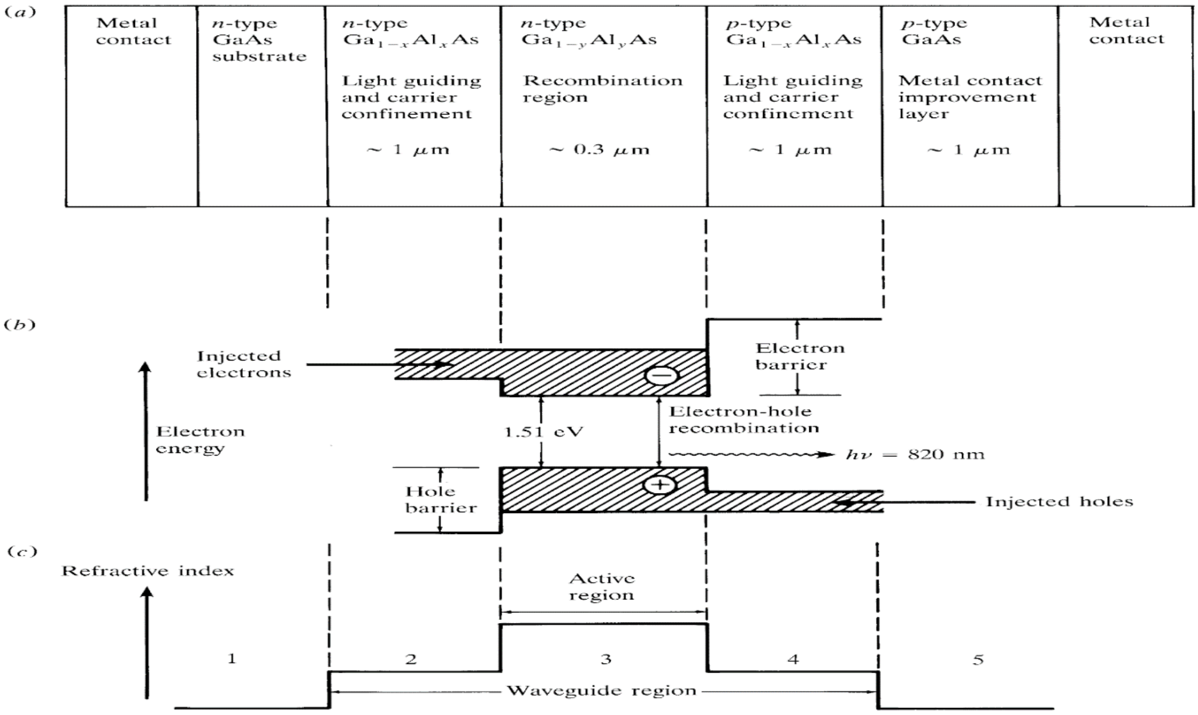
2. a) With neat sketches, explain the characteristics and function of the double hetero structure device

Ans.

Double Heterojunction Device

When two semiconductor materials are grown into sandwich.

