OLLSCOIL NA hÉIREANN, CORCAIGH
THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2005

B.E. DEGREE (ELECTRICAL)
HIGHER DIPLOMA IN PHYSICS

OPTICAL ELECTRONICS
EE4007

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Time Allowed: *3 hours*

FIVE QUESTIONS TO BE ANSWERED, AT LEAST TWO FROM EACH SECTION.
USE SEPARATE ANSWER BOOKS FOR EACH SECTION

The use of a Casio fx570w or fx570ms calculator is permitted.
The use of Log Tables and Graph paper are permitted.

Physical Constants:

Free electron mass, m_0 = 9×10^{-31} kg
Planck's constant, h = 6.626×10^{-34} J s
Electronic charge, q = 1.602×10^{-19} C
Boltzmann's constant, k_B = 1.38×10^{-23} J K^{-1}
Room temperature = 300 K
Speed of light in free space, c = 3×10^{8} m s^{-1}

SECTION A

1. (a) Describe the main characteristics of the radiation emerging from a laser as the laser medium is pumped from below to above threshold.

[4 *marks*]

(b) By making the assumption that the amplitude of a circulating wave within an optical cavity of length L settles down to a steady state value, show that the threshold population inversion density can be written in the form:

$$\left(N_2 - N_1\right)_{th.} = \frac{8\pi\nu^2\Delta\nu}{c^2} t_{spon}\left\{\alpha + \frac{1}{L}\ln\left(R_1R_2\right)^{-\frac{1}{2}}\right\},$$

where ν is the frequency of the circulating wave, $\Delta\nu$ is the transition line-width, t_{spon} is the spontaneous decay time constant of the upper laser level, R_1 and R_2 are the mirror reflectivities and α is a distributed loss coefficient. (Assume that the gain medium has a refractive index of unity and that it fills the optical cavity).

[*8 marks*]

(c) If one includes the phase shift incurred in a round trip, show that the longitudinal mode frequencies are given by the equation:

$$\nu_m = \frac{mc}{2L},$$

where m is an integer.

[4 *marks*]

(d) A He-Ne laser operating at 0.6328 μm has a cavity length (L) of 0.4 m. The mirror reflectivities R_1 and R_2 are 99.9% and 98%, respectively. The transition line-width ($\Delta\nu$) is 1.5 *GHz* and the spontaneous decay time constant (t_{spon}) is 0.3 μs. What is (i) the threshold population inversion density and (ii) the threshold gain coefficient?

(Neglect any distributed loss)

[4 *marks*]

2. By considering the process of amplification in an inverted medium, show that the intensity (I_ν) of an electromagnetic wave on traversing a slab of the medium of thickness dz will grow in intensity according to:

$$\frac{dI_\nu}{dz} = \gamma(\nu)I_\nu,$$

where ν denotes the frequency and $\gamma(\nu)$ is the gain coefficient. Show that $\gamma(\nu)$ is proportional to the population inversion and determine the proportionality factor.

[6 *marks*]

Consider the ideal laser medium shown in Fig.2 below. The pump excites atoms to the upper laser state 2 at a rate R_2; the lifetime in state 2 is $\tau_2 = 65ns$. Atoms in state 1, the lower laser level, decay back to state 0 so fast that the approximation $N_1 \approx 0$ is appropriate. The spontaneous lifetime for $2 \rightarrow 1$ transitions is $t_{spon} = 0.17 \mu s$ and its line-width is $\Delta \nu = 10 GHz$.

Assuming steady state:

(a) What is the stimulated emission cross-section? [4 *marks*]

(b) What must be the pump rate R_2 in order to achieve a small signal gain coefficient of 0.01 per cm of length? [4 *marks*]

(c) How much power (in W / cm^3) is expended in creating the gain coefficient in (b) above? [6 *marks*]

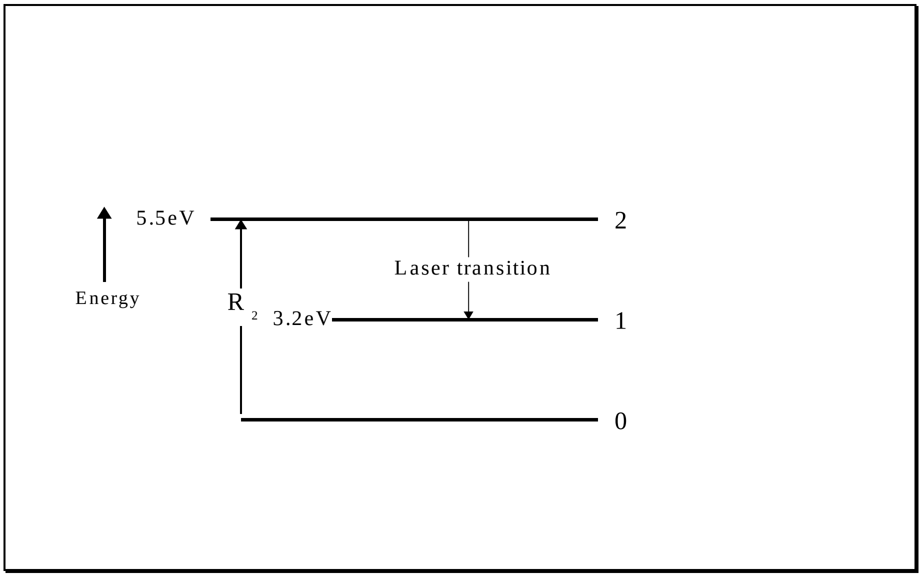

Fig.2

3. (a) Two spherical mirrors with radii of curvature 1m and 2.5m are available to form an optical cavity. Find the range of values of mirror separation *L*, which will make the cavity:

