COUPLERS & DEVICES

(1) Explain the principle of planar waveguide directional coupler using supermodes' interference. In a fused fiber coupler (FFC), the power variation equations are the same as previous one, but the transfer signatures are different, why?

(2) For a parallel waveguide directional coupler, the length of interaction is $\boldsymbol{L = 5\ mm}$. When this coupler is operated at $\boldsymbol{\lambda = 1.30\ \mu m}$, entire input light appears from the coupled port with no output from the transmitted port. Calculate the coupling coefficient $\boldsymbol{\kappa_{1.30}}$ at this wavelength. Also calculate the difference of effective mode indices ($\boldsymbol{n_{eff}}$) of the symmetric and antisymmetric modes travelling in the structure.

{Ans. $\boldsymbol{\kappa = 3.14\ cm^{-1}; \Delta\, n_{eff} = 0.00013}$}

(3) Consider a directional coupler made up of two fibers with identical propagation constants, *i.e.*, $\Delta\beta = 0$. Then the powers at throughput and transmitted port are respectively: $P_T = P_I \cos^2 \kappa z$ and $P_C = P_I \sin^2 \kappa z$. Calculate the coupling length at 1.3 μm wavelength. Given $\kappa = 0.8\ mm^{-1}$. If the coupling length is 5 mm at 1.3 μm, what is the corresponding coupling coefficient? If this coupler has interaction length of 4 mm, determine the splitting ration at this wavelength. {Ans. $L_C \approx 2\ mm, \kappa \approx 0.3\ mm^{-1}\ and\ SR = 1:300$}

(4) A directional coupler formed by two single-mode fibers exhibits coupling coefficient $\kappa_{1.30} = 0.694\ mm^{-1}$ at a wavelength $1.3\ \mu m$ and $\kappa_{1.35} = 0.7422\ mm^{-1}$ at a wavelength $1.35\ \mu m$. When operated at $1.3\ \mu m$, calculate the coupling length L_C for which the entire power appears at the coupled port. For this directional coupler, if the length of interaction were $L_C/2$, then what would have been the coupled power at $1.3\ \mu m$ and at $1.35\ \mu m$ respectively?

{Ans. $at\ 1.3\ \mu m\ L_C \approx 2.26\ mm, at\ 1.30\ \mu m\ P_C \approx 0.5, at\ 1.35\ \mu m, P_C \approx 0.55$}

(5) Explain the working principle of WDM/WDDM coupling using sinusoidal power variation at the output ports as a function of wavelengths λ_1 and λ_2.

(6) A wavelength de-multiplexing coupler made from identical parallel waveguides has coupling coefficients $\kappa = 6.496$ cm^{-1} at $\lambda_1 = 1.55$ μm and $\kappa = 4.872$ cm^{-1} at $\lambda_2 = 1.30$ μm wavelengths and interaction length of 9.67 mm. When unit power at each wavelength $\lambda_1 = 1.55$ μm and $\lambda_2 = 1.30$ μm is launched at one input port, calculate the powers at the two output ports at these wavelengths.

{Ans. $P_C(1.55) \approx 0.001, P_T(1.55) \approx 0.997, P_C(1.31) \approx 0.99, P_T(1.31) \approx 0.001$}

(7) The power slitting ratios (SR) of a directional coupler at 1300 nm and 1550 nm are 9:16 and 16:9 respectively for a given length of interaction. When the interaction length is increased to achieve an SR of 16:9 at 1300 nm, what would be the SR then at 1550 nm? {Ans. SR = 9:2}

(8) Consider a fiber optic directional coupler with an interaction length (equal to coupling length) of $5\ mm$. Obtain the corresponding coupling coefficient κ. What should be the value of κ so that a $5\ mm$ long coupler behaves as a $3\ dB$ splitter? {Ans. $\kappa \approx 0.3142\ mm^{-1}, \kappa \approx 0.1571\ mm^{-1}$}

(9) Explain the working principle of WDM/WDDM coupler using sinusoidal power variation at the output ports as a function of wavelengths λ_1 and λ_2. A coupler has the coupling coefficients $\kappa_{1550} = 6.496\ cm^{-1}$ and $\kappa_{1300} = 4.873\ cm^{-1}$ respectively at $\lambda = 1.55$ μm and 1.30 μm. What should be the minimum length of interaction so that the coupler acts as a WDM/WDDM at these wavelengths?