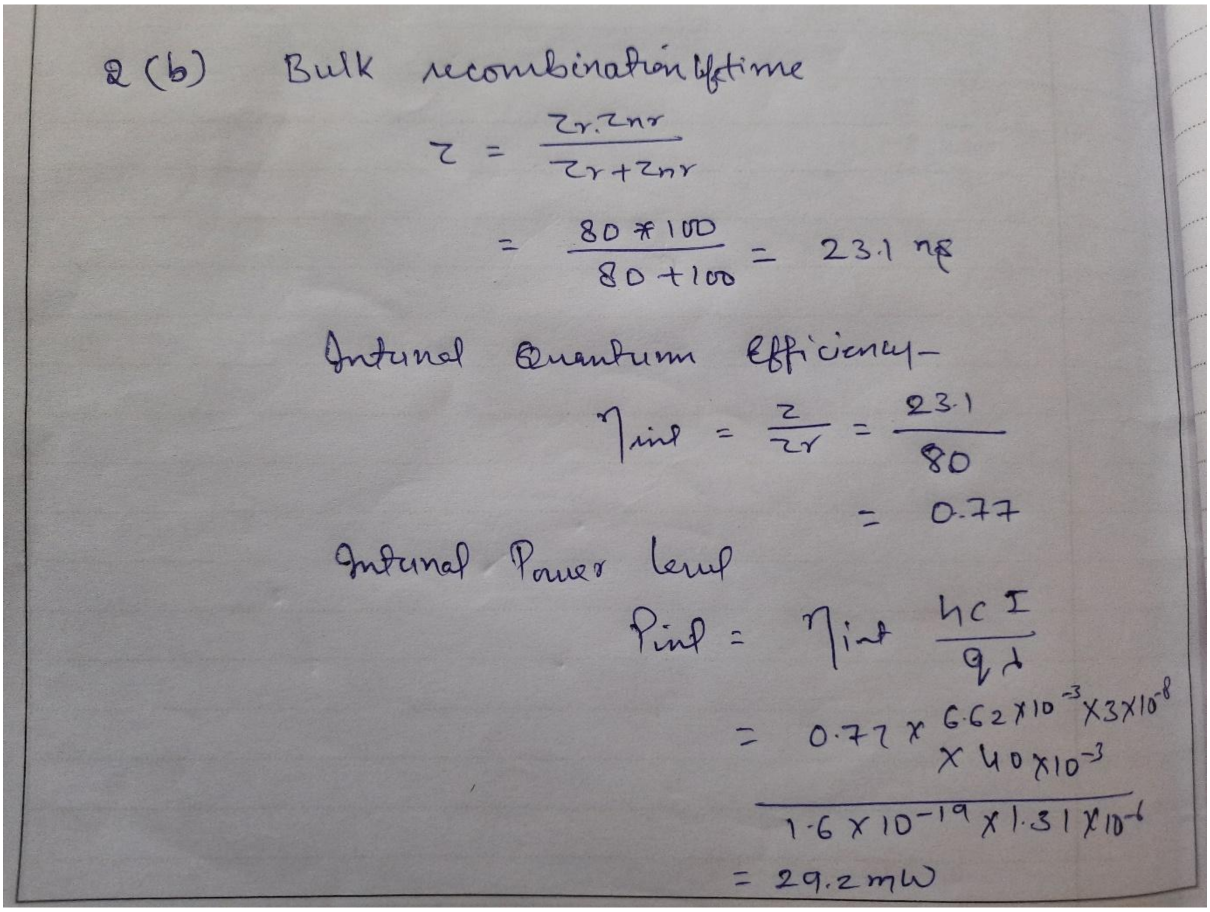
One material (AlGaAs) is used for the outer layers (cladding) and another of small band gap (GaAs) is used for inner layers.



- There are two types of regions get produced.
- To achieve carrier and optical confinement LED configurations such as double heterojunction are useful.
- This configuration is called so because of the two different alloy layers on each side of the active region.
- By means of this sandwich structure of differently composed alloy layers both the carriers and optical fields are confined in the active layer.
- This dual confinement leads to high radiance and high efficiency.

2.b)A double hetero junction InGaAsP LED emitting a peak wavelength of 1310 nm has radiative and non-radiative recombination times of 30 and 100 ns respectively. The drive current is 40 mA. Calculate the bulk recombination life time, internal quantum efficiency, internal power level.

Solution-



2 (b) Bulk recombination lifetime

$$\tau = \frac{\tau_r . \tau_{nr}}{\tau_r + \tau_{nr}}$$

$$= \frac{80 * 100}{80 + 100} = 23.1 \text{ ns}$$

Internal Quantum Efficiency-

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.1}{80}$$

$$= 0.77$$

Internal Power level

$$P_{int} = \eta_{int} \frac{hc I}{q \lambda}$$

$$= 0.77 \times \frac{6.62 \times 10^{-3} \times 3 \times 10^{-8} \times 40 \times 10^{-3}}{1.6 \times 10^{-19} \times 1.31 \times 10^{-6}}$$

$$= 29.2 \text{ mW}$$

3.a Explain working principles of pin photo diode and Reach-through Avalanche Photo Diode with necessary diagrams.

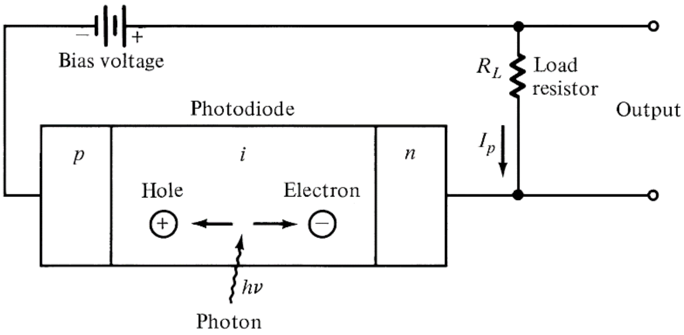
Ans.

