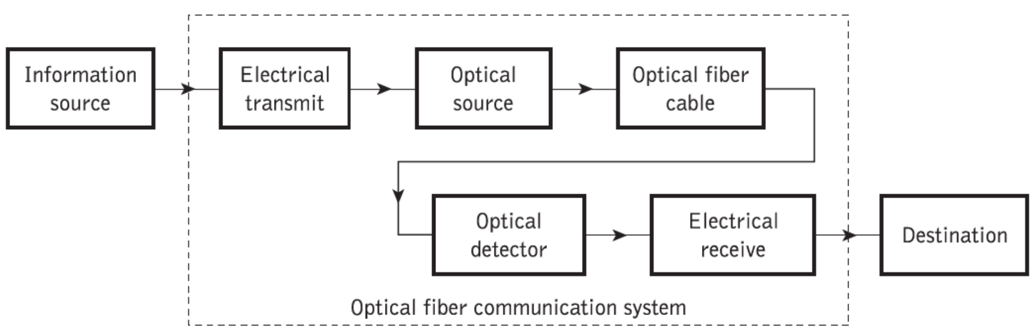
Even Semester Mid Examination (Answer Key)
III B. Tech Electronics and Communication Engineering

Subject: Optical Communication **Code:** EC317

<table>
<tr><th>Q.No.</th><th></th><th>Marks</th></tr>
<tr><td>1</td><td>
(a) Briefly describe the key elements of optical fiber communication system with neat block diagram
Ans:
▪ On transmitter side:
  ▪ Electrical transmitter, light source and its associated drive circuitry,
  ▪ a cable offering mechanical and environmental protection to the optical fibers contained inside
▪ On receiver side:
  ▪ a photodetector plus amplification and electrical receiver
▪ The information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier
▪ Optical Source: provides the electrical–optical conversion may be either a semiconductor laser or light-emitting diode (LED)
▪ The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier.
▪ Optical detector: Provides optical–electrical conversion. Photodiodes (p–n, p–i–n or avalanche), phototransistors and photoconductors are utilized for the detection of the optical signal
▪ Additional components include optical amplifiers, connectors, splices, couplers, regenerators (for restoring the signal-shape characteristics), and other passive components and active photonic devices.


</td><td>4+2</td></tr>
</table>

<table>
<tr>
<td></td>
<td>

(b) Define the optical spectral windows.

Ans:

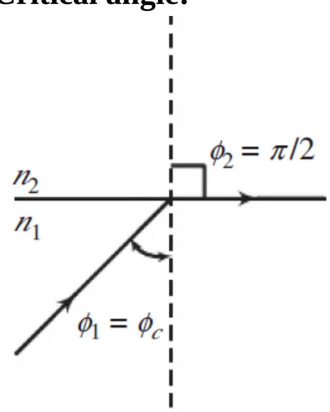
- **First window:** In early 1970s due to technology limitation, the optical fiber had a low loss window around 850nm is known as the ‘First window’. This window exhibited a relatively high loss of the order of 3 dB/km.
- **Second Window:** As the glass purification technology improved, the true silica loss profile emerged in 1980s and the optical communication shifted to 1300nm band (gives the loss profile) called the ‘ Second Window' . This window is attractive as it can support the highest data rate with theoretically zero dispersion for silica fibers and attenuation around 0.5 dB/km.
- **Third Window:** In 1990s the communication was shifted to 1550nm window, so called ‘Third Window’ due to invention of the Erbium Doped Fiber Amplifier (EDFA). The EDFA can amplify light only in a narrow band around 1550nm. Also this window has intrinsically lowest loss of about 0.2 dB/km. This band has higher dispersion, meaning lower bandwidth. However, this problem has been solved by use of so called ‘dispersion shifted fibers'.

</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>

(a) Define the following terms: Critical angle, Total Internal reflection, Acceptance angle and Numerical aperture

Ans:

Critical angle:



As $n_1 > n_2$, if the angle of incidence $\emptyset_1$ increases, the angle of refraction $\emptyset_2$ will go on increasing until a critical situation is reached, when for a certain value of $\emptyset_1 = \emptyset_c$, $\emptyset_2$ becomes 90^0, and the refracted ray passes along the interface. This angle $\emptyset_1 = \emptyset_c$ is called the **critical angle**.

