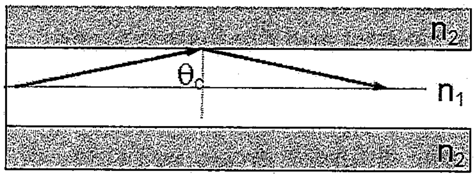
Answer

1.

a:

(i) Optical waveguide structure: A medium is surrounded by another medium whose refractive index is lower than that of the former. The medium with the higher refractive index acts as a "light trap". Light can be confined in the waveguide due to total internal reflection. Generally, an optical fibre is an optical waveguide consisting of two concentric cylinders of low optical-loss glass with slightly different refractive indices.

(ii) In order to allow light rays to transmit in a waveguide stably, they need to meet two conditions: (1) The incident angle of light rays in a waveguide need to meet the requirements for total internal reflection; (2) Only light rays with constructive interference can travel in a waveguide stably: same phase or phase difference must be equal to $m(2\pi)$, where m is 0, 1, 2, 3.... Therefore, only a number of certain incident angles as shown in the figure below can meet both above conditions, and thus form optical modes. Each incident angle corresponds to an optical mode. m is defined as an optical mode number.



(iii) The maximum number of optical modes can be described as

$$m_{\max} = \frac{2d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

where the "d" is the core layer thickness. Through tuning "d", you can increase number of optical modes. For large "d", you can obtain a number of optical modes, meaning a multimode waveguide. If "d" is reduced to allow you to obtain only one optical mode, it means a single mode waveguide

b:

(i) total internal reflection: when light or any other electromagnetic wave propagates from one medium to another medium, where the refractive index of the former is larger than that of the latter, the refraction angle is larger than the incident angle. If the incident angle is greater than the critical angle, the light or the electromagnetic wave is entirely reflected back to the first medium. This phenomenon is called total internal reflection

(ii) Numerical aperture: A measure of the light gathering ability of an optical instrument such as optical fibre, which can be described as NA=$\sqrt{n_1^2 - n_2^2}$, where n1 is the refractive index of the core layer of the optical fibre, and n2 is the refractive index of the cladding layer of the optical fibre.

(iii) Acceptance angle: This is a special angle with which light rays enter into an optical waveguide. Only the light rays within a critical entrance angle can propagate along an optical fibre, whereas the rays with an entrance angle greater than the critical angle are refracted into the cladding layer of the fibre and eventually lost by radiation. The critical entrance angle is called acceptance angle.

c:

n_1=1.50, and n_2=1.485, therefore,

$$d = \frac{\lambda}{2\sqrt{n_1^2 - n_2^2}} = 3.66\mu m$$

2

a:

(i) There exist a number of mechanisms for optical losses in a silica fibre, mainly due to (1) Intrinsic absorptions: ultraviolet absorption and infrared absorption; (2) Extrinsic absorption: Rayleigh scattering; OH^- (moisture) induced absorption; Impurity induced absorption;

(ii) Intermodal dispersion is due to the propagation delay differences between modes within a multimode optical fibre. Optical broadening depends on the transmission time between the slowest and the fastest modes
Intramodal dispersion: it occurs to both single mode optical fibres and multimode optical fibres. There exist two kinds of major mechanisms for optical dispersion: (1) Material dispersion: different group velocities of the various spectral components from the optical source, leading to optical pulse broadening; (2) Waveguide Dispersion: there exists a small fraction of the optical power propagating in the cladding layer and this is wavelength dependent, leading to the time-difference delay and thus pulse broadening

b:

(i) three major mechanisms: (1) Insufficient signal-to-noise ratio at the decision instant. For example, the binary 0 may be momentarily above the threshold, and thus be registered as a binary 1; (2) Timing variation may cause the waveform to be sampled at other than its maximum amplitude; (3) Intersymbol interference due to dispersion

(ii) An eye diagram is a method used for evaluating performance of the signals in high-speed digital transmissions, generated on an oscilloscope. The display obtained over two bit interval duration shows the results of superimposing all possible pulse sequences. A degradation in the quality of the digital signals shows a reduction in the size of eye or a closed eye.

c:

The minimum optical power requested by the photodetector

$$p_{\min} = h\tfrac{c}{\lambda}N_pB = 6.63\times10^{-34}\times\tfrac{3\times10^8}{1.55\times10^{-6}}\times10^3\times2.5\times10^9 = 3.2\times10^{-7}W$$

(i) Total optical loss $=10\log(\frac{P_{in}}{P_{\min}})$-0.3x10-0.1x2+20-10=35-3-0.2+20-10=41.8 dB

(ii) EDFA is Erbium-doped Fibre Amplifier. Erbium doping into silica generates a number of electronic states, among which an optical transition with a transition energy of ~0.8 eV (corresponding to 1.55 μm) can be obtained. A high power laser diode with a wavelength of 980 nm (commercially available) as a pumping source can lead to population inversion, and thus optical amplification at 1.55 μm. An optical amplifier can only compensate for attenuation. It cannot compensate for dispersion. It also amplifies both noise and signal.

