Prof I H White

Photonic Technology Paper 3B6

2008 Examination Cribs

Q1 (a) This is primarily a bookwork section. Good answers could:

(i) Describe the similarities and differences in device structures.
(ii) Explain the range of materials that can be used in the different types of device (as a result of their different operational requirements), their relative ease of manufacturing, and hence their different costs.
(iii) LED emission is primarily spontaneous whereas laser emission is primarily stimulated.
(iv) Compare the main performance characteristics relating to the optical emission of the devices, such as (i) maximum output power, (ii) device efficiency and typical drive requirements, (iii) spectral performance, (iv) dynamic modulation performance, (v) temperature performance and (vi) aging.
(v) Compare and contrast the different applications that the devices take.

(b) This is primarily a bookwork section, where detailed answers are expected. Good answers should include:

(i) An overall explanation of the use of a pn junction at which stimulated emission occurs (comments would be expected as to why localisation does occur at the junction). The positioning of contacts should be described.
(ii) Comments should be made on the choice of laser materials, indicating the need for direct bandgap materials.
(iii) Diagrams and an explanation of the use of cleaved facets to allow optical feedback necessary for lasing to be achieved. Comments would be expected as to the reflectivity for typical semiconductor materials, and the potential enhancement by appropriate coatings.
(iv) A detailed description and diagram should be provided concerning the use of epitaxial semiconductor heterostructures to confine light and carriers between contacts.
(v) Finally, good answers should indicate how stripes, ridges, mesas or buried heterostructures can be used to confine light and carriers in the transverse direction, hence enhancing the device. Advantages and disadvantages of the different techniques might be provided.
(vi) A rounded answer should then give examples of some of the device dimensions and performance characteristics of an efficient device.

(c) Assume that the laser turns on once the carrier concentration reaches threshold. Before threshold, therefore, it can be assumed that stimulated emission is absent. Using the electron rate equation for operation below threshold, the charge concentration in the active region is

$$dn/dt = I/eV - n/\tau_s$$

$$(\text{as } g(n - n_o)P = 0 \text{ as } P = 0)$$

The response to a step function input current is:

$$\text{CF: } dn/dt + n/\tau_s = 0 \Rightarrow dn/n = -dt/\tau_s \Rightarrow n = A\exp\{-t/\tau_s\}$$

$$\text{PI: } n = \tau_s I/eV$$

As a result, $n = A\exp\{-t/\tau_s\} + \tau_s I/eV$

However, $n = 0$ at $t = 0$, $n = (\tau s I/eV)(1-\exp\{-t/\tau s\})$

Assuming that lasing emission occurs after a delay time t_d, the charge (at that time) must be given by $n(t_d) = I_{th}\tau_s / eV$

$$n = n_{th} = I_{th}\tau_s / eV = (\tau_s I/eV)(1-\exp\{-t_d/\tau_s\}) \quad \text{(A)}$$

$$\Rightarrow t_d = \tau_s \ln [I/(I-I_{th})]$$

Manipulating (A), $I = I_{th}/(1-\exp\{-t_d/\tau_s\})$

For a delay of 2 ns, $I = 10/(1-\exp\{-2/3\}) = 20.5$ mA

(d) $P = hc/\lambda \times \eta_D \times (I - I_{th})/e = 8$ mW (i.e. 4 mW per facet)

Q2 (a) A good answer should include descriptions of the three major types of electron/photon interactions in materials, including diagrams to assist in explanations.

- **Spontaneous Emission**

  An electron in a high energy level falls, losing energy which is emitted predominately as a photon. This is the basis of operation of a light emitting diode.

- **Stimulated Absorption**

  An incident photon is absorbed in a material, causing the excitation of an electron to a higher energy level. This is the basis of operation of a photodiode.

- **Stimulated Emission**

  A photon, incident upon an electron in a higher energy level, causes the electron to fall to a lower level thus generating a second photon. This is, therefore, an amplifying action. Two photons are generated from one and, in turn, they can cause the generation of two further photons. Using this method, high optical powers can be generated and this operation is the basis of lasing action. The generated photon has the same frequency and phase as the incident photon and, therefore, very pure monochromatic and coherent light is generated.

Some answers may include comments on the role of phonons in the efficiency of each mechanism and the resulting dependence of the interactions on material structure.

(b) A good answer should state that the rate equations make the following assumptions:

(i) the carrier, photon and current densities are constant in the diode laser throughout its volume,
(ii) that the laser generates purely monochromatic light in one mode,
(iii) that the amplification of light by stimulated emission is linear with carrier concentration and,
(iv) that temperature effects are negligible.