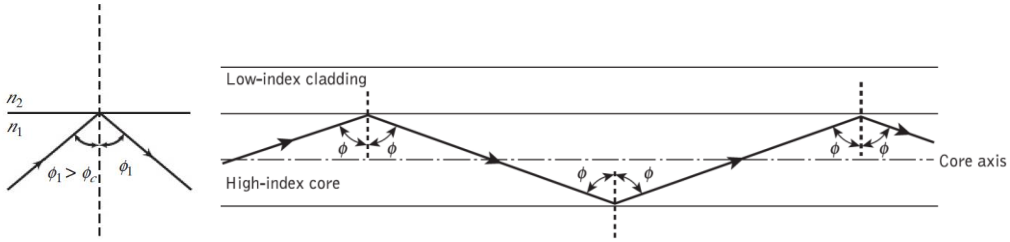
Total internal reflection:

- If the angle of incidence $\emptyset_1$ is further increased beyond $\emptyset_c$, the ray is no longer refracted but is reflected into the same medium. This is called total internal reflection. This phenomenon is responsible for the propagation of light through optical fibers.

</td>
<td>

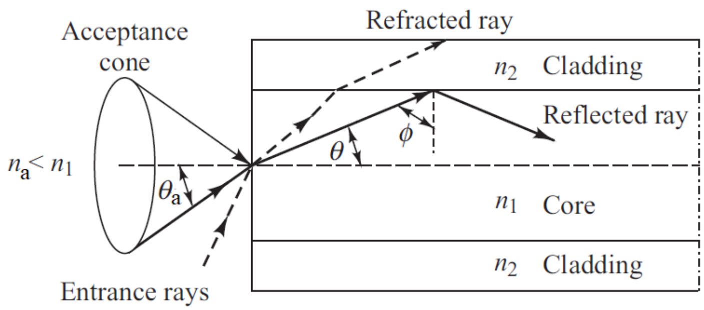
**2+1+
1.5+1.5**

</td>
</tr>
</table>



Acceptance angle:

- The maximum angle (θ_a) to the axis at which light may enter the fiber in order to be propagated is referred to as the **acceptance angle** for the fiber.



Numerical aperture:

- The term $n_a \sin\theta_a$ is called the numerical aperture (NA) of the fiber; it determines the light-gathering capacity of the fiber.

$$NA = n_a \sin\theta_a = \sqrt{{n_1}^2 - {n_2}^2}$$

- The *NA* may also be defined in terms of the relative refractive index difference Δ between the core and the cladding which is defined as

$$NA = n_1\sqrt{2\Delta}$$

Where $\Delta = \frac{{n_1}^2 - {n_2}^2}{2{n_1}^2}$

(b) An optical fiber has a numerical aperture of 0.15 and a cladding refractive index of 1.55. Determine: the acceptance angle for the fiber in water which has a refractive index of 1.33, and the critical angle at the core–cladding interface.

Sol:

Given that NA = 0.15

$n_2 = 1.55$, $n_w = 1.33$

acceptance angle $\theta_a = \sin^{-1}\left(\frac{NA}{n_w}\right) = 6.48^0$

$$n_1 = \sqrt{{n_2}^2 + NA^2} = 1.557$$

critical angle $\emptyset_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = 84.56^0$

(c) Draw a design curve of the fractional refractive index difference Δ versus the core radius 'a' for a silica-core (n_1= 1.458), single mode fiber to operate at 1.3µm.

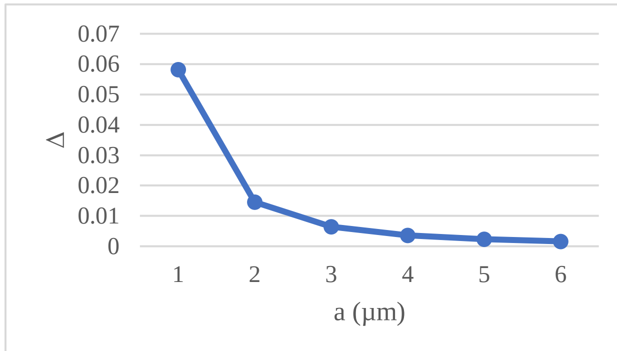
Ans:

For single mode fiber

$$V = \frac{2\pi a}{\lambda} NA = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta} = 2.405$$

$$\frac{8\pi^2 a^2}{\lambda^2} {n_1}^2 \Delta = 5.784 \;\Rightarrow\; \boldsymbol{a^2 \Delta = 0.0582\ \mu m^2}$$

core radius (a in µm)	relative R.I diff. (Δ)
1	0.0582
2	0.01455
3	0.006466667
	0.0036375
5	0.002328
6	0.001616667



(d) Suppose the fiber we select from the curve from part (c) has a 5µm core radius. Is this fiber still single mode at 820nm? If not, determine the number of modes exist in the fiber at 820nm?

