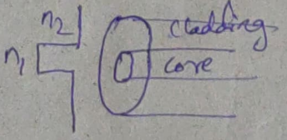
# Optical Windows

- First window at 850 nm (loss of order - 3 dB/km)
- 2nd " " at 1300 nm (loss/attenuation - 0.5 dB/km)
- 3rd " at 1550 nm (lowest loss of 0.2 dB/km)

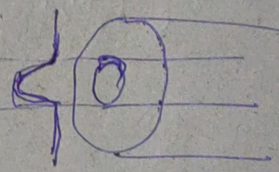
## Optical fiber :

- Based on RI profile of core.

① Step Index



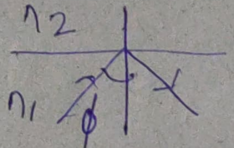

② Graded Index



$$n(r) = \begin{cases} n_1 ; & |r| \le a \text{ (core)} \\ n_2 ; & a < |r| \le b \text{ (cladding)} \end{cases}$$

- Relative Refractive index difference : $\Delta = \frac{n_1 - n_2}{n_2}$ (or) $\frac{n_1 - n_2}{n_1}$

- TIR :




$\phi > \phi_c$

Snell's Law : $n_1 \sin \phi_1 = n_2 \sin \phi_2$

- At Critical angle : $\sin \phi_c = \frac{n_2}{n_1}$

Cladding refractive index

Core refractive index

- Acceptance angle : $\theta_a$

- Numerical Aperture : $NA = \underset{\text{R.I of air}}{\underbrace{n_a}} \sin \theta_a = \sqrt{n_1^2 - n_2^2}$

$$\boxed{NA = \sqrt{n_1^2 - n_2^2} = n_1 \sqrt{2\Delta}}$$

- $\theta_a = \sin^{-1}(NA)$

- Single mode : if core thickness in nm 
- Multi mode : if core thickness is large 

- Number or Normalized Frequency : $V$

$$\boxed{V = \frac{2\pi a (NA)}{\lambda}}$$

a - radius of core
$\lambda$ - Operating Wavelength
NA - Numerical Aperture

- Normalized Propagation Constant : b

$$b = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2} \quad ; \quad \frac{\beta}{k} \text{ - effective refractive index}$$

$$k = \frac{2\pi}{\lambda}$$

Also, $kn_2 < \beta < kn_1$

\# For Single mode : $\boxed{V \leq 2.405}$

- Total number of modes : $M = \frac{V^2}{2}$ for step Index

$$M = \left(\frac{\alpha}{\alpha+2}\right)\frac{V^2}{2} \text{ for Graded index}$$

- $\alpha \neq 0$ , $\alpha = 1 \rightarrow$ for triangle and $V$ – Normalized frequency
  $\alpha = 2 \rightarrow$ for Parabolic
  $\hookrightarrow$ (considered in general)

## Distortion in Optical fiber

- Dispersion
  - Intermodal
    - Polarized mode
  - Intramodal
    - Material
    - Waveguide
- Attenuation
  - Material
    - Absorption
    - Scattering
  - Bending
  - Radiation

$\boxed{\text{Intermodal Dispersion Loss}}$ (Multimode)

- Delay Difference : $\boxed{\Delta T = \frac{L}{c} n_1 \Delta}$

- RMS Pulse Broadening : $\sigma_s \simeq \frac{L n_1 \Delta}{2\sqrt{3}c} \simeq \frac{L(NA)^2}{4\sqrt{3}n_1 c}$

# Standard formula : Group delay : $t_g = L\frac{d\beta}{d\omega}$

## $\boxed{\text{Intra Modal Dispersion Loss:}}$ (singlemode)

<u>Material Dispersion</u> : Due to Composition

- $t_g = \frac{L}{c}\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)$ ; here $n_1$ is a function of $\lambda$
  ↳ core R.I.

- $D_m = \left| \frac{\lambda}{c} \frac{d^2 n_1}{d\lambda^2} \right|$ in ns/nm-km

- RMS Delay Spread : $\sigma_{mat} = D_m \sigma_\lambda L$

- $\sigma_\lambda$ - Spectral Bandwidth.

- L - Length of optical fiber

<u>Wave guide Dispersion</u> : Due to Structure

- $t_g = \frac{L}{c} n_2 \left[1 + \Delta \frac{d(bk)}{dk}\right]$ ; b - is in terms of k & V
  ↳ normalized propagation constant

Also,

- $t_g = \frac{L}{c} n_2 \left[1 + \Delta \frac{d(bV)}{dV}\right]$ ; V - normalized freq.

