

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

COLÁISTE NA hOLLSCOILE, CORCAIGH  
UNIVERSITY COLLEGE, CORK

---

**AUTUMN EXAMINATIONS, 2004**

---

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

OPTICAL ELECTRONICS  
EE4007

Professor G.W. Irwin  
Professor P.J. Murphy  
Dr. S.L. Prunty  
Dr. A.P. Morrison

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,  $m_0 = 9 \times 10^{-31}$  kg

Planck's constant,  $h = 6.626 \times 10^{-34}$  J s

Electronic charge,  $q = 1.602 \times 10^{-19}$  C

Boltzmann's constant,  $k_B = 1.38 \times 10^{-23}$  J K<sup>-1</sup>

Room temperature = 300 K

Speed of light in free space,  $c = 3 \times 10^8$  m s<sup>-1</sup>

## SECTION A

1. (a) A power meter and optical spectrometer are employed to monitor the output of a laser. Describe in detail the main characteristics of the emerging radiation recorded by both instruments as the laser medium is pumped from below to above threshold. [8 marks]
- (b) The laser system shown schematically in Figure 1 below operates at a wavelength of  $0.4\mu\text{m}$ . Only state 2 (the upper laser level) is pumped directly from the ground state (0 state) with a pump rate  $R_2$  ( $\text{cm}^{-3} \text{s}^{-1}$ ). The upper laser level has a lifetime  $\tau_2 = 0.2\mu\text{s}$  and a spontaneous emission rate to state 1 (lower laser level) of  $10^6 \text{s}^{-1}$ . Atoms in state 1 have a lifetime of 50 ns. The transition line width is 60 GHz and the laser medium fills the optical cavity in the manner shown. Assuming steady state conditions:
- i. What is the stimulated emission cross-section at line centre? [3 marks]
  - ii. What is the threshold gain coefficient? (Use the mirror reflectivity values shown in Figure 1 below). [3 marks]
  - iii. What is the pump rate  $R_2$  that brings the laser to threshold? [3 marks]
  - iv. What is the cavity lifetime? [3 marks]

(Assume the refractive index of the active laser medium is unity).

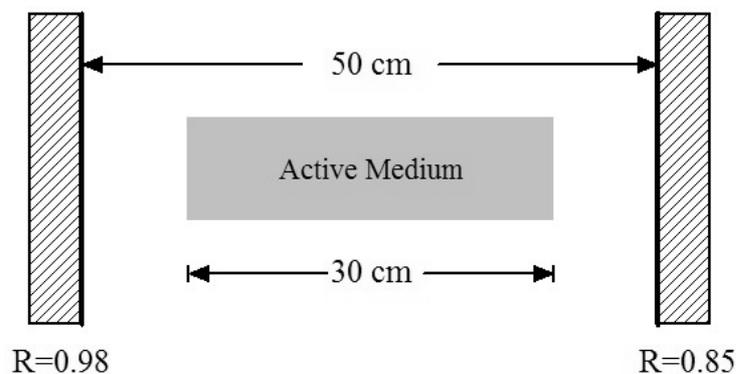


Figure 1: Schematic of laser system showing mirror reflectivity values

2. (a) Derive an expression for the cavity lifetime ( $\tau_c$ ) and indicate its significance in the context of laser systems. [6 marks]
- (b) A helium-neon laser ( $\lambda=0.63 \mu\text{m}$ ) operating in the fundamental Gaussian mode has mirrors separated by 0.3 m. The transition line-width  $\Delta\nu=1.5 \text{ GHz}$  and the effective refractive index of the gain medium is 1. Assume that the gain medium fills the optical cavity. The output mirror is flat and the other mirror is spherical with a radius of curvature of 17 m. The reflection coefficient of the spherical mirror is 1 and the flat output coupling mirror has a reflectivity of 0.98. The spontaneous lifetime of the optical transition is  $10^{-7} \text{ s}$ .

