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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2006

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$\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$10^{-23} J K^{-1}
Room temperature = 300 K
Speed of light in free space, c = 3$\times$10^{8} m s^{-1}

SECTION A

1.

(a) The ray transfer matrix for a thin convex lens of focal length f is given by:

$$\begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}.$$

Using the above, derive the ray transfer matrix for the optical system illustrated in Fig.1.1 below when propagation takes place from Plane I to Plane II (all distances indicated are in meters). The refractive index of the glass slab is 1.5 and the refractive index of air can be taken as unity. Express your final answer as the product of individual matrices.

[6 *marks*]

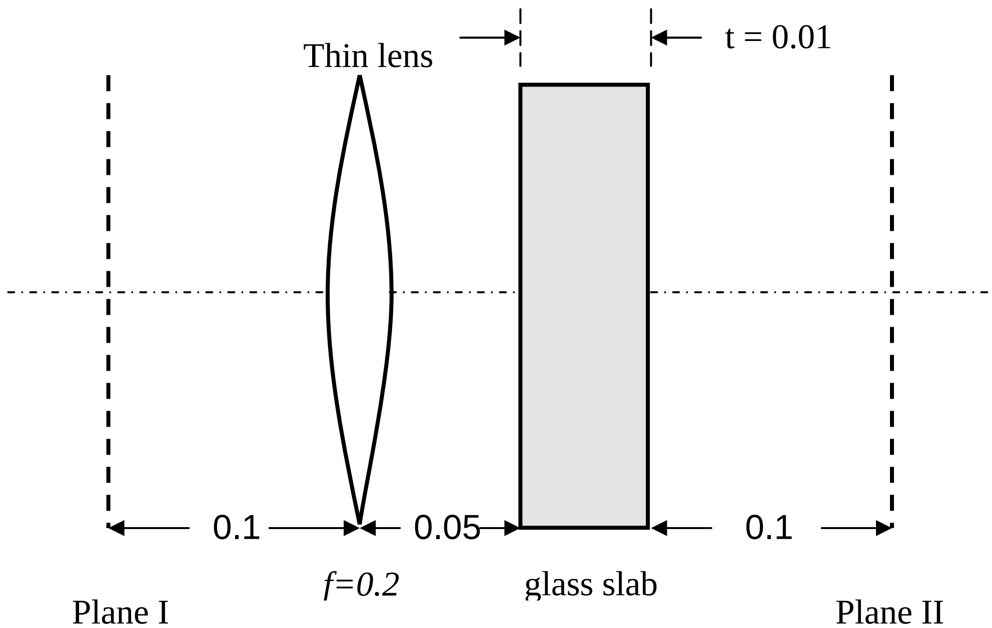

Fig.1.1

(b) A Gaussian beam emerges through the plane mirror of a high-power Carbon Dioxide laser ($\lambda = 10.6\mu m$). The optical cavity of this laser is illustrated schematically in Fig.1.2 below. The output power of the laser is 2000 watts. The beam is focused by a thin lens of focal length 0.15 meters that is placed a distance of 1.0 meters from the output mirror. Determine (i) the diameter of the focused beam and (ii) its position (to the nearest mm) relative to the lens position.

[8 *marks*]

(c) Estimate the optical intensity in Wcm^{-2} at the focal spot.

[2 *marks*]

(d) The focused laser beam as determined in (b) above is reliably employed to cut sheet metal at a constant linear speed provided that the optical intensity is not less than 50% of the value calculated in (c) above. Using this information in conjunction with your answer in (b), make an estimate of the maximum thickness of the sheet metal that can be cut using this laser if the constant cutting speed is to be maintained.

