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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

AUTUMN 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

Q.1.

(a) The ray transfer matrix for a convex spherical dielectric interface is given by the equation:

$$\begin{pmatrix} r_{out} \\ r_{out}^{/} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \dfrac{n_1 - n_2}{n_2 R} & \dfrac{n_1}{n_2} \end{pmatrix} \begin{pmatrix} r_{in} \\ r_{in}^{/} \end{pmatrix},$$

where n_1 is the refractive index of air, n_2 is the refractive index of the dielectric material and R is the radius of curvature of the convex surface. Using this result, show that the ray transfer matrix for a thin convex lens is:

$$\begin{pmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{pmatrix},$$

where the focal length (f) is given by:

$$\frac{1}{f} = (n_2 - n_1)\left[\frac{1}{R_1} + \frac{1}{R_2}\right],$$

and R_1 and R_2 are the radii of curvature of the lens surfaces. [12 *marks*]

(b) Using this ray transfer matrix derive the standard equation for the object-image relationship for a thin lens.

[8 *marks*]

Q.2. Lasers are normally divided into 3-level and 4-level systems. Discuss this statement and draw appropriate energy level diagrams to illustrate your answer. Estimate the relative pump power requirements to achieve population inversion in each case.

[4 *marks*]

A Helium-neon laser ($\lambda = 0.6328\mu m$) operating in the fundamental transverse mode has mirrors separated by 0.3 m. The transition line-width $\Delta\nu$ (full width at half-height) is 1.5 *GHz* and the cavity mirrors have power reflection coefficients of 0.995 and 0.98.

(a) What is the frequency difference between longitudinal modes in the resonator?

[2 *marks*]

(b) How many longitudinal modes are within $\pm\Delta\nu/2$ of line centre?

[3 *marks*]

(c) The energy of the upper pumped state is 20.6 electron volts above the ground state. What is the quantum efficiency of the laser?

[3 marks]

(d) Find the stimulated emission cross-section at line-centre given that $A_{21} = 6.5\times10^{6}\ \sec^{-1}$ (A_{21} represents the Einstein coefficient for spontaneous emission).

[3 *marks*]

(e) What is the cavity lifetime in nanoseconds?

[5 *marks*]

Q.3. 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.

[4 *marks*]

Given two mirrors of radius of curvature 1m and 1.5m, find the range of values of mirror separation L, which will make a stable cavity.

[5 *marks*]

A Gaussian beam from an argon ion laser operating at 514nm is focused with a 50cm 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 2mm and the lens is 1m from the position of the waist. Calculate the exact location of the focused spot (in mm.) and its size relative to the lens position.

[7 *marks*]

A circular aperture of 200 microns in diameter, concentric with the beam, is placed at the exact focused position. What fraction of the incident power is coupled through this aperture?

[4 *marks*]

Q.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 $\lambda = 1.0\mu\text{m}$, which is to be Q-switched, has an initial population inversion at 10^{18} atoms, a factor of 3 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 6×10^{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) 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) Explain what is meant by the following:

   i. Link Margin
   ii. Brewster Angle
   iii. Refractive index
   iv. Critical angle
   v. 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 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*]

8. (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 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^{-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*]