- i. What is the frequency difference between longitudinal modes in the optical resonator? [2 marks]
- ii. Show that the resonator is stable. [2 marks]
- iii. What is the threshold gain coefficient in  $\text{cm}^{-1}$ ? [2 marks]
- iv. What is the stimulated emission cross-section? [2 marks]
- v. What is the spot size on the flat mirror? [3 marks]
- vi. What is the Gaussian beam diameter at a distance of 20 m from the output mirror? [3 marks]
3. (a) Write the two fundamental equations for Gaussian beam propagation in free space, and derive an expression for the beam size at either mirror of the confocal resonator in terms of the wavelength and the mirror separation. [8 marks]
- (b) Given two mirrors of radius of curvature 1 m and 1.5 m, find the range of values of mirror separation  $L$ , which will make a stable cavity. [6 marks]
- (c) A Gaussian beam from laser operating at  $1.06 \mu\text{m}$  wavelength is focused with a 0.5 m focal length convex lens. The beam emerges from the laser with a beam waist (defined at the  $1/e^2$  points of the intensity profile) diameter of 3 mm and the lens is 1 m from the position of the waist. Calculate the exact location of the focused spot (to the nearest mm) and its size relative to the lens position. [6 marks]
4. (a) The Q-switching technique as applied to laser systems is capable of generating very large peak output powers. Give an outline of the technique and describe two typical Q-switching methods. [5 marks]
- (b) A laser at  $\lambda = 1 \mu\text{m}$ , which is to be Q-switched, has an initial population inversion at  $10^{18}$  atoms, a factor of 5 above the threshold value required for continuous wave (CW) oscillation in a high Q-cavity. The dominant photon loss within the cavity is coupling through one mirror to the outside world at a rate of  $5 \times 10^7 \text{ s}^{-1}$ . The population inversion after the Q-switched pulse is over is  $6 \times 10^{16}$  atoms.
- i. Find the peak power output of the laser. [5 marks]
- ii. Find the output energy in the Q-switched pulse. [5 marks]
- iii. Estimate the pulse width. [5 marks]

## SECTION B

5. (a) Explain what is meant by the following:
- Link Margin
  - Brewster Angle
  - Refractive index
  - Critical angle
  - Numerical aperture
- [5 marks]
- (b) Draw the simplified band-diagram representation of a single quantum well, separate confinement heterostructure laser diode (SQW-SCH LD). Label each layer. (Hint: show bandgap for each layer, full credit for naming appropriate materials for each layer in the laser you choose)
- [4 marks]
- (c) Draw the light power versus current characteristic for both a Light Emitting Diode and a Laser Diode. Explain the fundamental difference between the two characteristics.
- [4 marks]
- (d) A  $150\text{\AA}$  quantum well is formed from two materials having bandgap energies of 2.2 eV and 1.65 eV respectively. The ratio of the conduction band offset to the valence band offset for these materials is  $\Delta E_c : \Delta E_v = 0.6 : 0.4$ . The electron effective mass in the quantum well is  $0.11 m_0$ , where  $m_0$  is the free electron mass. If the valence band edge for the wider bandgap material is taken as the reference (zero) energy, at what energies do the quantised energy levels in the conduction band of the quantum well occur? How many discrete energy levels can be accommodated in the conduction band of this quantum well?
- [7 marks]
6. (a) It is required to design an integrated optic directional coupler with two thirds of the power going to one output port and one third to the other. The coupling length is given as 3 cm. What should be the length of the coupling region?
- [7 marks]
- (b) A fibre has an  $NA = 0.2588$ . A light source is coupled to this that will emit 75 % of its light into a  $60^\circ$  full-cone angle, 50 % into a  $30^\circ$  cone and 25 % into a  $15^\circ$  cone. What is the coupling efficiency when this source and fibre are connected?
- [6 marks]
- (c) A fibre has a core refractive index of 1.5 and a cladding refractive index of 1.49, and a core diameter of  $50\ \mu\text{m}$ . Consider the guided ray travelling at the steepest angle with respect to the fibre axis. How many reflections are there per meter for this ray?
- [7 marks]
7. (a) List five differences between Light-emitting diodes (LEDs) and Laser diodes.
- [4 marks]
- (b) What peak emission wavelength is to be expected from an LED having an active region with a band-gap of 2.4 eV? Draw the spectral output if  $\Delta\lambda = 20\ \text{nm}$ .
- [4 marks]

(c) Describe how an indirect band-gap material, such as GaP, can be used to make a light-emitting diode.

[3 marks]

(d) A GaAs/AlGaAs LED has an activation barrier of energy  $E_d = 0.82$  eV to long-term degradation. If the prefactor in the Arrhenius equation describing the degradation rate is  $C = 350$  hour<sup>-1</sup>, find the time after which the output radiant power will fall to half its initial value, assuming room temperature (25° C) operation.

[9 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 0.6 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]