Sol:

The V-number is directly proportional to *a/λ*

$$V \propto \frac{a}{\lambda}$$

$$\frac{V_1}{V_2} = \frac{\lambda_2}{\lambda_1}$$

$$V_2 = \frac{\lambda_1}{\lambda_2} V_1 = \frac{1.3}{0.82} \times 2.405 = \mathbf{3.813}$$

Or

For 5µm core radius, $\Delta = \frac{0.0582}{a^2} = 2.328 \times 10^{-3}$

$$V = \frac{2\pi \times 5}{0.82} \times 1.458\sqrt{2 \times 2.328 \times 10^{-3}} = 3.813$$

In this case $V > 2.405$, therefore fiber **is not operated in single mode**

The total number of modes $M = \frac{V^2}{2} \approx \mathbf{8}$

3 **(a) State the boundary conditions and the assumptions made while arriving at the solutions of the wave equation for an ideal step-index fiber.** **2+1+3**

Ans:

Inside the core of the optical fiber r < a and $q^2 > 0$ and therefore $\omega^2\mu\epsilon_1 > \beta^2$

$$\omega\sqrt{\mu\epsilon_1} = \frac{2\pi n_1}{\lambda} = kn_1 = k_1; where\ k = \frac{2\pi}{\lambda}$$

In the cladding of the optical fiber r > a and $q^2 < 0$ and therefore $\omega^2\mu\epsilon_2 < \beta^2$; $\omega\sqrt{\mu\epsilon_2} = \frac{2\pi n_2}{\lambda} = kn_2 = k_2$

$$k_2 < \beta < k_1$$

Where we can defined

$$q = U = \sqrt{{k_1}^2 - \beta^2} \quad for\ r < a$$

$$q = W = \sqrt{\beta^2 - {k_2}^2} \quad for\ r > a$$

Thus the expressions for longitudinal components of electric and magnetic fields can be written as:

Inside the core $(r < a)$

$$E_{z1} = A\, J_v(Ur)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$

$$H_{z1} = B\, J_v(Ur)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$

Inside the cladding $(r > a)$

$$E_{z2} = C\, K_v(Wr)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$

$$H_{z2} = D\, K_v(Wr)\, e^{jv\phi}\, e^{j(\omega t - \beta z)}$$

(b) The modes in an optical fiber waveguide are denoted either TE_{vm}, TM_{vm}, EH_{vm}, or HE_{vm}. What the mode subscripts *v* and *m* describe here?

Ans:

- The index *v* of the combination (*v*,*m*) represents the number of complete cycles of the field in the azimuthal plane (indicates the behavior of the field in the azimuthal plane, i.e. the variation of the field with respect to ϕ)
- the index ‘m’ represents the number of zero crossings in the azimuthal direction (maxima and minima in the azimuthal plane)
- For example TE_{02} would result in an intensity pattern that would be circularly symmetric about the axis with maximum intensity at the center of the fiber and there would be two concentric dark rings around the axis.

(c) A graded-index fiber with a triangular profile supports the propagation of 500 modes. The core axis refractive index is 1.46 and the core diameter is 75 μm. If the wavelength of light propagating through the fiber is 1.3 μm, calculate (a) the relative refractive index difference Δ of the fiber and (b) the maximum diameter of the fiber core which would give single-mode operation at the same wavelength.

Sol:

Given that M = 500; n_1 = 1.46; d = 75 μm; λ=1.3 μm

The total number of modes in graded index fiber $M = \frac{\alpha}{\alpha+2}\ \frac{V^2}{2} = 500$

