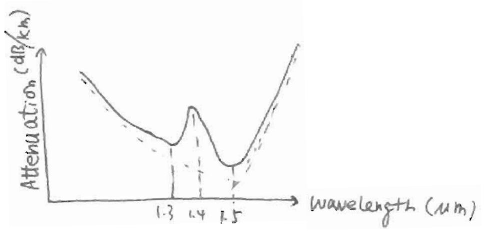
EEE412 Solutions

1.a:



Short wavelength: UV absorption, Rayleigh scattering, etc.
Long wavelength: IR absorption due to the excitation of molecular vibrations. 2
1.4 μm: absorption due to OH^-.
Therefore, it leaves two optical windows: 1.3 μm and 1.55 μm.

b:

(i) Mainly (1) material dispersion: Different group velocity of the various spectral components from the optical source; (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. 1.5

(ii) An LD has a narrower line-width and shorter recombination life-time than an LED, leading to smaller dispersion and faster modulation frequency. 1.5

c:

Attenuation: There exist a detection limit of any receiver, and thus the final optical power received by the detector should be higher than the limit, otherwise, it will cause a substantial bit-error rate.
Dispersion: There does not exist any purely monochromatical light, and thus optical pulses will broaden as they propagate in an optical fibre due to dispersion. If the broadening is great, two consecutive pulses can be not clearly identified. 2

d:

(i) Receiver sensitivity $P_R = N_p BE$, where E is a photon energy at 1.5 μm

$E = hc/\lambda = 0.8266$ eV $= 1.3242\times10^{-19}$ J

$P_R = 10^3\times2.5\times10^9\times1.3242\times10^{-19} = 3.31\times10^{-7}$W

The optical loss due to the optical fibre (P_{in}= the optical power of the laser)

$$Loss = 10\log\frac{P_{in}}{P_R} = 10\log\frac{2\times10^{-3}}{3.21\times10^{-7}} = 37.8dB$$

3

The maximum optical loss allowed: the loss due to the optical power- the power margin required.
Therefore, the maximum optical loss allowed: 37.8dB-10 dB =27.8 dB

(ii) The maximum transmission distance in terms of optical loss:
27.8dB/ α=27.8/0.4=69.5 km 3

(iii) $\Delta\tau \le 0.5$ T =0.5/B ($\Delta\tau$: optical pulse broadening; T: bit slot; B: bit rate)

$$\Delta\tau = L\bullet\Delta\lambda\bullet D \le 0.5/B \quad \Rightarrow L \le \frac{0.5}{B\bullet\Delta\lambda\bullet D}$$

Therefore, the maximum distance in terms of optical dispersion: 4

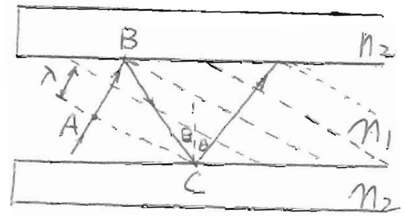
$$L_{\max} = \frac{0.5}{2.5\times10^9\times2\times2\times10^{-12}} = 50km$$

e: Transmitter : use a laser diode with a narrower line width, such as DFB laser or VCSEL
Receiver: use a higher sensitivity detector, such as APD. 3

2

a: Only light rays with constructive interference can travel in a slab waveguide stably: same phase or phase difference must be equal to m(2π), where m is an integer. Therefore, only a number of certain angles (i.e, θ in the figure below, of course, these angles have to meet the requirements for obtaining total reflection) can be obtained. These angles correspond to these certain angles, which form the optical modes. m is so-called optical mode number. 4

b:



The requirements for a stable light transmission (i.e., constructive interference):
Phase difference between A and C = integral number of 2π

$$\Delta\phi(AC) = k_1(AB+BC) - 2\phi = m(2\pi), \quad m = 0,1,2,\cdots \quad (1)$$

k_1 is the wavenumber, i.e., $k_1=(2\pi/\lambda)n_1$, 2 ϕ is phase change due to reflection, depending on angle θ

From the figure above

$$AB + BC = BC\cos(2\theta) + BC = BC[\cos(2\theta)+1] = BC[(2\cos^2\theta - 1)+1]$$

$$= \frac{d}{\cos\theta}[2\cos^2\theta] = 2d\cos\theta \qquad (2)$$

Combining equation 2 and equation 1, we have

$$k_1(2d\cos\theta) - 2\phi = m(2\pi) \qquad (3)$$

The θ has to be larger than the critical angle θ_m, allowing the total reflection to take place

Therefore, $\sin\theta \ge \sin\theta_m$

The total reflection requires: $\sin\theta_m = n_2/n_1$

Therefore, equation 3 can be modified:

$$m = \tfrac{1}{\pi}[\tfrac{2\pi d}{\lambda} n_1\cos\theta - \phi]$$
$$= \tfrac{1}{\pi}[\tfrac{2\pi d}{\lambda} n_1\sqrt{1-\sin^2\theta} - \phi]$$
$$\le \tfrac{1}{\pi}[\tfrac{2\pi d}{\lambda} n_1\sqrt{1-\sin^2\theta_m} - \phi]$$