{Ans: coupling length $L = 0.967\ cm$}

(10) Shown below a coupler circuit. Evaluate the expressions for power at the two output ports in terms of the input power P_I. This circuit, when operated at **1550 nm**, does not output any power at P_T. What is the minimum **length difference** (**>0**) between the two arms to achieve that?

{Ans: minimum difference in length $l_a - l_b = \frac{\lambda}{n} = \frac{1.55}{1.45} = 1.07\ \mu m$}

(11) Illustrate with the schematic configuration the working of a fiber loop mirror reflector. Hence obtain the intensity output functions. State an application and explain how it is deployed as a photonic circuit element.

(12) Draw the schematic of a fiber optic version of Mach-Zehnder Interferometer and calculate the intensities appearing at the two output ports as a function of phase difference between the two arms.

(13) Explain the working of a Sagnac interferometer. Derive an expression for the time delay between the two counter propagating beams in fiber and hence obtain the phase delay.

(14) A fiber optic Sagnac loop of radius 10 cm made with a single-mode fiber with $n_{\text{eff}} = 1.5$ at a wavelength λ= 500 nm, rotates with an angular velocity of π radian/sec. Calculate the time delay between the two counter-propagating light. Also calculate the phase lag between the beams.

{Ans. $\delta t = 9.86 \times 10^{-18} sec$; $\Delta\phi \approx 39.47 \times 10^{-3}\ rad$}

(15) Explain the transduction mechanism of optical fiber-based sensors. What are the principles of intensity-modulated and phase-modulated sensors? Explain with a schematic how a fiber sensor can be used to measure low amplitude vibration of an object.

FBG & DEVICES

(16) Explain with a schematic diagram how a fiber Bragg grating is fabricated experimentally? What is co-directional and contra-directional coupling here? What is a long period grating?

(17) Draw schematically the experimental setup to write Bragg grating on a waveguide using interferometric technique and state the advantage of the setup. Explain the principle of fiber Bragg Grating. State two applications in communications.

(18) Consider a fiber with $a = 3.5\ \mu m$ and $\Delta n = 0.007$. Assuming $n_2 = 1.45$, obtain the grating period required for a Bragg wavelength of 800 nm. {Ans. $\Lambda \approx 0.28\ \mu m$}

(19) Let us consider a step-index fiber having $n_2 = 1.45$, $a = 3\ \mu m$ and $NA = 0.1$. Obtain the cut-off wavelength λ_C of the LP_{11} mode. For the LP_{01} mode at $\lambda = 850\ nm$, the effective mode index is $n_{\text{eff}} = 1.4517$. Calculate the spatial grating period Λ required for creating a strong reflection at λ=850 using this fiber. {Ans. $\Lambda = 0.293\ \ \mu m$}

(20) The measured transmission spectrum of an FBG having grating length $L = 4.8\ mm$ shows the peak reflectivity of $R = 0.93$ at the corresponding Bragg wavelength $\lambda_B = 1532.1\ nm$. Calculate the required effective index modulation Δn_{eff}. If the core-overlap integral $I = 0.7$, then estimate the actual index modulation Δn. If the effective mode index of this LP_{01} mode is $n_{eff} = 1.4517$, then calculate the bandwidth of the reflected spectrum. {Ans. $\Delta n_{eff} \approx 2 \times 10^{-4}, \Delta n \approx 2.6 \times 10^{-4}, \Delta\lambda \approx 0.4$ mm}

(21) We need to have an FBG at $\lambda_B = 800\ nm$ that should have a reflectivity of R= 90% with a grating length $L = 25\ mm$. Calculate the required coupling coefficient. Assuming the core-overlap integral $I = 0.5$, estimate the actual index modulation Δn. If the effective mode index as $n_{\text{eff}} = 1.4517$, then calculate the bandwidth $\Delta\lambda$ of the reflected spectrum. {Ans. $\Delta n \approx 3.72 \times 10^{-5}, \Delta\lambda \approx 0.02$ nm}

(22) To fabricate an FBG at $\lambda_B = 800\ nm$ that should have a reflectivity of 90% with a grating length $L = 10\ mm$. Calculate the required coupling coefficient. Assuming the core-overlap integral $I = 0.5$, estimate the actual index modulation Δn. If the effective mode index as $n_{eff} = 1.4517$, then calculate the bandwidth $\Delta\lambda$ of the reflected spectrum. {Ans. $\Delta n \approx 9.3 \times 10^{-5}, \Delta\lambda \approx 0.05$ nm}

(23) We wish to write an FBG to use as a filter at $\lambda_B = 1550\ nm$ with a peak reflection of 99% and a bandwidth $\Delta\lambda = 1.0\ nm$. If the effective mode index $n_{eff} = 1.4517$, then calculate the required length of the FBG. Assuming the core-overlap integral $I = 0.75$, estimate the actual index modulation Δn.