	$$V = \sqrt{\frac{2M(\alpha+2)}{\alpha}} = \mathbf{54.77}$$ the **relative refractive index difference** Δ of the fiber $= \frac{V^2}{8\pi^2 a^2 {n_1}^2}\lambda^2 =$ $3000 \times \frac{1.3^2}{8\pi^2 \times 37.5^2 \times 1.46^2} = \mathbf{0.0214}$ the V-number is directly proportional to *a/λ* $$V \propto \frac{a}{\lambda}$$ let d_s is the maximum diameter of the fiber core for single-mode operation at the same wavelength, then $$\frac{V_m}{V_s} = \frac{d_m}{d_s} \Rightarrow \frac{54.77}{2.405} = \frac{75}{d_s}$$ $$d_s = \frac{75}{54.77} \times 2.405 \approx \mathbf{3.3\ \mu m}$$ **Or** $$d_s = 2a = \frac{\lambda V}{\pi n_1 \sqrt{2\Delta}} = \frac{1.3 \times 2.405}{\pi \times 1.46 \times \sqrt{2 \times 0.0214}} = 3.3\ \mu m$$	
4	**(a) Define intra-modal dispersion. Also, derive the expression for the pulse broadening due to material dispersion in step index fiber** Ans: ▪ There may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and it is known as intramodal dispersion (group velocity dispersion). **Material dispersion:** ▪ This arises due to the variations of the refractive index of the core material as a function of wavelength. ▪ This refractive index property causes a wavelength dependence of the group velocity of a given mode; that is, pulse spreading occurs when different wavelengths follow the same path. ▪ The group velocity is given by $v_g = \frac{d\omega}{d\beta}$; where the propagation constant $\beta = \frac{2\pi n_1(\lambda)}{\lambda}$ and $\omega = \frac{2\pi c}{\lambda}$ ▪ A time delay or group delay in the direction of the propagation $t_g = \frac{L}{v_g}$ $$t_g = \frac{L}{v_g} = L\frac{d\beta}{d\omega}\ or\ \frac{L}{c}\frac{d\beta}{dk}$$	**4+2+2**

$$\frac{d\beta}{d\lambda} = -\frac{2\pi}{\lambda^2}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \quad and \quad \frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2}$$

- Therefore

$$t_g = L\frac{d\beta/d\lambda}{d\omega/d\lambda} = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$$

- If the spectral width of the optical source is not too wide, then the delay difference per unit wavelength along the propagation path is approximately $\frac{dt_g}{d\lambda}$.
- For spectral components which are $\delta\lambda$ apart, symmetrical around center wavelength, the total delay difference $\delta\tau$ over a distance L is:

$$\delta\tau = \left|\frac{dt_g}{d\lambda}\right|\delta\lambda = \frac{L}{c}\lambda\left|\frac{d^2n_1}{d\lambda^2}\right|\delta\lambda$$

- The material dispersion of optical fibers is quoted in terms of the material dispersion parameter D_{mat} given by

$$D_{mat} = \frac{1}{L}\frac{\delta\tau}{\delta\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right|$$

D_{mat} has the units of ps nm^{-1} km^{-1}.

(b) A manufacturer's data sheet lists the material dispersion D_{mat} of a GeO_2-doped fiber to be 110 ps/(nm-km) at a wavelength of 860 nm. Find the rms pulse broadening per km due to material dispersion if the optical source is a GaAlAs LED that has a spectral width of 40 nm at an output wavelength of 860 nm.

Sol:

Given that $D_{mat} = 110$ ps/(nm − km)

Operating wavelength λ = 860 nm

RMS spectral width $\sigma_\lambda = 40\ nm$

The rms pulse broadening per km

$$\frac{\sigma_{mat}}{L} = D_{mat}\sigma_\lambda = \mathbf{4.4\ ns/km}$$

(c) A 15 km optical fiber link uses fiber with a loss of 1.5 dB/km and operating at 850 nm. The fiber has a joint at every kilometer with connectors which given an attenuation of 0.8 dB each. Determine the minimum mean optical power which must be launched into the fiber to maintain a mean optical power level of 0.3μW at the detector.

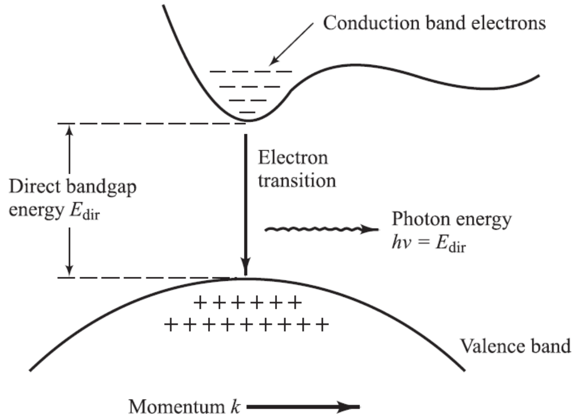
Sol:

