Dispositivos e Sistemas Optoelectrónicos
Teórico-prática
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Questões

Questão 1: Os lasers de díodo (LD) semicondutores são as fontes de luz mais usadas nos sistemas de comunicação de altas taxas de transmissão. Essencialmente, há dois tipos de laser de díodo com interesse para as comunicações óticas: os lasers Fabry-Pérot (FB) e os lasers DFB. Descreva o princípio de operação de um laser de díodo, realçando as diferenças entre os lasers de díodo FP e DFB, indicando as vantagens de um relativamente ao outro.

Questão 2: As fibras óticas permitem a transmissão de sinais pticos a longa distância com baixas perdas quando comparadas com outros meios. Indique os tipos de fibra ótica que conhece, descrevendo as respetivas caraterísticas, e indique as aplicações mais relevantes que conhece para cada um dos tipos de fibras que referir.

Questão 3: Nos sistemas de comunicação ótica as caraterísticas dos componentes do recetor, nomeadamente do conversor ótico-elétrico, determinam em boa medida a qualidade do desempenho dos sistemas. Enuncie as caraterísticas que devem ter os transdutores ótico-elétricos para satisfazerem as necessidades dos sistemas de comunicação a altas taxas de transmissão, e descreva o princípio de funcionamento dos transdutores mais usados nos sistemas de comunicação ótica de alto débito.

Question 4: Optical fibers are a common transmission medium used in optical communication systems. Compared with other transmission media such as space and wired, optical fibers provide low attenuation and strong immunity to electromagnetic interference. However, signal attenuation and distortion in optical fibers are important degradation factors. Explain how fiber attenuation and distortion limit the transmission data rate and transmission distance, and how we can overcome these degradation factors.

Question 5: In optical communications, a transmitter consists of a light source and a modulation circuit. The light source generates an optical frequency carrier, and the modulation circuit modulates the carrier according to the transmitted signal. Because of the problems of multiple longitudinal modes and phase noise, significant efforts have been made to generate only a single longitudinal mode and to reduce the noise. Enumerate the most relevant characteristics a light source must have to fulfill the needs of high data bit rate optical communication system.

Question 6: Semiconductor light sources are the most important kind of light sources used in optical communications. Their small size, low cost and low power consumption are among the reasons for the popularity. There are essentially two types of semiconductor light sources: light emitting diodes (LEDs) and laser diodes (LDs). Explain how they operate, stressing the main differences between this two types of light sources.

Problemas

Problema 1: Um sistema de comunicações óticas emprega 150 km de fibra monomodo, com perdas de 0.25 dB/km, e um recetor cuja sensibilidade é 25 nW. O sistema compreende ainda um amplificador ótico (EDFA) com ganho de 15 dB, 5 junções de fibra ("splices") com 0.25 dB de perdas por junção, 2 conetores com 0.5 dB de perdas por conetor. Determine a potência em mW que deve ter o transmissor se o sistema tiver uma margem de perdas ("loss margin") de 15 dB.

Problema 2: Considere uma fibra monomodo usada para comunicações de média distância. Se o coeficiente de dispersão da fibra for 5 ps /(nm×km). Se a fibra tiver 20 km de comprimento e a largura espectral da fonte de luz usada tiver uma largura a meia altura de 1.5 nm, centrada a 1310 nm, determine:

i) O produto *distância taxa de transmissão* ("bit rate distance product");
ii) As larguras de banda elétrica e ótica do sistema.

Problema 3: Uma fibra de índice em degrau para uso a 800 nm tem um núcleo co de 100 μm de diâmetro e índice de refração 1.460. Se o índice de refração da bainha for 1.456, calcule:

a) O número V da fibra;
b) O número de modos guiados pela fibra;
c) A dispersão modal de 10 km de fibra.

Problema 4: Uma fibra monomodo tem de dispersão material e de guia de onda, 10 ps/(km×nm) e -5 ps/(km×nm), respetivamente. Calcule a largura de banda de 100 km de fibra se a fonte laser tiver uma largura de risca de 0.01 nm.

Problema 5: Considere um foto-detector de InGaAs (o coeficiente de absorção do InGaAs a 1310 nm é $1x10^4$ cm^{-1} e o índice de refração é 3.6) usado num sistema de comunicações óticas a 1310 nm. Sabendo que a região de absorção tem 1 µm de espessura e está em contacto direto com o ar, determine a responsividade do foto-detetor.