{Ans. $\kappa L \approx 2.993, L \approx 2.29\ mm, \Delta n_{eff} = 6.45 \times 10^{-4},\ \Delta n \approx 8.6 \times 10^{-4}$}

(24) Assuming a sinusoidal RI modulation that is uniform with the core of the fiber, I corresponds to the fractional power in the core of the fiber and is approximately given by $I \approx 1 - exp\left[-2\left(\frac{a}{\omega_0}\right)^2\right]$. Consider a fiber with $a = 5\ \mu m$ and $NA = 0.09$ operated at $\lambda = 1.3\ \mu m$. Using the empirical relation $\frac{\omega}{a} \approx \left(0.65 + \frac{1.619}{V^{\frac{3}{2}}} + \frac{2.879}{V^6}\right)$, estimate the overlap integral I. {Ans. $\frac{\omega}{a} \approx 1.182,\ I \approx 0.76$}

(25) Design fiber Bragg gratings to be used as end mirrors for a fiber laser operating at 1.55 μm. The two gratings should have reflectivities of 93% and 99%. Calculate Λ, Δn and $\Delta\lambda$, assuming a length of 5 mm. Also assume I =1, $n_{\text{eff}} = 1.4517$. {Ans. $\Lambda \approx 0.534\ \mu m, \Delta n = 1.97 \times 10^{-4},\ \Delta\lambda = 0.4\ nm$}

(26) Consider a single-mode fiber with $a = 3.5\ \mu m$ and $\Delta n = 0.007$. (i) Obtain the cut-off wavelength when $n_2 = 1.447$. (ii) Calculate the mode effective index at 1550 nm assuming pure silica cladding $n_2 = 1.444$. (iii) Calculate the required grating period for a Bragg wavelength of 1550 nm. (iv) If you had assumed the effective index to be that for pure silica (instead of the estimated effective index), what would have been the period? (v) For this period, what would be the actual Bragg wavelength?

{Ans. (i) 1.5656 μm (ii) 1.4486 (iii) 0.5347μm (iv) 0.5367μm (v) 1.5563 μm}

(27) Assuming the effective index of the fiber mode to be approximately equal to the refractive index of pure silica, obtain the grating period required for a Bragg wavelength of 800 nm and at 1550 nm. Use the **Sellmeier formula** for estimating the refractive index of pure silica at these wavelengths.

(*Needs Sellmeier formula for pure silica*) {Ans. $\Lambda \approx 0.275\ \mu m$}

(28) Consider a single-mode fiber with silica cladding ($n_2 = 1.447$) a core diameter of 3 μm and $NA = 0.3$. What should be the FBG period for a resonance wavelength of $1532.1\ nm$? {Ans. $\Lambda \approx 0.526\ \mu m$}

DISPERSION PROPERTIES

(29) (*a*) What is waveguide dispersion? Using the definition of the normalised waveguide parameter as $b \approx \frac{\beta/k_0 - n_2}{n_1 - n_2}$, show that the time of travel of the mode is $= L\left(\frac{d\beta}{d\omega}\right) = \frac{Ln_2}{C}\left[1 + \Delta\frac{d(bV)}{dV}\right]$. Hence obtain the broadening of the pulse $\Delta\tau_w$ due to waveguide dispersion. Also show that the quantity dispersion takes the form $D_w = \frac{1}{L}\frac{\Delta\tau_w}{\Delta\lambda} = -\frac{\lambda}{a^2}\frac{(0.996)^2}{4\pi^2 n_2 C}$. Use $b = \left(1.1428 - \frac{0.996}{V}\right)^2$ as the empirical formula.

(b) For a SIF, take $a = 3\ \mu m$, $\Delta = 0.00154$, $n_2 = 1.45$, $\lambda_0 = 0.8\ \mu$m. Use the empirical formula $b = \left(1.1428 - \frac{0.996}{V}\right)^2$, to calculate waveguide dispersion $D_w = \frac{1}{L}\frac{\Delta\tau_w}{\Delta\lambda}$ in $\frac{ps}{km-nm}$. {Ans. $-5\ ps/km - nm$}

(30) (*a*) What is material dispersion? Obtain the expression for broadening $\Delta\tau_m$ of a pulse due to material dispersion only. Hence show that the quantity dispersion takes the form: $D_m = \frac{1}{L}\frac{\Delta\tau_w}{\Delta\lambda_0} = -\frac{\lambda_0}{C}\frac{d^2n}{d\lambda_0^2}$.