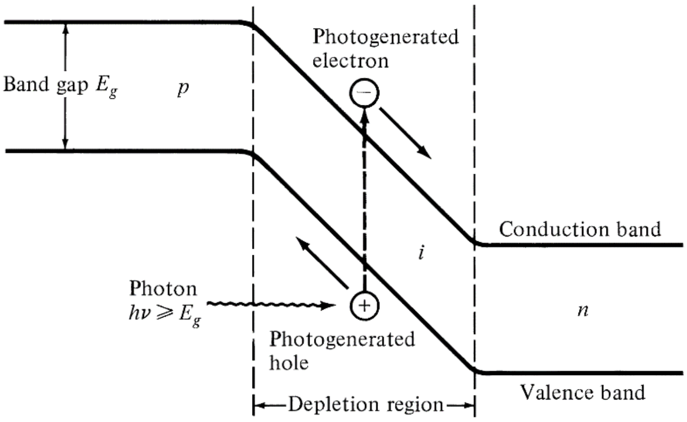
PIN Diode-
The pin photodetector circuit

- Consists of p and n regions separated by a very lightly n-doped intrinsic (i) region.
- In normal operation, a very large reverse bias voltage is applied across the diode to make sure that the intrinsic region is fully depleted of carriers.

- When an incident photon has an energy greater than or equal to the band-gap energy of the semiconductor material, the photon can give up its energy and excite an electron from the valence band to the conduction band.
- This process generates free electron-hole pairs known as *photocarriers*.

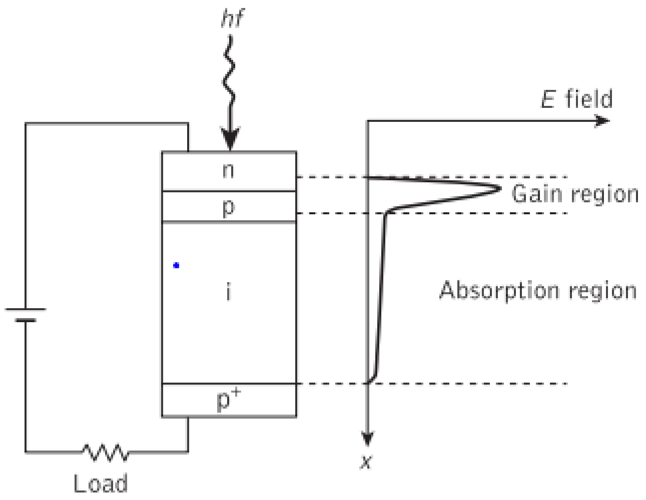
- The photodetector is designed is normally so that so that these carriers are generated mainly in the depletion region where most of the incident light is absorbed.
- This high electric field present in the depletion region causes the carriers to separate and be collected across the reverse-bias junction.
- This gives rise to a current flow in an external circuit with an electron flowing for every carrier pair generated.
- This current flow is known as photocurrent.





Avalanche Photo Diode-

- Avalanche photodiodes internally multiply the primary signal photocurrent before it enters the input circuitry of the following amplifier.
- This increases receiver sensitivity, since the photocurrent is multiplied before encountering the thermal noise associated with the receiver circuit.
- In order for carrier multiplication to take place, the photogenerated carriers must traverse a region where a very high electric field is present.
- In this high electric field region, a photogenerated electron or hole can gain enough energy so that it ionizes bound electrons in the valence band upon colliding with them.
- This carrier multiplication mechanism is known as impact ionization.

- 

It works on the principle of impact ionization. The phenomena is known as Avalanche multiplication.

4 .Discuss the different sources of noise in optical receiver.

Ans.

Principal noise sources associated with photodetectors that have no internal gain are:

a) Thermal Noise

b) Quantum noise

c) Dark-current noise

d) Digital Signalling Quantum Noise

a) Thermal Noise-

This is spontaneous fluctuation due to thermal interaction between free electrons and the vibrating ions in a conducting medium ,and it is especially prevalent in resistors at room temperature.