Problema 6: Estime o número de modos guiados a 1550 nm por uma fibra de perfil de índice em degrau, se o núcleo da fibra tiver 10 µm de diâmetro, e os índices de refração do núcleo e da bainha forem 1.45 e 1.44, respetivamente.

Problema 7: Considere um laser de díodo, baseado em heteroestruturas semicondutoras de InGaAlAs/InGaAs (índice de refração índice 3.6), cuja cavidade ótica tem 150 µm de comprimento. Sabendo que o pico de emissão do laser ocorre a 1550 nm, determine:

a) A separação em frequência dos modos permitidos pela cavidade.
b) O número de modos longitudinais que o laser emite, se o ganho do meio ativo em função do comprimento estiver centrado em 1550 nm e tiver uma largura a meia altura de 5 nm.
c) O comprimento máximo da cavidade para que o laser emitisse apenas um modo.

Problema 8: Lança-se 1 mW de potência ótica numa fibra monomodo. O recetor requere a potência mínima de 1 nW para produzir um sinal acima do ruído. A fibra opera a 1310 nm e tem perdas efetivas de 0.40 dB/km. Determine o comprimento máximo de fibra que pode ser usado sem ser necessário inserir repetidores para regenerar o sinal.

Problema 9: Considere um laser He-Ne emitindo $1{,}6\times10^{16}$ fotões por segundo, a 633 nm. Se o feixe laser for colimado e tiver 2 mm de raio, qual é a irradiância (potencia por unidade de área) do feixe.

Problema 10: Considere uma fibra ótica de vidro:

i) Determine o comprimento de onda de corte de uma fibra com um núcleo de 10 µm de diâmetro, e índices de refração do núcleo e bainha, 1.453 e 1.448;
ii) Qual será o número V dessa fibra se o comprimento de onda de operação for 1.310 µm?

Problem 11: You need to transmit data over an optical link of 200 km with fiber loss of 0.2 dB/km. The link has one EDFA with 10 dB gain, five splices with 0.1 dB loss per splice and two connectors with 0.3 dB per connector. The receiver sensitivity is 20 nW. Find the transmitter power in mW if the system has a loss margin of 15 dB.

Problem 12: For an optical communications system, the transmitter and receiver operate at 5 Gb/sec at a central wavelength of 1550 nm, using a laser with a spectral linewidth of 0.02 nm. The fiber has a dispersion parameter of M=-20 ps/nm.km.

a) What is the maximum length of fiber that allows the stated system bit rate?
b) Given the optical bandwidth of 7,07 GHz (10 GHz electrical bandwidth), then what would be the optical frequency spread in terms of wavelength (nm)
c) What would be the maximum fiber length?

Problem 13: Consider a typical optical transmission link with good receiver design that can tolerate a power loss of 25 dB at 1 Gb/s.

Estimate the maximum transmission distance if:

a) A multimode fiber at 850 nm with attenuation of 5 dB/km is used;
b) A single mode fiber with 0.5 dB/km at 1300 nm is used;
c) A single mode fibe with 0.2 dB/km at 1550 nm is used.

Problem 14: A step-index multimode fiber for use at 900 nm has a core diameter of 100 um and a refractive index of 1.460. The cladding has a refractive index of 1.456. Calculate the *V*-number, the number of modes and the modal dispersion per km of fiber.

Problem 15: 100 km SMF, material dispersion of 10 ps/km and waveguide dispersion of -5 ps/km. Laser diode with a linewidth of 0.1 nm.

a) What is the chromatic dispersion?
b) What is total dispersion?
c) Calculate the bandwidth of the fiber.

Problem 16: Consider an InGaAs photodetector for use at a wavelength of 1310 nm in optical communications with 1 um absorption region. The refractive index of doped InGaAs that is used in the detector at 1310 nm is 3.60; the photodetector surface is in direct contact with the air; the absorption coefficient of the InGaAs at 1310 nm is $1x10^4$ cm^{-1}. Assuming normal incidence, what will be the responsivity of the photodetector?

Problem 17: Estimate the number of allowed modes in a multimode step-index fiber that has a core of refractive index of 1.468 and diameter 100 um, and a cladding of refractive index of 1.447 if the source wavelength is 850 nm.