- $D_{wg} = \left| \frac{n_2 V \Delta}{\lambda c} \frac{d^2(bV)}{dV^2} \right|$ in ns/nm-km

- Total Dispersion Loss : $D_m + D_{wg} + D_{inter}$
  - → For multimode fiber : $D_{intermodal}$ - Dominates
  - → For single mode " : $(D_m + D_{wg})$ - Dominates

- Total pulse Broadening : $\sigma_\tau = \sqrt{\sigma_m^2 + \sigma_{wg}^2}$

- $\sigma_{wg} = D_{wg}\,\sigma_\lambda\,L$ in (ns)

- $\sigma_m = D_m\,\sigma_\lambda\,L$ in (ns)

- Total pulse Broad Length : $\tau = DL\lambda$

- $B.W_{(max)} = \dfrac{1}{2\tau}$ ; ($\tau$ - Delay Difference - $\Delta T$)

## PROBLEMS

1. A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47. *Determine:* (a) the critical angle at the core–cladding interface; (b) the *NA* for the fiber; (c) the acceptance angle in air for the fiber. (**Ans: (a) 78.5°; (b) 0.3; (c) 17.4°**)
2. The velocity of light in the core of a step index fiber is $2.01 \times 10^8$ m/s, and the critical angle at the core–cladding interface is 80°. Determine the numerical aperture and the acceptance angle for the fiber in air, assuming it has a core diameter suitable for consideration by ray analysis. The velocity of light in a vacuum is $2.998 \times 10^8$ m/s.
3. A step index fiber with a large core diameter compared with the wavelength of the transmitted light has an acceptance angle in air of 22° and a relative refractive index difference of 3%. Estimate the numerical aperture and the critical angle at the core–cladding interface for the fiber.
4. A step index fiber has a solid acceptance angle in air of 0.115 radians and a relative refractive index difference of 0.9%. Estimate the speed of light in the fiber core.

## PROBLEMS

- A multimode step index fiber with a core diameter of 80 μm and a relative index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate: (a) the normalized frequency for the fiber; (b) the number of guided modes. **(Ans: (a) 75.8, (b) 2873)**
- A manufacturing engineer wants to make an optical fiber that has a core index of 1.480 and a cladding index of 1.478. What should the core size be for single-mode operation at 1550 nm? **(Ans: 7.7 μm)**
- An applications engineer has an optical fiber that has a 3.0 μm core radius and a numerical aperture of 0.1. Will this fiber exhibit single-mode operation at 800 nm? **(Ans: Yes, V=2.356)**
- Suppose we have a 50 μm diameter graded-index fiber that has a parabolic refractive index profile ($\alpha = 2$). If the fiber has a numerical aperture NA = 0.22, what is the total number of guided modes at a wavelength of 1310 nm? **(Ans: 174)**

## PROBLEMS

- A graded index fiber with a parabolic index profile supports the propagation of 742 guided modes. The fiber has a numerical aperture in air of 0.3 and a core diameter of 70 μm. Determine the wavelength of the light propagating in the fiber. Further estimate the maximum diameter of the fiber which gives single-mode operation at the same wavelength. **(Ans: 1.2 μm, 4.4 μm)**
- A single-mode step index fiber which is designed for operation at a wavelength of 1.3 μm has core and cladding refractive indices of 1.447 and 1.442 respectively. When the core diameter is 7.2 μm, confirm that the fiber will permit single-mode transmission and estimate the range of wavelengths over which this will occur. **(Ans: <1139 nm)**

## PROBLEMS

A 6 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate:

(a) the delay difference between the slowest and fastest modes at the fiber output;

(b) the rms pulse broadening due to intermodal dispersion on the link;

(c) the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion

**Sol:**

(a) The delay difference

$$\Delta T = \frac{L}{c} n_1 \Delta = 6 \times 1.5 \times \frac{0.01}{3 \times 10^5} = 300\ ns$$

(b) The rms pulse broadening due to intermodal dispersion

$$\sigma_s = \frac{L}{2\sqrt{3}c} n_1 \Delta = 86.7\ ns$$

(c) The maximum bit rate may be estimated in two ways:

$B_{T,max} = \frac{1}{2\Delta T} = 1.7\ Mbps$ or $B_{T,max} = \frac{0.2}{\sigma_s} = 2.3\ Mbps$

## PROBLEMS

- A glass fiber exhibits material dispersion given by $|\lambda^2(d^2n_1/d\lambda^2)|$ of 0.025. Determine the material dispersion parameter at a wavelength of 0.85 μm, and estimate the rms pulse broadening per km for a good LED source with an rms spectral width of 20 nm at this wavelength.

**Sol:**

Given that $\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right| = 0.025$

Operating wavelength $\lambda = 850$ nm

RMS spectral width $\sigma_\lambda = 20\ nm$

The material dispersion

$$D_{mat} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right| = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right| = \frac{0.025}{3 \times 10^5 \times 850} = 98.04\ \text{ps nm}^{-1}\ \text{km}^{-1}$$

The rms pulse broadening per km

$$\frac{\sigma_{mat}}{L} = D_{mat}\sigma_\lambda = 1.96\ ns/km$$

## PROBLEMS

- 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.