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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2009

B.E. DEGREE (ELECTRICAL & ELECTRONIC)
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 = 9×10^{-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.

Determine the ray transfer matrix between Planes I and II for the optical arrangement shown in Fig.1 (the lenses are thin). By assuming that the incident ray is parallel to the optic axis ($r'_{in} = 0$), derive an expression for s in terms of f_1, f_2 and d if the ray crosses the optic axis exactly at Plane II. If $d = f_1 + f_2$ show that the ray will not cross the optic axis after emerging from the lens f_2, and sketch this optical arrangement.

[20 *marks*]

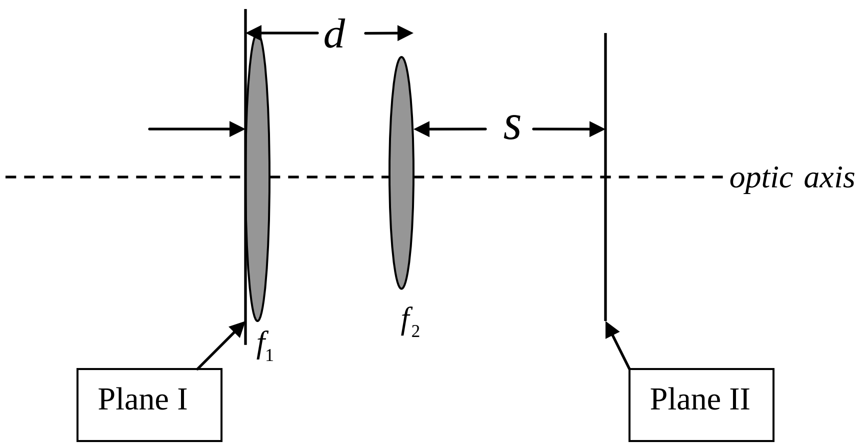

Fig.1.

2.

(i) Write a short note on each of the following terms and indicate its physical significance in the context of lasers (use appropriate diagrams and equations to illustrate your answer):

- Longitudinal mode spacing
- Mode volume

[4 *marks*]

(ii) Two concave mirrors of radii of curvature 1*m* and 1.5*m* are used to form an optical cavity. Find the range of values of mirror separation L which will make the cavity:
(a) Stable.
(b) Unstable.
(c) Marginally stable.

[6 *marks*]

(iii) 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. Determine the increase in mode volume of this resonator in comparison to a confocal resonator of similar length.

[10 *marks*]

3.

(i) Lasers can be classified into so-called 3-level and 4-level systems. Discuss this statement paying particular attention to the configuration of the energy levels involved, and to the input pump power requirements to achieve threshold conditions in each case.

[4 *marks*]

(ii) A laser system is shown schematically in Fig.3 which operates at a wavelength of 0.4 microns. Only the upper laser level (state 2) is pumped directly from the ground state (0 state) with a pump rate $\Re_2$ $(cm^{-3}/\text{sec.})$. The upper laser level has a lifetime of $\tau_2 = 0.2\mu\text{sec}s$ and a spontaneous lifetime of $1\mu s$, while 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 as shown in the accompanying diagram.

Assuming steady state conditions:

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

[4 *marks*]

(b) What is the threshold gain coefficient? (Use the mirror reflectivity values R_1 and R_2 as shown in Fig.3).

[4 *marks*]

(c) What is the pump rate $\Re_2$ that brings the laser to threshold?

[4 *marks*]

(d) What is the cavity lifetime?

[4 *marks*]

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

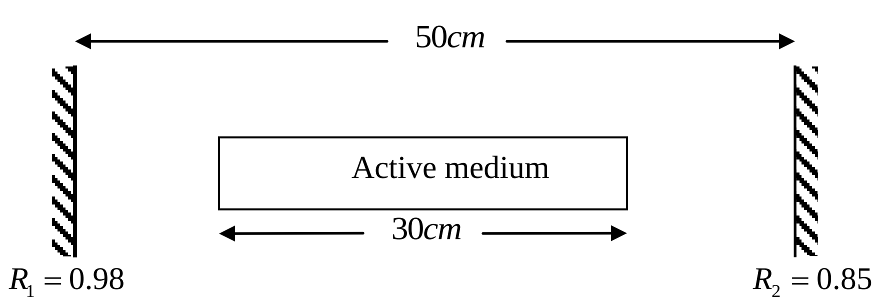

Fig.3.

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(a) Describe the technique of Q-switching as applied to laser systems and list as many applications as you can that exploit the unique properties of the Q-switched output.

[6 *marks*]

(b) Using the rate equation approach, derive expressions for:

- The peak output power.
- The energy in the Q-switched output.

in terms of the population inversion. [6 *marks*]

(c) Make an estimate of the maximum optical energy contained in a single pulse of a Q-switched ruby laser ($\lambda = 0.6943\mu m$). The chromium ion density is $1.6\times10^{19}\,cm^{-3}$. The laser rod is 10 *mm* in diameter and 10 *cm* long and it is mounted in an optical cavity with mirror reflectivities of 0.98 and 0.88. The beam emerges through the 0.88 reflectivity mirror and the 0.98 reflectivity mirror has zero transmission.

[8 *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) 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 definition of the Brewster angle? What value does the Brewster angle have 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*]

7. (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) What are band-tail states and what is their effect? [*4 marks*]

   (c) 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? [*4 marks*]

   (d) 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? [*8 marks*]

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

(b) Describe the operation of the p-i-n photodiode, paying particular attention to the quantum efficiency and speed of operation. [*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 at that wavelength is 68% and its dark current is considered negligible. The background radiation is also considered negligible. Calculate the *rms* photocurrent and the *rms* shot noise current if the bandwidth is 8 MHz. Design a transimpedance amplifier to produce 10 mV/nW of input optical power at 800 nm. [*11 marks*]