It is given by -

$$\overline{i_t^2} = \frac{4KTB}{R}$$

Where K is Boltzman's constant.T is absolute temperature . B post detection bandwidth of the system.

b) Quantum Noise

The quantum behavior of electromagnetic radiation must be taken into account at optical frequencies since hf > KT and quantum fluctuations dominate over thermal fluctuations. The detection of light by a photodiode is a discrete process since the creation of an electron–hole pair results from the absorption of a photon, and the signal emerging from the detector is dictated by the statistics of photon arrivals. Hence the statistics for monochromatic coherent radiation arriving at a detector follow a discrete probability distribution which is independent of the number of photons previously detected. It is found that the probability P(z) of detecting z photons in time period τ when it is expected on average to detect zm photons obeys the Poisson distribution.

- c) Dark Current Noise –
  The photodiode dark current is the current that continues to flow through the bias circuit of the device when no light is incident on the photodiode.This is combination of bulk and surface currents.

  $$\overline{i_d^2} = 2eBI_d$$

  E is the charge on an electron and Id is the dark current.

d) Digital Signalling Quantum Noise

For digital optical fibre systems it is possible to calculate a fundamental lower limit to the energy that a pulse of light must contain in order to be detected with a given probability of error.

The premise on which this analysis is based is that the ideal receiver has a sufficiently low amplifier noise to detect the displacement current of a single electron–hole pair generated within the detector (i.e. an individual photon may be detected).

Thus in the absence of light, and neglecting dark current, no current will flow. Therefore the only way an error can occur is if a light pulse is present and no electron–hole pairs are generated. The probability of no pairs being generated when a light pulse is present may be obtained from Poission distribution and is given by:

$$P(0|1) = \exp(-z_m)$$

5. a) Discuss different types of non-linear scattering losses.

Answer:

Non-Linear Scattering Losses

This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels. The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers. These scattering mechanisms in fact give optical gain but with a shift in frequency, thus contributing to attenuation for light transmission at a specific wavelength.

Stimulated Brillouin scattering

Stimulated Brillouin scattering (SBS) may be regarded as the modulation of light through thermal molecular vibrations within the fiber. The scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in this scattering process produces a phonon* of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength. The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, making SBS a mainly backward process.

As indicated previously, Brillouin scattering is only significant above a threshold power density. Assuming that the polarization state of the transmitted light is not maintained, it may be shown [Ref. 16] that the threshold power PB is given by:

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts}$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, αdB is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. This expression allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs.

Stimulated Raman scattering

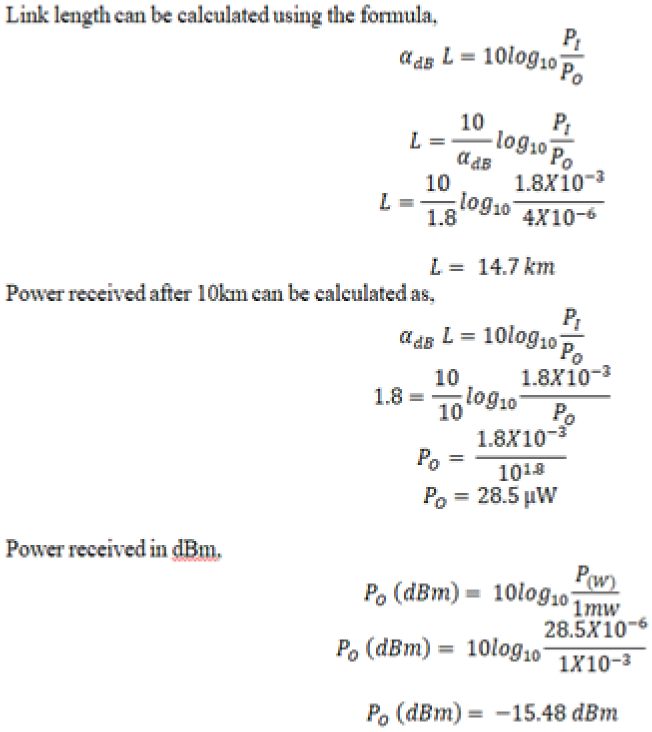
Stimulated Raman scattering (SRS) is similar to SBS except that a high-frequency optical phonon rather than an acoustic phonon is generated in the scattering process. Also, SRS can occur in both the forward and backward directions in an optical fiber, and may have an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber. Using the same criteria as those specified for the Brillouin scattering threshold, it may be shown that the threshold optical power for SRS PR in a long single-mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts}$$

5. b) The mean optical power launched into an optical fiber link is 1.8mW and the fiber attenuation is 1.8dB. Determine the maximum possible link length without repeaters when the

minimum optical power level required at detector is 4µW. Calculate the power received in dBm after 10km.