[4 *marks*]

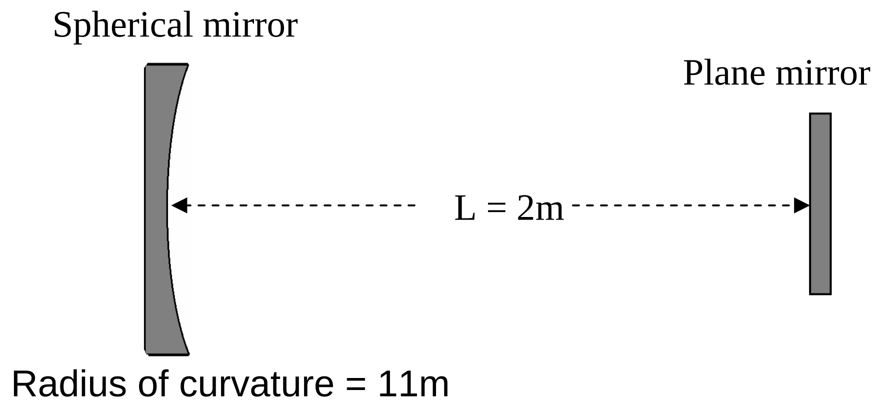

Fig.1.2.

2.

(a) In the context of lasers, what is the <u>significance</u> of the following terms?

- Threshold gain-coefficient
- Cavity lifetime
- Mode volume

(use appropriate equations and diagrams to illustrate your answer in each case)

[6 *marks*]

(b) Write the equation that describes the stability condition for optical resonators and draw the stability diagram in terms of the *g-parameters*.

[2 *marks*]

(c) Starting with the familiar equations for Gaussian beam propagation, derive an equation for the beam waist in the case of the *confocal* resonator. Express your answer in terms of the length of the resonator and the wavelength of the radiation.

[4 *marks*]

(d) An optical resonator is formed using large radius of curvature mirrors separated by a distance L. Assume that both mirrors have the same radius of curvature (R) and that the relation $R/L = 10$ applies. Show that this resonator will result in an increase in *mode volume* by a factor of 4.36 in comparison to the *confocal* resonator of similar length.

[8 *marks*]

3.

(a) A laser system is illustrated by its energy level diagram in Fig.3. Note that the atoms are being pumped to the upper level at a rate R_2, with no pumping taking place into the lower laser level (that is, $R_1 = 0$). The lifetime in the upper and lower levels is indicated by τ_2 and τ_1, respectively. Apart from stimulated emission, atoms can also accumulate in the lower level as a result of spontaneous transitions taking place from the upper level, and the spontaneous lifetime for this transition is denoted by $t_{spon.}$. Accordingly, write rate equations for the populations in these levels as a result of pumping, relaxation, and stimulated emission and define all the parameter appearing in your equations.

[6 *marks*]

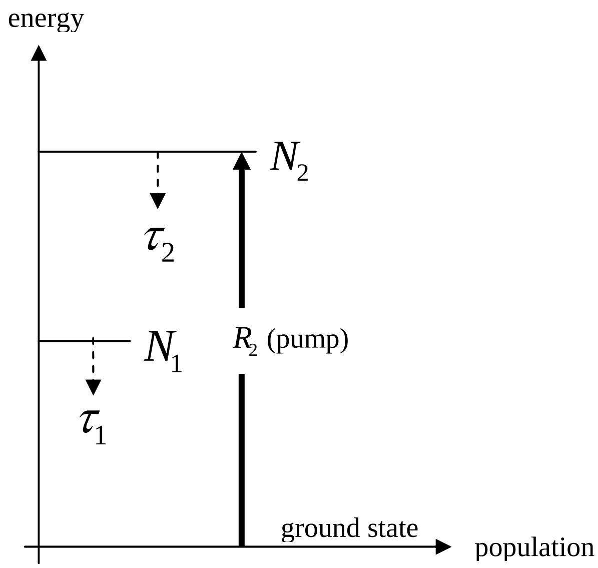

Fig.3.