(*b*) For an optical fiber made of pure silica the value of $\frac{d^2n}{d\lambda_0^2} = 4 \times 10^{-2}\mu m^{-2}$ at wavelength. $\lambda_0 = 0.8\ \mu m$. Calculate the material dispersion $D_m = \frac{1}{L}\frac{\Delta\tau_m}{\Delta\lambda_0}$ in $ps/km - nm$. {Ans. $100\ ps/km - nm$}

(31) (*a*) How is dispersion compensating fiber designed? For an optical fiber made of glass the value of $\frac{d^2n_1}{d\lambda^2} = -4.2 \times 10^{-3}\mu m^{-2}$ at a wavelength $\lambda = 1.55\ \mu m$. Calculate the material dispersion $D_m = \frac{1}{L}\frac{\Delta\tau_m}{\Delta\lambda}$ in $ps/km - nm$. {Ans. $22\ ps/km - nm$}

(*b*) Consider the same optical fiber having $a = 2.02\ \mu m$, $\Delta = 0.013$ and $n_2 = 1.45$. Now calculate the waveguide dispersion $D_w = \frac{1}{L}\frac{\Delta\tau_w}{\Delta\lambda}$ in $ps/km - nm$ at this wavelength $\lambda = 1.55\ \mu m$. What conclusions you draw form this estimation? {Ans: $-22\ ps/km - nm$}

(32) (*a*) For an optical fiber made of glass the value of $\frac{d^2n_1}{d\lambda_0^2} = -2.67 \times 10^{-2}\mu m^{-2}$ at a wavelength $\lambda = 1.523\ \mu m$ and has the core radius, $a = 2.3\ \mu$m and $\Delta = 0.0075$. Calculate the material dispersion $D_m = \frac{1}{L}\frac{\Delta\tau_m}{\Delta\lambda}$ in $ps/km - nm$. {Ans. $19\ ps/km - nm$}

(*b*) Consider the same optical fiber having $a = 2.3\ \mu m$, $\Delta = 0.0075$ and $n_2 = 1.446$. Calculate the waveguide dispersion $D_w = \frac{1}{L}\frac{\Delta\tau_w}{\Delta\lambda}$ in $ps/km - nm$ at this $\lambda = 1.523\ \mu m$. {Ans: $-17\ ps/km - nm$}

(33) Calculate the broadening of a narrow pulse (in ns) at the output of a 1 km long step-index multimode fiber having $n_1 = 1.5$ and $\Delta = 0.01$. What will be broadening of that pulse when it travels through 1 km in a multimode parabolic index profile fiber having $n_1 = 1.45$ and $\Delta = 0.01$? OPGHp.27.14[2+2]

OPTICAL FIBER PROPERTIES

(34) Consider a step-index fiber with $n_2 = 1.447$, $\Delta = 0.003$ and $a = 4.2$ µm operated at $\lambda = 1.30$ µm. Estimate the spot-size (ω) of the fiber. If this fiber is operated at $\lambda = 1.55$ µm, by how much the spot-size changes? {Ans. Increases by 0.7 µm} OPGHp.29.7[3]

(35) A step-index fiber has core radius $a = 3.0$ µm with $n_1 = 1.50$ and $n_2 = 1.49$. When light of $\lambda = 0.851$ µm is injected into this fiber, which of the LP_{lm} modes will be excited? How many modes will be propagating (including the degenerate modes)?

Given that the zeroes of $J_1(x)$: 0,3.8327, 7.0156, .. and $J_0(x)$: 2.4048, 5.5201, 8.6537, ...

{Ans. modes excited will be 6} OPGHp.29.5[3]

(36) Calculate the broadening of a narrow pulse (in ns) at the output of a 1 km long step-index multimode fiber having $n_1 = 1.5$ and $\Delta = 0.01$. What will be broadening of that pulse when it travels through 1 km in a multimode parabolic index profile fiber having $n_1 = 1.45$ and $\Delta = 0.01$? {Ans. $\Delta\tau = 0.25$ ns} OPGHp.27.14[2+2]