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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

AUTUMN 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 calculators 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) Write coupled rate equations for the population inversion and the photon number for an idealized 4-level laser system (assume that the relaxation from the lower laser level is so fast that the approximation $N_1 \approx 0$ applies). Justify the inclusion of the various terms appearing in your equations.

[6 *marks*]

(b) Under steady state conditions, derive an expression for the threshold population inversion, and show also that the population inversion (above the threshold for laser oscillation) remains clamped at the threshold value.

[4 *marks*]

(c) A $Nd^{3+}:YAG$ laser has the following parameters: $\lambda = 1.06\mu m$, $t_{spon.} = 0.55ms$, $\Delta\nu = 120GHz$ and refractive index $n = 1.82$. Assuming a cavity lifetime (τ_c) of $20ns$, find the threshold population inversion density.

[6 *marks*]

(d) Determine the power in Wcm^{-3} given off by spontaneous emission just below threshold in (c) above.

[4 *marks*]

(Velocity of light = $3\times10^8 ms^{-1}$, Planck's constant $h = 6.62\times10^{-34} J-s$)

2.

(i) Outline the main differences between 3-*level* and 4-*leve*l laser systems.

[4 *marks*]

(ii) 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):

- Cavity lifetime
- Mode volume

[4 *marks*]

(iii) The energy level diagram for an idealized low pressure gas laser is shown in Fig.2. The pumping mechanism only pumps atoms from the ground state to the upper laser level at a rate R_2, and the lifetime in this upper level is $\tau_2 = 560\mu s$ while the spontaneous lifetime in this level is $1.5ms$. Atoms in the lower laser level have a lifetime of $100\mu s$. The transition line-width is $50MHz$. Assuming steady state laser action takes place in an optical cavity $0.5m$ long with mirror reflectivity values of 0.96 and 0.99 and the gain medium fills the cavity, determine:

(a) The stimulated emission cross-section at line centre.
(b) The threshold gain coefficient (assume all losses are due to output coupling).
(c) The pump rate R_2 that brings the laser to threshold.

(d) The pump power (per unit volume) expended in bringing the laser to threshold.

[12 *marks*]

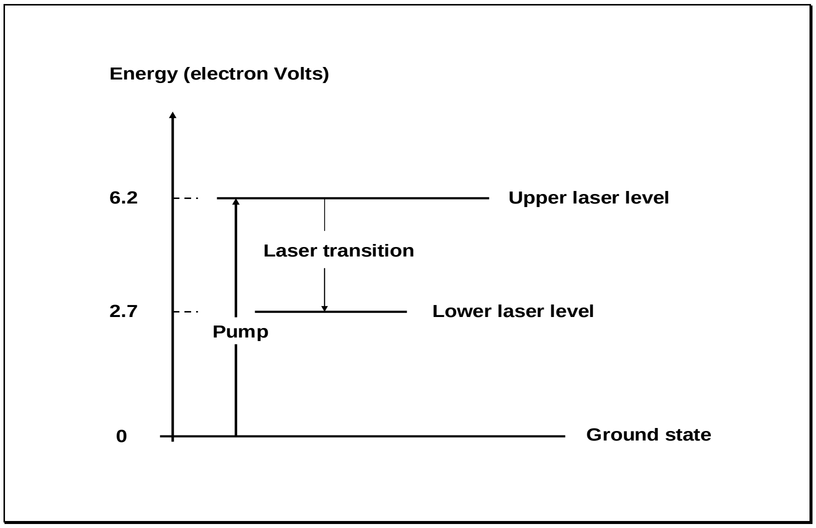

Fig.2

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 $1m$ 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 $5m$ 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) What is the beam diameter at a distance of 100 m from the output mirror?

[4 *marks*]

(iv) Calculate the peak output power intensity (in kW/cm^2) at the plane mirror.

[6 *marks*]

4.

Outline the Q-switching technique as applied to laser systems and describe at least three different Q-switching methods. [5 *marks*]

A ruby rod for a Q-switched laser ($\lambda = 0.6943\mu m$) is 10 cm long and has a radius of 3mm. The rod is placed in an optical cavity with a threshold gain coefficient of

$0.02 cm^{-1}$ and the total cavity loss is entirely due to output coupling. The Cr^{3+} doping density is 1.6×10^{19} atoms cm^{-3} and the stimulated emission cross-section is $1.3 \times 10^{-20} cm^2$. The pumping agent creates an initial population of 10^{19} atoms cm^{-3} in the upper laser state (state 2). Assume that the pumping occurs by virtue of absorption at $\lambda = 0.45 \mu m$, and that 100% of the atoms pumped to higher states relax to state 2. The spontaneous lifetime of state 2 is 3ms.