Answer:



Link length can be calculated using the formula,

$$\alpha_{dB}\, L = 10\log_{10}\frac{P_I}{P_O}$$

$$L = \frac{10}{\alpha_{dB}}\log_{10}\frac{P_I}{P_O}$$

$$L = \frac{10}{1.8}\log_{10}\frac{1.8X10^{-3}}{4X10^{-6}}$$

$$L = 14.7\ km$$

Power received after 10km can be calculated as,

$$\alpha_{dB}\, L = 10\log_{10}\frac{P_I}{P_O}$$

$$1.8 = \frac{10}{10}\log_{10}\frac{1.8X10^{-3}}{P_O}$$

$$P_O = \frac{1.8X10^{-3}}{10^{1.8}}$$

$$P_O = 28.5\ \mu W$$

Power received in dBm,

$$P_o\,(dBm) = 10\log_{10}\frac{P_{(W)}}{1mw}$$

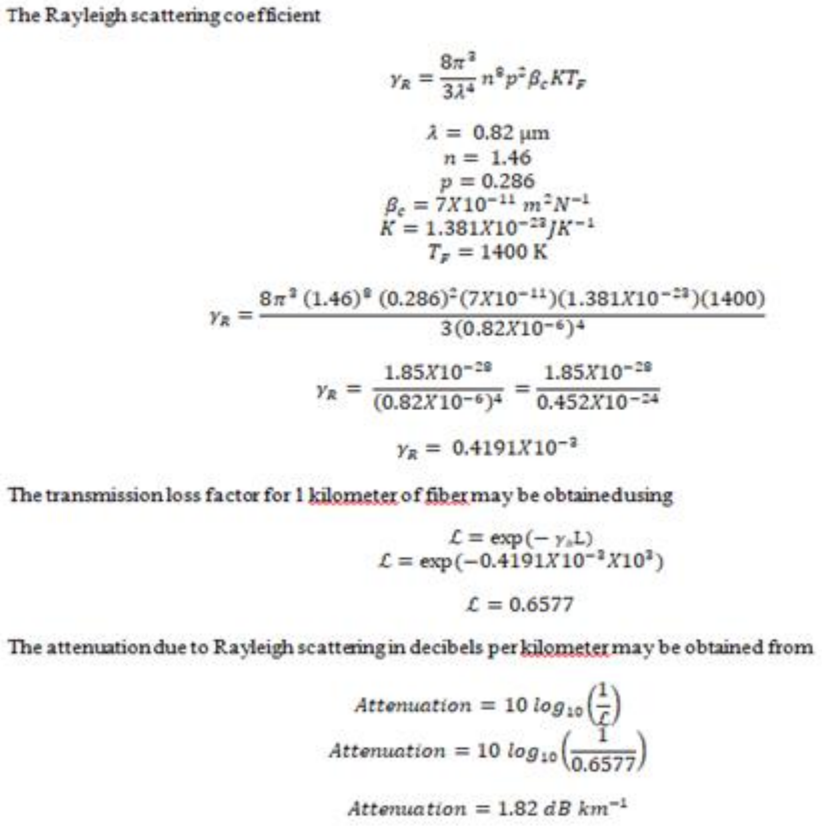
$$P_o\,(dBm) = 10\log_{10}\frac{28.5X10^{-6}}{1X10^{-3}}$$

$$P_o\,(dBm) = -15.48\ dBm$$

6. a) Silicon has an estimated fictive temperature of 1400 K with an isothermal compressibility of $7X10^{-11}$ m^2N^{-1}. The refractive index and photo elastic co-efficient for silica are 1.46 and

0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to fundamental Rayleigh scattering in silica at optical wavelength of 0.82 µm. Boltzmann's constant is $1.381 \mathrm{x} 10^{-23}$ JK^{-1}.