Problem 18: Consider a single-mode fiber that has a core of n_1 = 1.4532, and a cladding of n = 1.4483.

a) What should be the core radius of a single-mode fiber that has a core of n_1 = 1.4532, cladding of n = 1.4483, and is to be used with a source wavelength of 1.55 um?

b) What is the *V*-number if the fiber has a diameter of 8.2 um and is operating at 1.55 um?

Problem 19: In an LED the spread in the output wavelengths is related to a spread in the emitted photon energies. Assuming that the spread in the photon energies between the half intensity points of an LED is typical around $3k_BT$, estimate the corresponding linewidth $\Delta\lambda$ between the *half intensity points* in the LED output spectrum for an LED designed to operate at 1550 nm at room temperature (300 K).

Problem 20: Consider an InGaAs-based heterostructure laser diode that has an optical cavity of length 200 um. The peak radiation is at 1550 nm and the refractive index of InGaAs is about 3.6.

a) What is the mode integer *m* of the peak radiation and the separation between the modes of the cavity?

b) If the optical gain vs. wavelength characteristics has a FWHM wavelength width of about 6 nm, how many modes are there within this bandwidth?

c) How many modes are there if the cavity length is 20 um?

Selected definitions and basic equations

Photon energy

$$E_{ph} = h\upsilon = \hbar\omega;\ \omega = 2\pi\upsilon$$

Photon momentum

$$p_{ph} = \frac{h}{\lambda} = \hbar k$$

Photon flux Φ_{ph} and irradiance (intensity)

$$\Phi_{ph} = \frac{\text{Photons crossing area } A \text{ in time } \Delta t}{A\Delta t} = \frac{\Delta N_{ph}}{A\Delta t}$$

$$I = h\upsilon\Phi_{ph}$$

Propagation constant (wave vector)

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

Phase velocity

$$v = \lambda\upsilon = \frac{\omega}{k};\quad v = \frac{c}{n} = \frac{c}{\sqrt{\varepsilon_r}}$$

Changes in wavelength and frequency

$$\frac{\delta\lambda}{\lambda} = -\frac{\delta\upsilon}{\upsilon};\quad \delta\lambda = -\frac{\lambda^2}{c}\delta\upsilon = -\frac{c}{\upsilon^2}\delta\upsilon$$

Group velocity

$$v_g = \frac{d\omega}{dk}$$

Group index

$$v_g(\text{medium}) = \frac{c}{N_g};\quad N_g = n - \lambda_o\frac{dn}{d\lambda_o}$$

Electric and magnetic fields

$$E_x = vB_y = \frac{c}{n}B_y$$

Poynting vector and irradiance

$$\mathbf{S} = v^2\varepsilon_o\varepsilon_r\mathbf{E}\times\mathbf{B};\quad I = S_{\text{average}} = \frac{1}{2}v\varepsilon_o\varepsilon_r E_o^2$$

Snell's law and the Brewster angle

$$n_1\sin\theta_i = n_2\sin\theta_t; \sin\theta_c = \frac{n_2}{n_1}; \tan\theta_p = \frac{n_2}{n_1}$$

Phase change in total internal reflection (TIR)

$$\tan\left(\tfrac{1}{2}\phi_\perp\right) = \frac{[\sin^2\theta_i - n^2]^{1/2}}{\cos\theta_i};\ n = \frac{n_2}{n_1}$$

$$\tan\left(\tfrac{1}{2}(\phi_{//} + \pi)\right) = \frac{[\sin^2\theta_i - n^2]^{1/2}}{n^2\cos\theta_i}$$

Attenuation in second medium in TIR

$$\alpha_2 = \frac{2\pi n_2}{\lambda_o}\left[\left(\frac{n_1}{n_2}\right)^2\sin^2\theta_i - 1\right]^{1/2}$$

Reflectance, transmittance (normal incidence)

$$R = R_\perp = R_{//} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2;$$

$$T = T_\perp = T_{//} = \frac{4n_1n_2}{(n_1 + n_2)^2}$$

Fabry–Perot cavity

$$\upsilon_m = m\left(\frac{c}{2L}\right) = m\upsilon_f,\quad m = 1, 2, 3, \ldots$$

$$\delta\upsilon_m = \frac{\upsilon_f}{F};\quad F = \frac{\pi R^{1/2}}{1 - R}$$

Single slit diffraction

$$I(\theta) = I(0)\text{sinc}^2(\beta);\quad \beta = \frac{1}{2}(ka\sin\theta)$$

Airy disk, angular radius, divergence

$$\sin\theta_o = 1.22\frac{\lambda}{D}$$

$$\text{Divergence} = 2\theta_o \approx 2\times 1.22\frac{\lambda}{D}$$

Diffraction grating

$$d(\sin\theta_m - \sin\theta_i) = m\lambda;\quad m = 0, \pm1, \pm2, \ldots$$

V-number, normalized frequency

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2};\ V = \frac{2\pi a}{\lambda}\text{NA}$$