(a) How much spontaneous power does the ruby crystal radiate before the Q-switch is opened? [3 *marks*]
(b) How much pump power is required to maintain the population in state 2 at 10^{19} atoms cm^{-3}? [3 *marks*]
(c) What is the peak output power of the Q-switched pulse? [3 *marks*]
(d) How much energy is contained in the output pulse? (assume that the energy extraction efficiency is 90%) [3 *marks*]
(e) Estimate the duration of the output pulse. [3 *marks*]

SECTION B

5. (a) Calculate the link margin for the system specified in the diagram below. [*8 marks*]

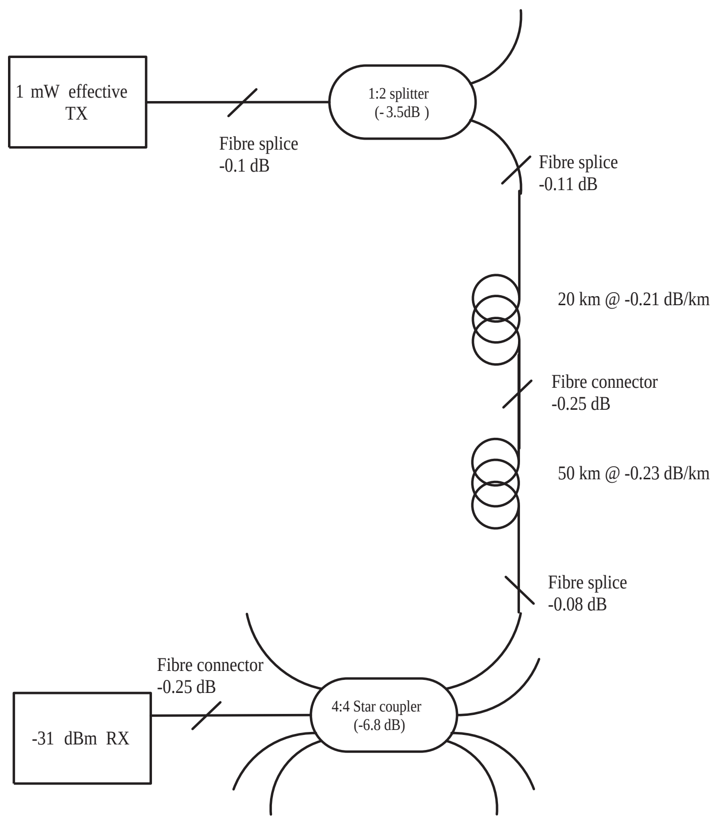

Figure 1:

(b) Explain the following terms:

i. Modal distortion
ii. material dispersion
iii. soliton
iv. Fibre attenuation
v. Link margin

[*5 marks*]

(c) If the material dispersion for silica is 110 ps/nm.km at 820 nm and 15 ps/nm.km at 1.5 μm determine whether it is more advantageous to use an 820 nm LED having a spectral linewidth of 10 nm or a 1550 nm LED having a 60 nm spectral width. Justify your answer numerically. What will be the total pulse spreading for each LED if the link length is 25 km? [*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° full-cone angle, 50 % into a 30° cone and 25 % into a 15° 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 μm. 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) 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*]

8. (a) Explain the term Noise Equivalent Power (NEP) with reference to semiconductor photodetectors. [*5 marks*]

(b) Describe the process of impact ionization as applied to avalanche photodiodes. How does this provide internal gain? What is the advantage of internal gain in the photodiode? [*5 marks*]

(c) A photodiode having a circular active area of 1 cm radius has a responsivity of 0.55 A/W to light at 633 nm. The noise equivalent power for the photodiode is 2.5×10^{-12} W Hz$^{-1/2}$. This photodiode is to be used in a LIDAR (Light detection and ranging) system in conjunction with a He-Ne laser having a non-divergent beam with 5 mW average output power. Assume no attenuation of the laser light, a bandwidth of 1 Hz and assume the target is a perfect diffuse reflector (i.e. reflected light is scattered uniformly in all directions) - what is the maximum target distance that can be measured in this system? What is the photocurrent produced? [*10 marks*]