Answer:



The Rayleigh scattering coefficient

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

$$\begin{gathered} \lambda = 0.82\ \mu m \\ n = 1.46 \\ p = 0.286 \\ \beta_c = 7X10^{-11}\ m^2 N^{-1} \\ K = 1.381X10^{-23} JK^{-1} \\ T_F = 1400\ K \end{gathered}$$

$$\gamma_R = \frac{8\pi^3 (1.46)^8 (0.286)^2 (7X10^{-11})(1.381X10^{-23})(1400)}{3(0.82X10^{-6})^4}$$

$$\gamma_R = \frac{1.85X10^{-28}}{(0.82X10^{-6})^4} = \frac{1.85X10^{-28}}{0.452X10^{-24}}$$

$$\gamma_R = 0.4191X10^{-3}$$

The transmission loss factor for 1 kilometer of fiber may be obtained using

$$\begin{gathered} \mathcal{L} = \exp(-\gamma_R L) \\ \mathcal{L} = \exp(-0.4191X10^{-3}X10^3) \end{gathered}$$

$$\mathcal{L} = 0.6577$$

The attenuation due to Rayleigh scattering in decibels per kilometer may be obtained from

$$\begin{gathered} Attenuation = 10\ log_{10}\left(\frac{1}{\mathcal{L}}\right) \\ Attenuation = 10\ log_{10}\left(\frac{1}{0.6577}\right) \end{gathered}$$

$$Attenuation = 1.82\ dB\ km^{-1}$$

6. b) Write short note on: i) Intermodal dispersion ii) Intramodal dispersion

Answer:

i) Intermodal dispersion

Pulse broadening due to intermodal dispersion (sometimes referred to simply as modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes. This dispersion mechanism creates the fundamental difference in the overall dispersion for the three types of fiber shown in Figure 3.9. Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers. Hence, the overall pulse broadening in multimode graded index fibers is far less than that obtained in multimode step index fibers (typically by a factor of 100). Thus graded index fibers used with a multimode source give a tremendous bandwidth advantage over multimode step index fibers.

Under purely single-mode operation there is no intermodal dispersion and therefore pulse broadening is solely due to the intramodal dispersion mechanisms. In theory, this is the case with single-mode step index fibers where only a single mode is allowed to propagate. Hence they exhibit the least pulse broadening and have the greatest possible bandwidths, but in general are only usefully operated with single-mode sources.

ii) Intramodal dispersion

Chromatic or intramodal dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies (in the case of the injection laser corresponding to only a fraction of a percent of the center frequency, whereas for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

7. a) With neat sketches, explain the role and types of splicing techniques used in fiber optics communication.

Answer:

Fiber Splicing

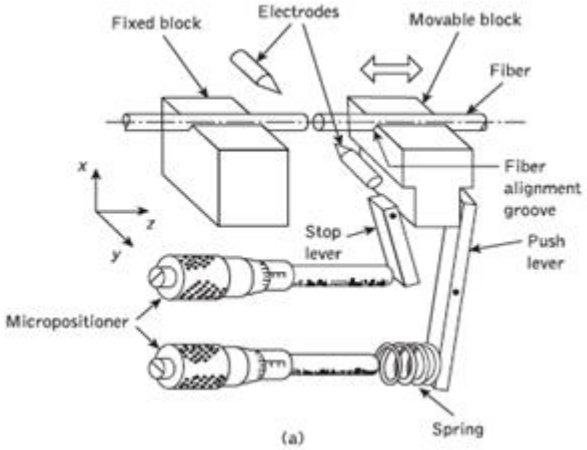
A permanent joint formed between two individual optical fibers in the field or factory is known as a fiber splice. Fiber splicing is frequently used to establish long-haul optical fiber links where smaller fiber lengths need to be joined, and there is no requirement for repeated connection and disconnection. Splices may be divided into two broad categories depending upon the splicing technique utilized. These are fusion splicing or welding and mechanical splicing. Fusion splicing is accomplished by applying localized heating (e.g. by a flame or an electric arc) at the interface between two butted, prealigned fiber ends causing them to soften and fuse. Mechanical splicing, in which the fibers are held in alignment by some mechanical means, may be achieved by various methods including the use of tubes around the fiber ends (tube splices) or V-grooves into which the butted fibers are placed (groove splices).