8

Therefore, the largest m will be $m_{\max} = \tfrac{1}{\pi}[\tfrac{2\pi d}{\lambda}\sqrt{n_1^2 - n_2^2} - \phi]$

c: if ϕ is ignored,

$$m_{\max} = \tfrac{1}{\pi}[\tfrac{2\pi d}{\lambda}\sqrt{n_1^2-n_2^2}] = \tfrac{2d}{\lambda}\sqrt{n_1^2-n_2^2} = \tfrac{2\times85\times10^{-6}}{1.5\times10^{-6}}\sqrt{1.49^2-1.47^2} = 27.5 < 28$$

4

The maximum number of optical mode: 28+1=29 (including m=0).

d: You reduce the thickness of the core layer, i.e., reduce "d" . 4

3.

(i) Spontaneous emission: after electrons are exited from VB to CB, the electrons will fall back to the valence band quickly, and then emit photons with random phases and directions. 3

(ii) Stimulated emission: photons stimulate recombination between electrons and holes, and then the electrons will fall back to the valence band and thus emit photons with the same phase, direction and energy. 3

(iii) Population inversion: normally, the number of electrons in a system decreases exponentially with an increase in energy of the electronic states. However, under certain conditions, the number of the electrons at a high energy state can be higher than that at a low energy state. 3

b:

(i) The reflectivity of the uncoated facet: $R = (\frac{n_1-1}{n_1+1})^2 = (\frac{3.39-1}{3.39+1})^2 = 0.296$

It means that the mirror causes (1-0.296) of the light out of the cavity
For a 400 μm cavity, $\alpha_m = \frac{1}{2l}\ln\frac{1}{R_1 \times R_2}$ (here, R_1=R_2=0.296)
Therefore, $\alpha_m = \frac{1}{2\times400\times10^{-4}}\ln\frac{1}{0.296\times0.296}$, so that the mirror loss, α_m=30.4 cm^{-1} 4

(ii) $I_{th} \propto g_{th}$, where I_{th}: threshold current; and g_{th}: threshold gain
$g_{th} = \frac{1}{\Gamma}(\alpha_i + \frac{1}{2L}\ln\frac{1}{R_1R_2})$, where Γ: optical confinement factor; α_i : internal loss, 10cm^{-1}

For the as-cleaved facets, R_1=R_2=0.296 so that $g_{th} = \frac{1}{\Gamma}(10 + \frac{1}{2\times400\times10^{-4}}\ln\frac{1}{0.296\times0.296}) = 40.4/\Gamma$
For one coated facet, R_1=0.296 and R_2=0.8 so that $g_{th} = \frac{1}{\Gamma}(10 + \frac{1}{2\times400\times10^{-4}}\ln\frac{1}{0.296\times0.8}) = 28.0/\Gamma$ 4
Therefore, the percentage of the reduction in threshold current: $\frac{40.4/\Gamma - 28.0/\Gamma}{40.4/\Gamma} = 30.7\%$

(iii) You increase the reflectivity of the coated facet to 100%, such as using DBR, etc, or optimise the cavity length. 3

4.

a (i) Photocurrent gain: ratio of the carrier recombination time to the transit time of the carrier between two electrodes 2
(ii) length of photoconductor and mobilities of the carriers 2

b:

(i) If the applied voltage is not high

Electron Transit time: $t_{tr}^e = \frac{L^2}{\mu_e V} = \frac{(30\times10^{-4})}{7000\times4.5} = 2.857\times10^{-10}\,\text{sec}$ 3

Photocurrent gain: $g = \frac{\mu_e+\mu_h}{\mu_e}\frac{\tau}{t_{tr}^e} = (1+\frac{400}{7500})\frac{90\times10^{-9}}{2.857\times10^{-10}} = 331.8$

(ii)

3

At low applied bias, the drift velocity increases with increasing the applied bias, and thus the transit time decreases. Therefore, the photocurrent gain increases. However, when the applied bias is above the certain level, the electrons in the lower valley will be field-excited to the upper valley, where the effective mass of the electrons is heavier and the mobility decreases. Therefore, the drift velocity decreases, and the photocurrent gain decreases.

c:

(i) The quantum efficiency:

$(1-e^{-\alpha L})(1-R) = (1-e^{-1\times10^{4}\times1\times10^{-4}})(1-0.4) = 0.63\times0.6 = 37.9\%$ 3

(ii) You can increase the thickness of the active region or use anti-coating in order to minimise reflection. 3

d: (i) Photo-generated carriers in the depletion region travel at their saturation velocities. When they receive enough energy from the applied electrical field during such transit, an ionizing collision with lattice takes place. This collision process generates a large number of second electron-hole pairs, which drift in opposite direction, together with the primary carriers. This can repeat many times, generating a large number of electrons and holes. Therefore, a large gain can be obtained. 2

(ii) The performance of APD is limited by shot noise and excess noise. In addition, the ratio of α_e/α_h is required to be either zero or infinite, but the α_e/α_h is ~1 in most compound semiconductors. 2