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**Solve all the following questions:-**

- a. A graded index fiber with a parabolic refractive index profile core has a refractive index at the core axis of 1.5 and a relative index difference of 1%. Estimate the maximum possible core diameter which allows single-mode operation at a wavelength of  $1.3 \mu\text{m}$ .
- b. The input power to an optical fiber is 2 mW while the power measured at the output end is  $2 \mu\text{W}$ . If the fiber attenuation is 0.5 dB/km, calculate the length of the fiber.
- c. In a step-index multi-mode fiber, with acceptance angle air to fiber interface of  $20^\circ$  and the fiber core diameter is  $50 \mu\text{m}$ . Find the approximate number of guided modes M at the wavelength  $1.3 \mu\text{m}$ .
- d. Silica has an estimated fictive temperature of 1400 K with an isothermal compressibility of  $7 \times 10^{-11} \text{ m}^2 \text{ N}^{-1}$ . The refractive index and the photoelastic coefficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wavelength of  $1.30 \mu\text{m}$ . If the Boltzmann's constant is  $1.381 \times 10^{-23} \text{ J K}^{-1}$ .
- e. State the main differences between Rayleigh and Brillouin scattering in optical fiber.
- f. Briefly explain the reasons for pulse broadening in optical fibers.
- g. An 8 km optical fiber link without repeaters uses multimode step index fiber which has a bandwidth-length product of 400 MHz km. It may be assumed that a return to zero code is used. Estimate the total pulse broadening and the rms pulse broadening on the link.

Best wishes of success  
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a-

$$V_c = 2.405(1 + 2/\alpha)^{0.5} = 2.405 \sqrt{2} = 3.4$$

$$\text{The maximum diameter} = (V_c \lambda_c) / (3.14 \times \text{NA})$$

$$= (3.4 \times 1.30) / (3.14 \times 1.5 \times (0.02)^{0.5}) = 6.6 \mu\text{m}$$

b- Given :  $P(0) = 2 \text{ mwatt} = 2 \times 10^{-3} \text{ watt}$   $P(z) = 2 \mu\text{watt} = 2 \times 10^{-6} \text{ watt}$   $\alpha$   
 $= 0.5 \text{ dB/km}$

$$\alpha = \frac{10}{L} \log_{10} \left( \frac{P(0)}{P(L)} \right)$$

$$0.5 = \frac{10}{L} \log_{10} \left( \frac{2000}{2} \right)$$

$$L = 20 \log_{10} \left( \frac{2000}{2} \right) = 60 \text{ km}$$

C. MMSF,  $\theta_a = 20^\circ$

$$\text{NA} = \sin(20) = 0.342$$

$$V = \text{Pi} \times D \times \text{NA} / \lambda = (3.14 \times 50 \times 0.342) / (1.3) = 41.3$$

$$M = V^2 / 2 = (41.3)^2 / 2 = 853 \text{ mode.}$$

d.

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

$$= \frac{248.15 \times 20.65 \times 0.082 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3\lambda^4}$$

$$= \frac{1.895 \times 10^{-28}}{\lambda^4} \text{ m}^{-1}$$

At a wavelength of  $1.3 \mu\text{m}$ :

$$\gamma_R = \frac{1.895 \times 10^{-28}}{2.856 \times 10^{-24}} = 0.664 \times 10^{-4} \text{ m}^{-1}$$

$$\mathcal{L}_{km} = \exp(-\gamma_R L) = \exp(0.664 \times 10^{-4} \times 10^3) = 0.936$$

$$\text{Attenuation} = 10 \log_{10} \left( \frac{1}{\mathcal{L}_{km}} \right) = 10 \log_{10}(1/0.936) = 0.3 \text{ dBkm}^{-1}$$

e. State the main differences between Rayleigh and Brillouin scattering in optical fiber.

Face of comp.	Rayleigh	Brillouin
Type of scattering	Linear(elastic)	Nonlinear (inelastic)
Direction of scattering	In all direction	<i>backward direction</i>
Transfer power of propagating mode	The propagating mode transferred linearly into a different mode	The propagating mode transferred nonlinearly into a different mode
Frequency shift	there is no change of frequency on scattering	there is a change of frequency on scattering
Main reason	It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light.	usually occurs at high input optical power levels
Scattering formula	Rayleigh scattering formula $\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$	Brillouin scattering is only significant above a threshold power density $P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dBV} \text{ watt}$
attenuation proportionality	attenuation proportional to $1/\lambda^4$	attenuation proportional to $\lambda^2$

f. Briefly explain the reasons for pulse broadening in optical fibers.

The main reasons of pulse broadening in optical fibers are 1- material dispersion 2- waveguide dispersion 3- intermodal dispersion

g. An 8 km optical fiber link without repeaters uses multimode step index fiber which has a bandwidth-length product of 400 MHz km. It may be assumed that a return to zero code is used. Estimate the total pulse broadening and the rms pulse broadening on the link.

Ans. Given: L = 8 km, fiber type: MMSF , B.L=400 MHz km, RZ code

Required:  $\tau$  and  $\sigma$

Solution: in RZ code bit rate=bandwidth = 400/8= 50 Mbps.

the total pulse broadening:  $\tau = 1/(2 * \text{bit rate}) = 1/100 \text{ Mbps} = 10 \text{ nS}$ ,

rms pulse broadening :  $\sigma = 0.2 / \text{bit rate} = 0.2/50 \text{ Mbps} = 4 \text{ nS}$