Normalized index difference

$$\Delta = (n_1 - n_2)/n_1$$

Acceptance angle and numerical aperture (NA)

$$2\alpha_{\max}; \sin\alpha_{\max} = \frac{(n_1^2 - n_2^2)^{1/2}}{n_0}; \sin\alpha_{\max} = \frac{\text{NA}}{n_0}$$

Normalized propagation constant

$$b = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2} \approx \frac{(\beta/k) - n_2}{n_1 - n_2}$$

$$b \approx \left(1.1428 - \frac{0.996}{V}\right)^2 \text{ for } 1.5 < V < 2.5$$

Single mode waveguides

Planar waveguide: $V < \pi/2$

Step-index fiber: $V < 2.405$

Mode field diameter

$$2w = 2a(0.65 + 1.619V^{-3/2} + 2.879V^{-6}); \quad 0.8 < V < 2.5$$

Dispersion in multimode step-index fiber

$$\frac{\Delta\tau}{L} \approx \frac{n_1 - n_2}{c} = \frac{n_1\Delta}{c}$$

Dispersion coefficient

$$\Delta\tau/L = \text{Spread in group delay per unit length} = D\Delta\lambda$$

$$D = \frac{\Delta\tau}{L\Delta\lambda}$$

Chromatic dispersion

$$\frac{\Delta\tau}{L} = |D_m + D_w + D_p|\Delta\lambda$$

Maximum RTZ bit rate

$$B \approx \frac{0.25}{\sigma}$$

Attenuation in optical fibers

$$\alpha_{\mathrm{dB}} = \frac{1}{L}10\log\left(\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right) = 4.34\alpha$$

where α is the attenuation coefficient.

Optical gain coefficient

$$g(\upsilon) = \sigma_{\mathrm{em}}(\upsilon)N_2 - \sigma_{\mathrm{ab}}(\upsilon)N_1$$

Optical gain

$$G = \exp(gL)$$

Threshold gain in lasers

$$g_{\mathrm{th}} = \alpha_s + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) = \alpha_t$$

Photon cavity lifetime

$$\tau_{\mathrm{ph}} \approx n/c\alpha_t$$

Bandgap light and wavelength

$$\lambda_g(\mu\mathrm{m}) = \frac{1.24}{E_g(\mathrm{eV})}$$

Responsivity of a photodetector

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident optical power (W)}} = \frac{I_{ph}}{P_o}$$

External quantum efficiency of a photodetector

$$\eta_e = \frac{I_{ph}/e}{P_o/h\upsilon}$$

Phase change between e- and o-waves

$$\phi = \frac{2\pi}{\lambda}(n_e - n_o)L$$

Visible Spectrum

Typical and approximate wavelength ranges, and color perception by an average person

Color	Violet	Blue	Green	Yellow	Orange	Red
λ (nm)	390–455	455–492	492–577	577–597	597–622	622–780

LED Colors

Typical wavelength ranges and colors as usually specified for LEDs
(Manufacturers' labeling can differ significantly)

Color	Violet	Blue	Aqua green	Emerald green	Green	Yellow	Amber	Orange	Red-orange	Red	Deep red	Infrared
λ (nm)	400–450	450–490	490–524	525–564	565–579	580–587	588–594	595–606	607–615	616–632	633–700	>700

Equivalent Power Levels in dBm in Optical Communications

Power	100 pW	1 nW	10 nW	100 nW	1 μW	10 μW	100 μW	1 mW	10 mW	100 mW	200 mW	500 mW	1 W
dBm	−70	−60	−50	−40	−30	−20	−10	0	10	20	23	27	30

Bands in Optical Communications

O-band (Original)	E-band (Extended)	S-band (Short wavelengths)	C-band (Conventional)	L-band (Long wavelengths)	U-band (Ultralong wavelengths)
1260–1360	1360–1460	1460–1530	1530–1565	1565–1625	1625–1675