The variables have the following meaning: n is the carrier concentration in the laser, P is the photon density in the lasing mode, g is a gain constant, n_o is the transparency carrier density (where gain = loss), τ_s is the spontaneous recombination time of carriers, τ_p is the photon lifetime in the cavity (i.e. the effective time for which the photon remains in the cavity after generation before either leaving or being reabsorbed), β is the coupling coefficient (the ratio of spontaneous emission at the lasing wavelength to that generated totally), V is the laser active region volume, e is the electronic charge and I is the laser current.

In terms of the electron rate equation:

$$\frac{dn}{dt} = -\frac{n}{\tau_s} + \frac{I}{eV} - g(n - n_o)P$$

The LHS of the equation concerns the net rate of change of carrier concentration. The RHS has the following terms in order: (i) spontaneous emission, which causes a depletion of carriers per unit time), (ii) current injection (which causes an increase in carrier concentration), and (iii) net stimulated emission and absorption which causes carrier depletion and enhancement respectively.

$$\frac{dP}{dt} = g(n - n_o)P + \beta\frac{n}{\tau_s} - \frac{P}{\tau_p}$$

The LHS of the equation concerns the net rate of change of photon density of the lasing mode. The RHS has the following terms in order: (i) stimulated emission, which causes a growth in photon density, (ii) spontaneous emission (which causes an increase in photon density, but which is diluted by the spectral overlap of the stimulated and spontaneous emission), and (iii) loss of photons from facets and through scattering, as defined by a lifetime.

A good answer will give a detailed explanation of each term.

(c) Assume that the laser is in steady state, dn/dt = dP/dt = 0 and assume that β is very small.

Below threshold, when P = 0 (there is no lasing light generated), the electron rate equation becomes simply

$$0 = -n/\tau_s + I/eV$$

$$=> \quad n = I\tau_s/eV$$

so that the overall operation of the laser can be understood. The carrier concentration in the laser increases linearly with current until threshold, when it saturates to a constant value.

$$(=> I_{th} = eVn_{th}/\tau_s)$$

Rewriting the photon rate equation,

$$0 = g(n - n_o)P - P/\tau_p$$

$$=> \quad P\{g(n - n_o) - 1/\tau_p\} = 0$$

As P may have values greater than 0 (and not less!),

$$g(n - n_o) - 1/\tau_p = 0$$

$$=> n = n_o + 1/(g\tau_p)$$

However all the terms on the right hand side of the equation are constants. Maintaining a steady state for all values of lasing photon density greater than zero, the carrier constant in the laser is constant. Let this value be called the threshold carrier density, n_{th}.

$$=> I_{th} = (eV/\tau_s).(n_o + 1/g\tau_p)$$

Considering the electron rate equation,

$$0 = -g(n - n_o)P - n/\tau_s + I/eV$$

But $n = n_{th}$ for all P>0, so in this regime,

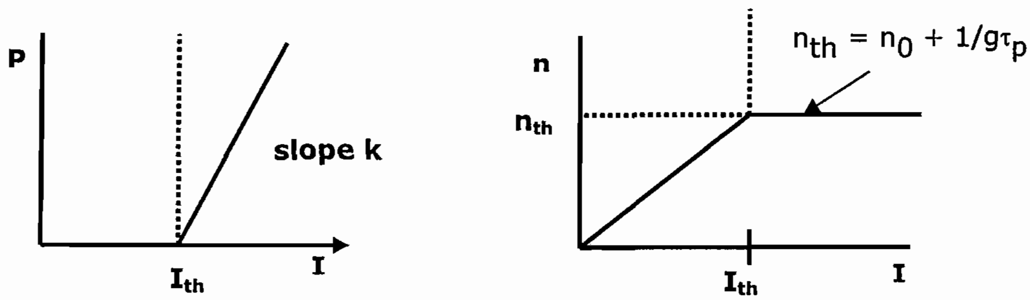
$$P = \frac{\{I/eV - n_{th}/\tau_s\}}{g(n - n_o)}$$

Letting $I_{th} = eVn_{th}/\tau_s$,

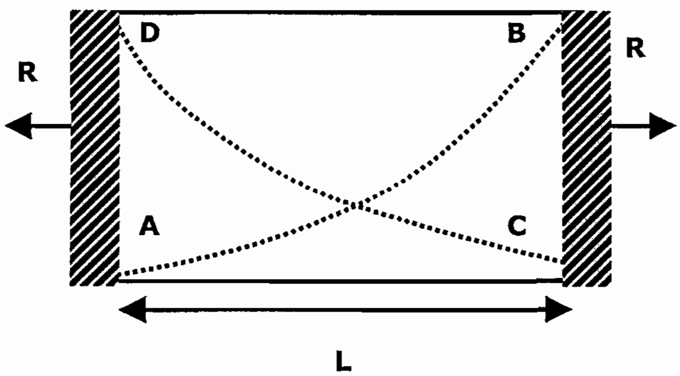
$$=> \quad P = \frac{\{I - I_{th}\}}{eV\,g(n_{th} - n_o)} = k(I - I_{th})$$

where the slope $\quad k = 1/eVg(n_{th} - n_o)$

As a result the optical power generated by the laser may be shown to be proportional to the current above the threshold current. Below lasing, no stimulated emission is emitted but above, the light increases linearly with current.