(iii) L=41.8/0.4=104.5 km

3

a:

(i) PIN photodiodes: it is a junction diode in which a i-region (i.e., undoped region) is sandwiched between p-doped and n-doped regions. It normally works under a high bias, which is still lower compared with avalanche photodiodes. The transit time can be further reduced by reducing the thickness of the i-region, and thus the response speed can be very high. It leads to a wide bandwidth. Generally, a PIN photodiode does not exhibit a gain.

(ii) Avalanche photodiodes: it is a reverse-biased p-n junction operating under a bias which is close to the breakdown voltage. The photo-generated carriers undergo a series of impact ionisation processes during a transit in the depletion region, which leads to carrier multiplication and thus a very large gain. It can detect a very weak signal, but it also generates extra noise due to the avalanche process.

b:

(i) Two major factors: (1) Transit Time for carriers across i-region under reverse biased; (2) RC characteristic time due to junction capacitance. If the transit time is shorter than the RC characteristic time, the maximum bandwidth is determined by the RC characteristic time; If the transit time is longer than the RC characteristic time, the maximum bandwidth is determined by the transit time.

(ii) Transit time $t_{tr} = L/v = 10 \times 10^{-6} / 10^5 = 1 \times 10^{-10}$ s = 0.1ns
$C = \varepsilon\varepsilon_0 A/L = 12 \times 8.85 \times 10^{-12} \times \pi \times (100 \times 10^{-6})^2 / 10 \times 10^{-6} = 0.33$pF
RC=0.017 ns The maximum bandwidth is determined by the transit time, giving $f=1/t_{tr}$=10 GHz

(iii) Considering the RC, you can reduce the size of the optical window and increase the i-region thickness in order to reduce the RC. However, a reduction in size of the optical window leads to a reduction in optical absorption, and an increase in the thickness of the i-region leads to an increase in transit time. Therefore, an optimised thickness of the i-region is necessary.

c:

Responsivity: $R=\eta e\lambda/(hc)=0.85\times1.60\times10^{-19}\times1.55\times10^{-6}/(6.63\times10^{-34}\times3\times10^{8})$
$=1.06\ AW^{-1}$

Primary current: $I_p=P_0R=1.0\times1.06=1.06\ \mu A$

Multiplication factor: $M=I/I_p=20/1.06=19$

d:

Cut-off wavelength: an intrinsic absorption process can take place under the conditions that the energy of incident photon is greater than or at least equal to the bandgap energy of the material used to fabricate the photodetector. The threshold wavelength is called cut-off wavelength.
For silicon, its bandgap energy E_g=1.11 eV. Therefore, $\lambda=hc/E_g=1.117\ \mu m$
At a low temperature, the noise can be reduced, leading to a reduction in dark current, and thus an increase in ratio of signal to noise.

4

a

(i) Relaxation oscillations: $\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau_{sp}} - gN_{ph}$

Relaxation oscillations is a kind of phenomena that lasers exhibit exponentially damped oscillations in output power when they are turned on. It generally exists for several nanoseconds.

Based on carrier density rate equation given above, when the photon population builds up rapidly after injection. At the same time, the carrier density also decreases quickly, until it is below above the certain value (so-called steady-state injected carrier density for injection current density> the threshold current density J_{th}). At this point, the dN/dt term becomes negative and the photon density N_{ph} becomes very small. In this case, the carrier density starts to increase again, and so does the photon density. The process repeats itself as a damped oscillation till a steady state can be achieved.

(ii) Frequency chirp: the modulation of single-mode laser diodes can cause a dynamic shift of the peak wavelength emitted from the device.

Formation mechanism: The variation carrier density with time (in particular, due to relaxation oscillations) leads to a change in refractive index of the active region of laser diode, resulting in a change in the (frequency) wavelength of lasing.

b

(i) Light emitting diodes: it is based on spontaneous emission, and the emitted photons have a random phase and direction

Laser diode: it based on stimulated emission, and the emitted photons have the same phase, direction and energy.

Compared with an LED, a laser diode has a narrower line-width and shorter recombination life-time, leading to smaller dispersion and faster modulation frequency.

(ii) WDM is a technology which multiplexes a number of optical carrier signals onto a single optical fibre by using different wavelengths of laser diodes, and then demultiplexes them into individual signals. This allows it to transmit signals in many channels through a single fibre. A dense WDM system contains a large number of optical channels with a small spacing between optical channels, typically less than 1 nm. In order to eliminate any interference among these channels, transmitters need to have a narrow line-width of less than 1 nm. Therefore, LEDs cannot meet the requirements, and it is necessary to use laser diodes, in particular, DFB lasers

c

Low dimensional laser diodes: quantum dot laser diodes and quantum wire laser diode.

A reduction in dimensionality leads to an increase in density of state (DOS) near the band edge for low dimensional structures. This leads to a reduction in threshold for lasing, compared with quantum well or bulk material based laser diodes. Furthermore, due to the enhancement in carrier confinements as a result of reduced dimensionality, the temperature stability is also improved.