ENGINEERING TRIPOS PART IIA 2004

Solutions to Module 3B6
Photonic Technology
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Cribs to Photonic Technology 3B6, 2004

Q.1 (a) Answers are primarily from bookwork

- LEDs generate light by spontaneous emission, so this should be described.

The answer should include a description of a typical Surface Emitting Light Emitting Diode structure, highlighting techniques that are used to minimise thermal effects and maximise efficiency

(b) $$P_{LED} = \frac{hc}{\lambda} \cdot \frac{I}{e} \cdot \eta_{int} \cdot \eta_{ext}$$

$$\Rightarrow V_{ref} = IR_s + V_f = \frac{P_{LED} \cdot \lambda \cdot e}{hc\,\eta_{int}\,\eta_{ext}} + \frac{hc}{e\lambda}$$

$$= \underline{1.39\,V}$$

(c) $$\eta_{int} = 1/\tau_{rr} / (1/\tau_{rr} + 1/\tau_{nr}) \Rightarrow \tau_{rr} = \frac{\tau_{nr}}{\eta_{int}}(1-\eta_{int})$$

$$\Rightarrow \tau_{rr} = \underline{2\,ns.}$$

$$\tau_s = 1/(1/\tau_{rr} + 1/\tau_{nr}) = \underline{1.2\,ns.}$$

(d) The answer should describe how the drive pulse is modified with a positive spike at the start and a negative spike at the pulse end to enhance modulation response.

Q. 2(d) This is mainly a bookwork section and answers should show how mesa, ridge or buried heterostructure devices all provide improved performance.

3(a) Bookwork but to include

	Free space	Guided wave
Pros	Unregulated EM spectrum High data rates cf. radio Low physical infrastructure levels	Low attenuation (>100 km links possible) High data rates (>10 Gb/s) Compact + light cables Immune to EMI Flexible cabling architectures
Cons	Atmospheric variations in channel Short (<1km) link lengths Accurate tracking or pointing required	Relatively poor source efficiency Fibres not mechanically robust Difficult to use spectrally efficient modulation formats (OOK almost universally used

(b) (i) Bookwork

(ii) $V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$

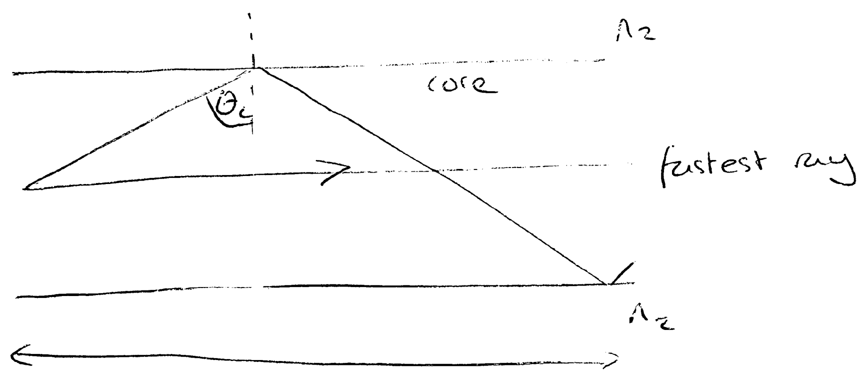
$= \frac{2\pi \; 50\times10^{-6}}{1.3\times10^{-6}}\sqrt{1.458^2 - 1.450^2} = 36.86$

Note $V \gg 2.4 \Rightarrow$ fibre is heavily multi-moded

No. of modes $N \approx \frac{V^2}{2} = \frac{36.86^2}{2} = 679$

(iii) Bookwork but should include discussion of chromatic, waveguide + inter-modal dispersion. Inter-modal dispersion is by far the biggest contributor to dispersion in step index MMF. It is therefore safe to assume that chromatic + waveguide effects can be ignored.

Inter-modal dispersion



Critical angle given by

$$\sin\theta_c = \frac{n_2}{n_1} \quad \text{(Snell's Law)}$$

Fastest ray takes time t_{min} to traverse L

$$t_{min} = \frac{L n_1}{c}$$

Slowest ray takes

$$t_{max} = \frac{L n_1}{c \sin\theta_c} = \frac{L n_1^2}{c n_2}$$

Difference between fastest & slowest rays

$$\Delta t = t_{max} - t_{min}$$

$$= \frac{L n_1^2}{c n_2} - \frac{L n_1}{c}$$

$$\text{Dispersion} = \frac{\Delta t}{L} = \frac{n_1}{c}\left(\frac{n_1}{n_2} - 1\right) = \frac{n_1}{c n_2}(n_1 - n_2)$$

$$= \frac{1.458}{3\times10^8 \times 1.450}(1.458 - 1.450)$$

$$= 26.8 \text{ ps/m} \quad \text{or} \quad 26.8 \text{ ns/km}$$

(iv) $t_{out}^2 = t_{in}^2 + \Delta t^2$

So for 1.25 Gb/s, $t_{in} = \frac{1}{1.25\times10^9} = 0.8\text{ ns}$

$t_{out} = 1.5\, t_{in} = 1.2\text{ ns}$

$\Rightarrow \Delta t^2 = t_{out}^2 - t_{in}^2 = 1.2^2 - 0.8^2 = 0.8\text{ ns}^2$