Given that L = 15 km; $\alpha_L = 1.5\ dB/km$; $\lambda = 850\ nm$; connector loss = 0.8 dB

mean optical power level at the detector $P_{out} = 0.3$μW

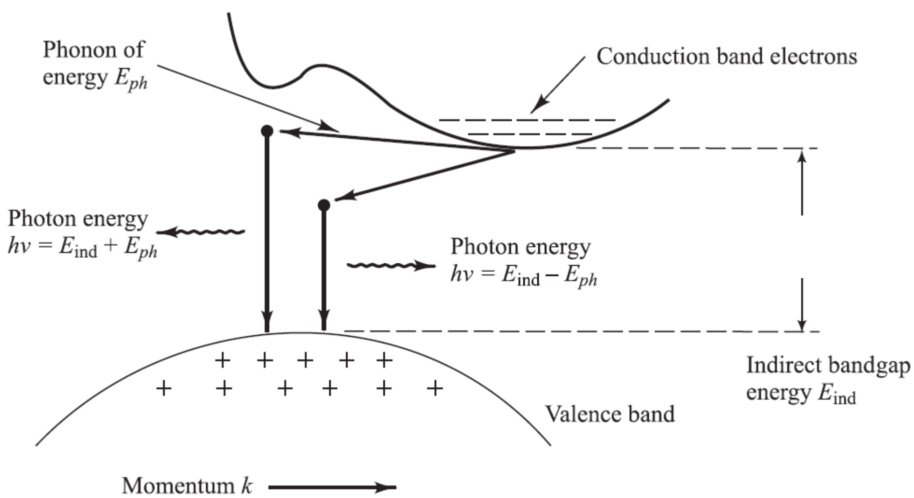
	The link has 14 connectors (at 1 km intervals). Therefore, the loss due to the connectors is 11.2 dB. Hence, the overall signal attenuation for the link is: $$\alpha(dB) = 10\log_{10}\left(\frac{P_{in}}{P_{out}}\right) = \alpha_L \times L + 11.2 = \mathbf{33.7\ dB}$$ the minimum mean optical power which must be launched into the fiber $$P_{in} = P_{out} \times 10^{33.7/10} = \mathbf{703\ \mu W}$$	

5	Write short note on **any two** of the following:
	(a) Working mechanism of the light emitting diode (LED)
	Ans:
	▪ If the p-n junction is forward biased, the majority carriers from both sides cross the junction and enter the opposite sides. This results in an increase in the minority carrier concentration on the two sides. This process is known as minority carrier injection.
	▪ The injected carriers diffuse away from the junction, recombining with majority carriers. (This releases the energy which is equal to the initial difference in the energies of the two charged particles)
	▪ This recombination of electrons and holes may be
	    ▪ Either radiatively (in which case a photon energy is emitted)
	    ▪ Or non-radiatively (where the recombination energy is dissipated in the form of heat)
	▪ The phenomenon of emission of radiation (photon) by the recombination of injected minority carriers with majority carriers is called as injection luminescence or electroluminescence. This is the mechanism by which light is emitted in LED.
	
	(b) Direct and indirect band gap semiconductor materials:
	Direct band gap semiconductor materials:
	nd gap materials, the minimum energy levels of conduction band and the
	ergy levels of valence band occur at same values of momentum
	nsition of an electron across the energy gap provides an efficient mechanism for
	ion
	aSb, InAs
		4



Indirect band gap semiconductor materials:

- For indirect band gap materials, the minimum conduction band and the maximum valence band energy levels occur at different values of momentum
- Here, the electron and hole recombination requires the simultaneous emission of a photon in order to conserve the momentum
- Ex: Si, Ge, GaP



(c) Internal quantum efficiency of the LED

$$internal\ quantum\ efficiency\ \eta_{int} = \frac{no.\ of\ radiative\ recombinations\ (photons)}{Total\ number\ of\ recombinations}$$

- Generally, the excess minority carrier density decays exponentially with time t

$$n(t) = n_0 e^{-t/\tau}$$

where n_0 is the initial injected excess electron density and τ represents the total carrier recombination lifetime.

	The rate of electron-hole recombination in a semiconductor material can be expressed as $$-\frac{dn(t)}{dt} = \frac{n_0}{\tau} e^{-\frac{t}{\tau}} = \frac{n(t)}{\tau}$$ Here, ‘n_0’ is the initial charge carrier density in the semiconductor material and ‘τ’ is the average life-time of a carrier against recombination. the total rate of recombination can be written as $\frac{n(t)}{\tau} = \frac{n(t)}{\tau_{rr}} + \frac{n(t)}{\tau_{nr}}$ Where ‘τ_{rr}’ be the life-time of a carrier against radiative recombination and ‘τ_{nr}’ be the life-time of a carrier against non-radiative recombination. $$\eta_{int} = \frac{\frac{n(t)}{\tau_{rr}}}{\frac{n(t)}{\tau_{rr}} + \frac{n(t)}{\tau_{nr}}} = \frac{1}{1 + \frac{\tau_{rr}}{\tau_{nr}}}$$	