(d)



Considering the lasing mode as it propagates along a laser cavity, assume that stimulated emission encounters a gain per unit length (due to stimulated amplification), G, and a loss per unit length due to scattering and absorption, α, as it passes along the laser. The gain G in practice creates extra photons to compensate for those photons lost as the signal travels over a distance of unit length.

Therefore the stimulated light A starting at one facet will be incident on the opposite facet with an optical power

$$B = \exp\{(G - \alpha)L\}\ A$$

At that point part of the signal is reflected with a coefficient R and the signal then passes back amplified by 1 the same amount as above and again reflected by the initial facet. Lasing action will occur in the net round trip gain of the signal is unity i.e. if

$$A.\ \exp\{(G - \alpha)L\}.R\exp\{(G - \alpha)L\}.R = A$$

$$=> \ G = \alpha + (1/L)\ln(1/(R))$$

This value of G is equal to the ratio of photons lost as the signal travels a unit length. The light output from the laser is therefore equivalent to a loss per unit length of

$$(1/L)\ln(1/(R)).$$

As a result the proportion of photons leaving the cavity per unit time is given by

$$(1/L)\ln(1/(R))v_g$$

so that the output power, P_{out}, is given by,

$$P_{out} = (1/2)(hc/\lambda)PV\ \ (v_g/L)\ln(1/(R))$$

$$=> \qquad P_{out} = \frac{hcPVv_g \ln(1/R)}{2\lambda L}$$

Q3 (a) Mainly a bookwork question. A good answer would include:

- a diagram of the photodiode
- a discussion of the transport types (diffusion, drift) as well as the other main speed limiting process (capacitance)
- the effect of the depletion region width and the absorption profile
- a statement that the depletion region width depends on doping and applied bias
- a comment on the trade off of narrow depletion region (high capacitance) and wide (low capacitance but long drift time)

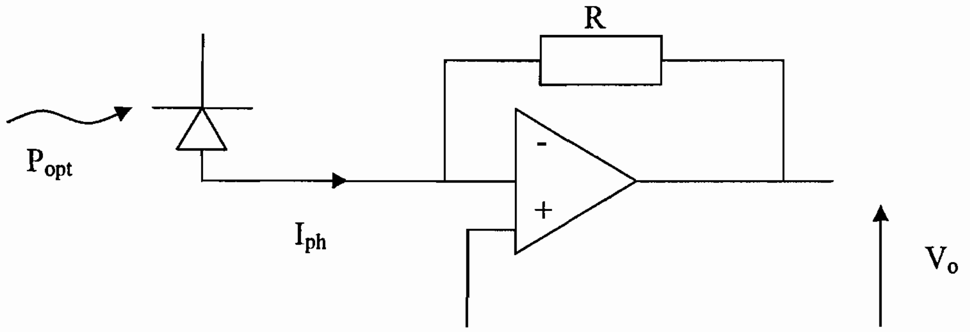
(b) Mainly bookwork. Ideally explanation would include equation for SNR for an APD detected photosignal

$$\text{ie } SNR = \frac{I_{ph}{}^2 M^2}{2e(I_{ph} + I_d)M^{2+x}B + \dfrac{4kTB}{R}}$$

As M is increased, the thermal noise power remains constant as the signal and shot noise powers increase. As for M = 1, thermal noise is the dominant process, the SNR will initially rise before falling for high values of M as the shot noise dominates (NB the excess noise factor x)

(c) M = 30, η = 0.85, Id = 0.8 nA, x = 0.5, R = 1 kΩ, B = 2 GHz, λ = 1550 nm, T = 20°C = 293 K

(i)



$V_o = - I_{ph}R$

$$= -M\eta\frac{e\lambda P_{opt}M}{hc}R$$

$$\frac{V_0}{P_{opt}} = -\frac{M\eta e\lambda R}{hc}$$

$$= -\frac{300.85x1.602x10^{-19}x1.55x10^{-6}x10^3}{6.63x10^{-34}x3x10^8}$$

= - 31.8 kV/W

(ii) Bookwork - main noise processes are:
- shot noise due to photocurrent and dark current in the photodetector (plus avalanche excess noise if APD as here)
- thermal noise in resistors (eg load resistor and amplifier input impedance)

(iii) Quantum limited receiver error rate is dominated by Poisson statistics.

Assume average energy per pulse E

Average number of photocarriers per pulse

$$N = \frac{M\eta\lambda}{hc}E$$

Poisson distribution - probability of k carriers photogenerated given average carrier number N

P(k/N) = exp (-N). N^k/K!

