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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2008

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 Departmental approved non-programmable calculators is permitted.
The use of Log Tables and Graph paper are permitted.

Physical Constants:

Free electron mass, $m_0 = 9\times10^{-31}$ kg
Planck's constant, h = 6.626×10^{-34} J s
Electronic charge, q = 1.602×10^{-19} C
Boltzmann's constant, $k_B = 1.38\times10^{-23}$ J K^{-1}
Room temperature = 300 K
Speed of light in free space, $c = 3\times10^8$ m s^{-1}

SECTION A

1.

(a) The familiar rate equations for the population (N_2) in the upper laser level and the single mode cavity photon number (*n*) in the case of an idealized 4-level laser system (assume that the lifetime in the lower laser level is so short that the approximation $N_1 \approx 0$ applies) are given by:

$$\frac{dN_2}{dt} = R_p - \frac{N_2}{\tau_2} - KnN_2 \quad \text{and} \quad \frac{dn}{dt} = KN_2(n+1) - \frac{n}{\tau_c},$$

where $K = 1/pt_{spon.}$, and $p = 8\pi\nu^2 V\Delta\nu / c^3$ represents the total number of modes, while the other terms have their usual meaning. By using certain simplifying assumptions, show that the cavity photon number can be expressed in terms of a normalized pumping rate ($r = R_p / R_{p,th}$) under steady state conditions.

[12 *marks*]

(b) In particular, show the dramatic increase in photon numbers as one goes from 1% below to 1% above threshold.

[4 *marks*]

(c) Write an equation for the output power of the laser in terms of the normalized pump rate *r*.

[4 *marks*]

2.

(a) Lasers can be divided into (i) 3-level and (ii) 4-level systems. Discuss this statement with reference to the energy levels involved and the pump power requirements to reach threshold in each case.

[6 *marks*]

(b) A helium-neon laser ($\lambda = 0.6328\mu m$) operating in the fundamental Gaussian mode has mirrors separated by 0.3m. The transition line-width $\Delta\nu$ is 1.5*GHz* and the refractive index of the gain medium can be taken as unity. Assume that the gain medium fills the optical cavity. The output beam from the laser is transmitted through a plane mirror (infinite radius of curvature) and the other mirror is spherical with a radius of curvature of 17*m*. The reflection coefficient of the spherical mirror is 1 while the flat output coupling mirror has a reflectivity of 0.98. The spontaneous lifetime of the upper laser level is 10^{-7} 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 cm^{-1}?

[*2 marks*]

(iv) What is the stimulated emission cross-section?

[*2 marks*]

(v) What is the beam diameter on the flat mirror?

[*3 marks*]

(vi) What is the Gaussian beam diameter at a distance of 20m from the output mirror?

[*3 marks*]

3.

(i) A laser operating at a wavelength λ employs a confocal optical resonator with mirror separation *L*. Derive expressions for the beam size at the centre of the resonator and at either mirror. Show that this resonator configuration is marginally stable.

[4 *marks*]

(ii) A carbon dioxide laser operating at $10.6\,\mu m$ has a cavity length of 1*m* and produces 80W of continuous output power in a Gaussian output beam. The stable optical cavity is formed using a plane mirror and a spherical mirror of 5*m* radius of curvature. The curved mirror is a total reflector for the wavelength of interest and the output from the laser is taken through the partially transmitting plane mirror. Determine the Gaussian beam diameter (in *mm*) at (a) the plane mirror and (b) the curved mirror.

[6 *marks*]

(iii) The beam on emerging from the laser resonator encounters a thin converging lens of focal length 0.3*m*, which is placed 0.5*m* from the output mirror. The lens focuses the beam to a small spot size (equal to the beam waist diameter). Determine (a) the beam waist at the focal spot, and (b) its position relative to the lens to the nearest *mm*.

[6 *marks*]

(iv) Calculate the peak power intensity (in kW / cm^2) at the focal spot.

[4 *marks*]

4.

(a) In relation to laser safety matters, define the following terms:

- Designated Laser Area (*DLA*).
- Maximum Permissible Exposure (*MPE*).
- Nominal Hazard Zone (*NHZ*).

[6 *marks*]

(b) Give a brief outline of the three main control measures to prevent exposure to dangerous levels of laser radiation.

[4 *marks*]

(c) Apart from exposure to the beam, list other possible non-beam hazards associated with laser systems, and provide some general guidelines for the design of Class 3B and Class 4 laser facilities.

[4 *marks*]

(d) A helium-neon laser ($\lambda = 0.6328\mu m$) has an output power of 10 mW and an output beam diameter of $2mm$ ($1/e^2$ intensity points). A spectator located $100m$ from the laser in an outdoor laser display show receives an accidental eye exposure (corresponding to the natural "blink-reflex" of the eye) to the beam. The *MPE* in terms of beam irradiance is $2.54mWcm^{-2}$ for accidental viewing of visible radiation. Assuming that the radiation emerging from the laser propagates as a Gaussian beam, perform a simple computation to ascertain if the spectator has exceeded the *MPE*.

[6 *marks*]

SECTION B

5. (a) Explain what is meant by the following:

   i. Soliton
   ii. Symmetric slab waveguide
   iii. Acceptance angle
   iv. Multimode distortion
   v. Quantum well

   [*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 150Å 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) List five differences between Light-emitting diodes (LEDs) and Laser diodes.

   [*4 marks*]

   (b) Show using diagrams the physical effect compressive strain and tensile strain has on a mismatched epi-layer. Is the epi-layer lattice constant greater or smaller than that of the substrate for tensile strain to occur?

   [*4 marks*]

   (c) List suitable semiconductor materials for light emission at wavelengths around 650 nm, 780 nm, and 1300 nm. (one of each).

   [*3 marks*]

   (d) A GaAs/AlGaAs LED has an activation barrier of energy E_d = 0.6 eV to long-term degradation. If the prefactor in the Arrhenius equation describing the degradation rate is C = 250 hour^{-1}, find the time after which the ouptut radiant power will fall to half its initial value, assuming room temperature (25° C) operation.

   [*9 marks*]

7. (a) Calculate the reflectance at normal incidence for a ray of light striking a plane semiconductor surface. (refractive index for air = 1, semiconductor = 3.5). 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/semiconductor (n=3.5) interface? [*4 marks*]

   (d) If glass(n=1.5)/semiconductor(n=3.5)/glass 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*]

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 and the background current are both considered negligible. Calculate the *rms* photocurrent and the *rms* shot noise current if the bandwidth is 8 MHz. [*11 marks*]