(b) The laser system as depicted in the energy level diagram above operates at a wavelength of 0.54 microns. Only state 2 (the upper laser level) is pumped directly from the ground state (0 state) with a pump rate $R_2\ (cm^{-3}/\sec.)$. The upper laser level has a lifetime $\tau_2 = 0.2\mu\sec s$ and a spontaneous emission rate to state 1 (lower laser level) of $10^6\ \sec^{-1}$ (that is, $t_{spon.} = 10^{-6} s$). Atoms in state 1 have a lifetime (τ_1) of 50 ns. The transition line width is 60 *GHz*. The gain medium is 20 cm long while the optical cavity is 50 cm in length with mirrors having reflectivity values of 99% and 96%.
Assuming steady state conditions:

(i) What is the stimulated emission cross-section at line centre?

[3 *marks*]

(ii) What is the threshold gain coefficient?

[3 *marks*]

(iii) What is the pump rate R_2 that brings the laser to threshold?

[6 *marks*]

(iv) What is the cavity lifetime?

[2 *marks*]

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

4.

(a) Give a brief description of the Q-switching technique as applied to laser systems.

[4 *marks*]

(b) Write appropriate coupled rate equations for the cavity photon number and the population inversion and show that these equations provide a reasonably accurate picture of Q-switched behaviour. Explain the origin of all terms appearing in your equations.

[4 *marks*]

(c) Use your equations in (b) above to derive an expression for the optical energy in a Q-switched pulse.

[6 *marks*]

(d) What is the maximum output energy that can be extracted in a single Q-switched pulse from a cylindrical ruby laser rod, which is 80 mm long and 6 mm in diameter? The chromium ion density in the crystal is $1.6 \times 10^{19}\ cm^{-3}$ and the laser wavelength is 0.6943 μm. It can be assumed that all the entire cavity loss is due to output coupling and that the final population inversion, N_f, is zero. What is the other main assumption made in your calculation for estimating the maximum output energy?

[6 *marks*]

SECTION B

5. A point-to-point optical fibre link is to be designed to cover a total distance of 250 km. The required link margin is 14 dB with a receiver sensitivity of -26 dBm, and the single mode fibre used has an attenuation of 0.18 $dB.km^{-1}$. Assume the maximum laser output power is 3 mW, with negligible coupling and isolator losses.

   (a) For the conditions described, what is the maximum length link achievable using a single strand of this fibre? [*5 marks*]

   (b) How many optical amplifiers are required to make the 250 km link feasible? (EDFA gain is 5 dB, splice loss is 0.25 dB per splice) [*5 marks*]

   (c) If the data-rate for the link is 1.25 $Gb.s^{-1}$, what is the average number of photons per bit arriving at the receiver? (Assume $\lambda = 1.55\mu$ m.) [*5 marks*]

   (d) To cover the 250 km with a single fibre, without regeneration, the laser power can be increased to 10 mW without complication. What would the receiver sensitivity need to be in this case to meet the original design criteria? (fibre attenuation unchanged, all other losses negligible) [*5 marks*]

6. (a) Describe in *detail* the main causes of attenuation in silica glass fibres. [*7 marks*]

   (b) Describe *three* factors influencing the choice of source and fibre for short-haul (local-area) optical communications networks versus long-haul optical communications networks. [*7 marks*]

   (c) Explain *briefly* the following:

      i. Optical time domain reflectometry (OTDR)
      ii. Dense wavelength division multiplexing (DWDM)
      iii. Dispersion-shifted fibre

   [*6 marks*]

7. (a) Describe qualitatively the difference between multiple quantum wells and a superlattice. (Use diagrams to illustrate your answer) [*4 marks*]

   (b) A semiconductor material used to make a 60Å wide quantum well of depth 220 meV has an electron effective mass of 0.15 m_0 (where m_0 is the free electron mass). How many quantised energy levels reside in the conduction band of this quantum well? [*5 marks*]

   (c) What are band-tail states and what is their effect? [*5 marks*]

   (d) In compound semiconductors the electron velocity increases with increasing electric field up to a peak velocity before decreasing to a saturation value at higher electric field values. Explain why this happens and what is the effect called? [*6 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 850 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*]