Probability error

P.E. = 0.5 {P(0/1) + P(1/0)}

NB assume half of the bits are "zero" and half "one" and that P(1/0) = 0

P.E. = 0.5 exp (-N).N^0/0!

= 0.5 exp (-N)

= 10^{-10}

Rearranging

exp (-N) = 2 x 10^{-10}

N = - ln (2 x 10^{-10})

= 22.33 photocarriers

NB this is the average number - should not be rounded

=> $E = \frac{hc}{M\eta\lambda}N$ (energy of "1" pulse to achieve this average number)

$$= \frac{6.63x10^{-34}x3x10^{8}}{30x0.85x1.55x10^{-6}}x22.33$$

= 1.123 x 10^{-19}J

Assuming equal numbers of "1" and "0" => 1.25 x 10^9 "1" pulse/s

=> P_{sens} = 1.123 x 10^{-19} x 1.25x 10^9

= 0.140 nW

(iv) Assuming negligible thermal noise

$$SNR = \frac{I_{ph}{}^2 M^2}{2e(I_{ph} + I_d)BM^{2+x}}$$

23 dB = 200

$$\Rightarrow 30^2 I_{ph}{}^2 = 400\ e\ (I_{ph} + I_d)\ B\ 30^{2-5}$$

$$I_{ph}{}^2 - 400e(I_{ph} + I_d)B30^{0.5} = 0$$

$$I_{ph}{}^2 - 30^{0.5} x400x1.6x10^{-19} x2x10^9 I_{ph} - 30^{0.5} x400x1.6x10^{-19} x2x10^9 x0.8x10^{-9} = 0$$

$$I^2{}_{ph} - 7.02x10^{-7} I_{ph} - 5.62x10^{-16} = 0$$

$$I_{ph} = \frac{7.02x10^{-7} \pm \sqrt{(7.02x10^{-7})^2 + 4x5.62x1.023x10^{-16}}}{2}$$

$= 0.73\mu A$

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

$$\Rightarrow P_{opt} = \frac{hc}{\eta e\lambda} I_{ph}$$

$$= \frac{6.63x10^{-34} x3x10^8 x0.73x10^{-6}}{0.85x1.602x10^{-19} x1.55x10^{-6}} = 0.69\mu W$$

Q4 (a) Bookwork. Dispersion and attenuation.

Dispersion should include dispersion plot (zero dispersion at 1300 nm)

Attenuation should give attenuation curve - with labelled features (minimum attenuation at ~ 1550 nm)

(b) Bit period $T = 10$ ns

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

$$= \frac{L}{c}\frac{n_1}{n_2}(n_1 - n_2) \quad \text{(can be quoted or derived)}$$

so $$\frac{\Delta t}{L} = \frac{1}{3x10^8}\frac{1.50}{1.49}(1.50 - 1.49)$$

= 33.57 ps/m

(33.57 ns/km)

Pulse broadening t_{in} = 10 ns

t_{out} =1.25 x 10 ns = 12.5 ns

t_{disp} = 33.57 x L ns (NB L in km)

$t_{out}^2 = t_{in}^2 + t_{disp}^2$

$t_{disp}^2 = t_{out}^2 - t_{in}^2 = 12.5^2 - 10^2 = 56.25\ ns^2$

t_{disp} = 7.5 ns = 33.57 x L

=> L = 7.5 ÷33.57 = 223 m

The link length could be extended by using a smaller index step or (more likely) graded index fibre.

(c) Normalised frequency V $$= \frac{2\pi a}{\lambda}\left(n_1^2 - n_2^2\right)^{1/2}$$

= 2.4 for single mode

a = radius = 5 μm

$$(n_1^2 - n_2^2)^{½} = \frac{V\lambda}{2\pi a} = \frac{2.4x1.55}{2\pi x5}$$

= 0.118

$$\Rightarrow \quad n_1^2 - n_2^2 = 0.01402$$

$$n_2^2 = n_1^2 - 0.01402$$

$$= 2.2359$$

$$n_2 = 1.4953$$

(d)

Transmit power		+ 3 dBm
Losses	Coupling	-4dB
	Attenuation (120 x 0.15)	-18 dB
	Connectors (2 x 0.5)	-1 dB
	Splices (4 x 0.25)	-1 dB
Margin		M dB
Sensitivity		-25 dBm

Power budget = Transmit power - sensitivity

= 28 dB

Power budget = Losses plus margin

= 24 dB + M dB

Margin M = 4 dB

(e) The use of WDM would enable this. To obtain full marks, the answer should include a diagram of a WDM link. A very good answer would include a discussion of the trade-off between the number of WDM channels and channel bandwidth. Sensible granularity would be 40λ x 10 Gb/s or 10λ x 40 Gb/s.