$\Delta t = \sqrt{0.8} = 0.894\text{ ns}$

$\Delta t = \text{dispersion} \times L_{max}$

$\Rightarrow L_{max} = \frac{\Delta t}{\text{dispersion}} = \frac{0.894\text{ ns}}{26.8\text{ ns/km}}$

$= 0.0334\text{ km}$ or 33.4 m

(c) You could use single mode fibre but the most common technique for these distances would be to use graded index multimode fibre. Dispersion of order < 1ns/km are possible, allowing 550m lengths to be achieved.

4(a) Bookwork but to include descriptions of quantum, thermal and shot noise terms

(b) (i) Photocurrent I_{ph} for given input power P

$$I_{ph} = \eta \frac{e\lambda}{hc} P$$

Responsivity $R = \frac{I_{ph}}{P} = \frac{\eta e \lambda}{hc}$

$$= \frac{0.9 \times 1.602\times10^{-19} \times 1535\times10^{-9}}{6.62\times10^{-34} \times 3\times10^{8}}$$

$= 1.114$ A/W $= 1.11$ A/W (3s.f.)

(ii) For given pulse energy E

No of photogenerated electrons $N = \frac{\eta \lambda E}{hc}$

For quantum limited sensitivity, assume prob. density function for electrons is Poisson

$P(N|S) = \exp(-S) \frac{S^N}{N!}$ where $P(N|S)$ is prob. of N electrons being generated from S photons

Assume that if one electron (or more) is detected, bit is received as a "1"

$$\text{Prob Error} = \frac{1}{2}\left(P(0|S) + \underbrace{P(1|0)}_{\text{if no other noise} \Rightarrow = 0} \right)$$

$$= \frac{1}{2} \exp(-S) \frac{S^0}{0!} = 10^{-12}$$

$\Rightarrow \exp(-S) = 2\times10^{-12}$

$\Rightarrow S = 27$ photons / bit

So quantum limited sensitivity can be calculated as follows

Assume half the bits in a stream are "1"s & half "0"s

Average no. of photons/sec @ 27 photons/bit

$= 0.5 \times 10^9 \times 27 = 135 \times 10^9$ photons/sec

Quantum limited sensitivity $= 135 \times 10^9$ photons/s $\times \frac{hc}{\lambda}$

$= 135 \times 10^9 \times 6.62 \times 10^{-34} \times \frac{3 \times 10^8}{1535 \times 10^{-9}}$

$= 17.5$ nW

$= -47.6$ dBm

(iii) $SNR = \dfrac{\left(\frac{\eta e \lambda}{hc} P_{sig}\right)^2}{\left[\underbrace{2e\left(\frac{\eta e \lambda}{hc} P_{sig} + I_d\right)}_{\text{shot noise}} + \underbrace{\frac{4kT}{Z}}_{\text{thermal noise}}\right] B}$ ← (sig current)^2

$= \dfrac{(R P_{sig})^2}{\left[2e(R P_{sig} + I_d) + \frac{4kT}{Z}\right] B}$ Z = load impedance

$= \dfrac{(1.114 \times 4 \times 10^{-6})^2}{\left(1.602 \times 10^{-19}(1.114 \times 4 \times 10^{-6} + 0.5 \times 10^{-9}) + \frac{4 \times 1.38 \times 10^{-23} \times 298}{10^3}\right) 10^{10}}$

this term dominated.

$= 111.1$

$= 20.5$ dB

(c) (i) Bookwork

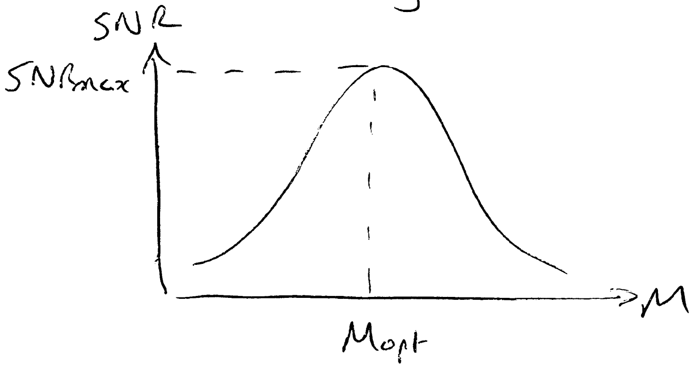
(iii) SNR for APD $= \dfrac{M^2 (R P_{sig})^2}{\left[2eM^{2+x}(RP + I_d) + \frac{4kT}{Z}\right] B}$

signal power increased by M^2

shot noise increased by M^{2+x} - dominates for high M

thermal noise unchanged.

By inspection, the SNR v. M curve will look something like



Can find Mopt (+ ∴ SNR max) by finding $\dfrac{d(SNR)}{dM}$ and setting $= 0$