Fusion splices

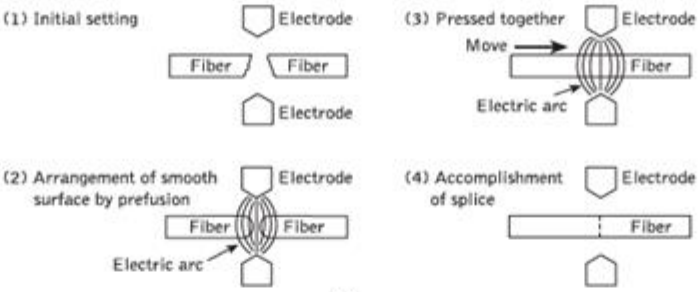
The fusion splicing of single fibers involves the heating of the two prepared fiber ends to their fusing point with the application of sufficient axial pressure between the two optical fibers. It is therefore essential that the stripped (of cabling and buffer coating) fiber ends are adequately positioned and aligned in order to achieve good continuity of the transmission medium at the junction point. Hence the fibers are usually positioned and clamped with the aid of an inspection microscope.

Flame heating sources such as microplasma torches (argon and hydrogen) and oxhydric microburners (oxygen, hydrogen and alcohol vapor) have been utilized with some success.

However, the most widely used heating source is an electric arc. This technique offers advantages of consistent, easily controlled heat with adaptability for use under field conditions. A schematic diagram of the basic arc fusion method is given in Figure (a) illustrating how the two fibers are welded together. Figure (b) shows a development of the basic arc fusion process which involves the rounding of the fiber ends with a low-energy discharge before pressing the fibers together and fusing with a stronger arc. This technique, known as prefusion, removes the requirement for fiber end preparation which has a distinct advantage in the field environment. It has been utilized with multimode fibers giving average splice losses of 0.09 dB.



(a)

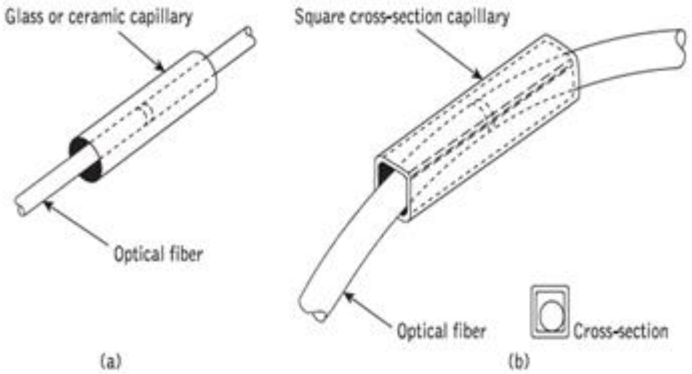


(b)

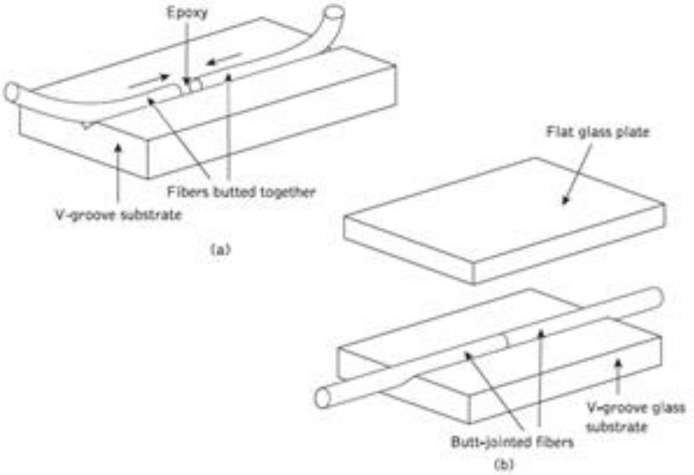
Mechanical splices

A number of mechanical techniques for splicing individual optical fibers have been developed. A common method involves the use of an accurately produced rigid alignment tube into which the prepared fiber ends are permanently bonded. This snug tube splice is illustrated in Figure and may utilize a glass or ceramic capillary with an inner diameter just large enough to accept the optical fibers. Transparent adhesive (e.g. epoxy resin) is injected through a transverse bore in the capillary to give mechanical sealing and index matching of the splice. Average insertion losses as low as 0.1 dB have been obtained with multimode graded index and single-mode fibers using ceramic capillaries. However, in general, snug tube splices exhibit problems with capillary tolerance requirements. Hence as a commercial product they may exhibit losses of up to 0.5 dB.

A mechanical splicing technique which avoids the critical tolerance requirements of the snug tube splice is shown in Figure (b). This loose tube splice uses an oversized square-section metal tube which easily accepts the prepared fiber ends. Transparent adhesive is first inserted into the tube followed by the fibers. The splice is self-aligning when the fibers are curved in the same plane, forcing the fiber ends simultaneously into the same corner of the tube, as indicated in Figure (b). Mean splice insertion losses of 0.073 dB have been achieved using multimode graded index fibers with the loose tube approach.