- Stable
- Marginally stable
- Unstable

[*6 marks*]

(b) A carbon dioxide laser ($\lambda = 10.6\mu m$) employs an optical resonator using a spherical and a flat mirror. The fundamental Gaussian beam emerges from the resonator through the flat mirror with a beam diameter of 4 mm ($1/e^2$ intensity points). The beam encounters a thin convex lens of focal length 0.3m placed a distance of 1m from the flat mirror. Determine the beam waist diameter of the focused beam at the other side of the lens and its location relative to the lens position.

[*8 marks*]

(c) A circular aperture of 1mm diameter is placed at the exact focused position of the beam in (b) above. What fraction of the incident power is coupled through this aperture?

[6 *marks*]

4. Outline the Q-switching technique as applied to laser systems and describe at least three different Q-switching methods. [5 *marks*]

A Ruby rod for a Q-switched laser ($\lambda = 0.6943 \mu m$) is 10 cm long and 3mm radius, and is placed in an optical cavity with mirrors having negligible absorption losses and the cavity lifetime is 6.14 ns. The Cr^{3+} doping density is 1.6×10^{19} atoms cm^{-3} and the stimulated emission cross-section is $1.3 \times 10^{-20} cm^{2}$. The pumping agent creates an initial population of 10^{19} atoms cm^{-3} in the upper laser state. Assume that the pumping occurs by virtue of absorption at $\lambda = 0.45 \mu m$, and that 100% of the atoms pumped to higher states relax to state 2. The spontaneous lifetime of state 2 is 3ms.

(a) How much spontaneous power does the ruby crystal radiate before the Q-switch is opened? [3 *marks*]
(b) How much pump power is required to maintain the population in state 2 at 10^{19} atoms cm^{-3}? [3 *marks*]
(c) What is the peak output power of the Q-switched pulse? [3 *marks*]
(d) How much energy is contained in the output pulse? (Assume that the energy extraction efficiency is 90%) [3 *marks*]
(e) Estimate the duration of the output pulse. [3 *marks*]

SECTION B

5. (a) Calculate the reflectance at normal incidence for a ray of light striking a plane glass surface. (refractive index for air = 1, glass = 1.5). What is the value of the reflection coefficient? [*4 marks*]

   (b) What is meant by s-polarisation and p-polarisation? [*4 marks*]

   (c) What is the Brewster angle? What value is the Brewster angle for the air/glass interface? [*4 marks*]

   (d) If air/glass/air were used to form a symmetric slab waveguide, what thickness should the glass be to guarantee single mode operation at a wavelength of 650 nm? [*4 marks*]

   (e) What is the critical angle for the waveguide described in part (d)? [*4 marks*]

6. (a) Draw the simplified band diagram for Silicon and GaAs. Label the Γ, X and L valleys, the heavy-hole band, the light-hole band and the split-off band. [*4 marks*]

   (b) Outline three advantages of III-V semiconductors over silicon in the design and fabrication of light emitting diodes. [*6 marks*]

   (c) A single quantum well double heterostructure laser diode is to operate at λ = 855 nm. The quantum well is infinitely deep and the well material has a bandgap energy of 1.2 eV. If the electron effective mass and the heavy-hole effective mass were both one tenth of the free electron mass, what width should the quantum well be to provide the required emission wavelength? [*10 marks*]

7. (a) Draw and label a block-diagram representation of a broadcast optical communication system. [*4 marks*]

   (b) Explain the following terms:

      i. Modal distortion
      ii. Polarisation mode dispersion
      iii. Bit-error rate
      iv. Fibre attenuation
      v. Link margin

   [*5 marks*]

   (c) A semiconductor laser operating at 1.55 μm is used in a digital optical communications network. If the average power from the laser is 5 dBm and the data rate is 10 Gb/s, how many photons are there per bit of information? [*6 marks*]

   (d) To increase the maximum length of a fibre optic link, is it more advantageous to use a lower loss fibre, use a more powerful transmitter or a more sensitive receiver? Justify your answer. [*5 marks*]

8. (a) What is meant by the term *internal quantum efficiency* in the context of semiconductor photodiodes? [*4 marks*]

(b) A particular photodiode has a responsivity of 0.5 A/W at 633 nm. What is its quantum efficiency at this wavelength? [*5 marks*]

(c) A silicon p-i-n photodiode is illuminated by 75 nW of light having a wavelength of 800 nm. The quantum efficiency of the device is 68% and its dark current is considered negligible. Calculate the *rms* photocurrent and the *rms* shot noise current if the bandwidth is 8 MHz. [*11 marks*]