Other common mechanical splicing techniques involve the use of grooves to secure the fibers to be jointed. A simple method utilizes a V-groove into which the two prepared fiber ends are pressed. The V-groove splice which is illustrated in Figure (a) gives alignment of the prepared fiber ends through insertion in the groove. The splice is made permanent by securing the fibers in the V-groove with epoxy resin. Jigs for producing Vgroove splices have proved quite successful, giving joint insertion losses of around 0.1 dB. V-groove splices formed by sandwiching the butted fiber ends between a V-groove glass substrate and a flat glass retainer plate, as shown in Figure (b), have also proved very successful in the laboratory. Splice insertion losses of less than 0.01 dB when coupling single-mode fibers have been reported using this technique. However, reservations are expressed regarding the field implementation of these splices with respect to manufactured fiber geometry, and housing of the splice in order to avoid additional losses due to local fiber bending.



Multiple splices

Multiple simultaneous fusion splicing of an array of fibers in a ribbon cable has been demonstrated for both multimode and single-mode fibers. In both cases a 12-fiber ribbon was prepared by scoring and breaking prior to pressing the fiber ends onto a contact plate to avoid difficulties with varying gaps between the fibers to be fused. An electric arc fusing device was then employed to provide simultaneous fusion. Such a device is now commercially available to allow the splicing of 12 fibers simultaneously in a time of around 6 minutes, which requires only 30 seconds per splice. Splice losses using this device with multimode graded index fiber range from an average of 0.04 dB to a maximum of 0.12 dB, whereas for single-mode fiber the average loss is 0.04 dB with a 0.4 dB maximum.

7. b) A MMGI fiber has a core refractive index of 1.46, cladding refractive index of 1.45. The critical radius of curvature at which maximum bending loss occurs is 0.84 µm. Determine the wavelength of the transmitted light.

Answer:

$$R_c = 0.84X10^{-6}$$

$$n_1 = 1.46$$

$$n_2 = 1.45$$

Critical Radius of Curvature R_c

$$R_c \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{3/2}}$$

$$0.84X10^{-6} = \frac{3\,(1.46)^2\lambda}{4\pi\,(1.46^2 - 1.45^2)^{3/2}}$$

$$0.84X10^{-6} = \frac{6.3948\,\lambda}{0.06235}$$

$$\lambda = 8.19\ nm$$

8. Explain the following parameters: i) Absorption; ii) Group delay; iii) Scattering loss;

iv) Chromatic dispersion; v) Bending loss.

Answer:

i) Absorption

Material absorption is a loss mechanism related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light may be intrinsic (caused by the interaction with one or more of the major components of the glass) or extrinsic (caused by impurities within the glass).

Intrinsic absorption

An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near-infrared region. However, it does have two major intrinsic absorption mechanisms at optical wavelengths which leave a low intrinsic absorption window over the 0.8 to 1.7 µm wavelength range,, which shows a possible optical attenuation against wavelength characteristic for absolutely pure glass.

Extrinsic absorption

In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic absorption from transition metal element impurities.

ii) Group delay

Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero (i.e. d2n/dλ2 ≠ 0). The pulse spread due to material dispersion may be obtained by considering the group delay τg in the optical fiber which is the reciprocal of the group velocity υg. Hence the group delay is given by:

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}(n_1 - \lambda\frac{dn_1}{d\lambda})$$

where n1 is the refractive index of the core material.

iii) Scattering loss

Linear scattering losses

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. It must be noted that as with all linear processes, there is no change of frequency on scattering. Linear scattering may be categorized into two major types: Rayleigh and Mie scattering. Both result from the nonideal physical properties of the manufactured fiber which are difficult and, in certain cases, impossible to eradicate at present.

Nonlinear scattering losses

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power. Several nonlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high optical power levels. This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels. The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers.

iv) Chromatic dispersion

Chromatic or intramodal dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies (in the case of the injection laser corresponding to only a fraction of a percent of the center frequency, whereas for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

Material dispersion: Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

Waveguide dispersion: The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, and hence dispersion.

v) Bending loss

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained. Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium. As this is not possible, the energy associated with this part of the mode is lost through radiation.There are two types of bending losses- Macro & Micro