THE UNIVERSITY OF NEW SOUTH WALES

SCHOOL OF PHYSICS

FINAL EXAMINATION

JUNE 2009

PHYS3710

Lasers and Applications

Time Allowed – 2 hours

Total number of questions - 7

Answer ALL questions

All questions ARE NOT of equal value

Candidates must supply their own, university approved, calculator.

Answers must be written in ink. Except where they are expressly required, pencils may only be used for drawing, sketching or graphical work.

Candidates may keep this paper.

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School of Physics

PHYS3710

LASERS AND APPLICATIONS

c(speed of light in vacuum) = $3\text{x}10^8$m/s

Planck's constant h = $6.6\text{x}10^{-34}$Js

Boltzmann's constant k = $1.3\text{x}10^{-23}\text{JK}^{-1}$

Mass of electron $m_0 = 9.1\text{x}10^{-31}$kg

Charge of electron e = $1.6\text{x}10^{-19}$C

1eV = $1.6\text{x}10^{-19}$J

$$E_{ave} = \frac{h\nu}{e^{h\nu/kT} - 1} \qquad u(\nu) = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{h\nu/kT}-1} \qquad R = \frac{A_{ul}}{B_{ul}u(\nu)} = e^{\frac{h\nu_{lu}}{kT}} - 1$$

$$I(\nu) = I_0 \frac{\Delta\nu/4\pi^2}{(\nu-\nu_0)^2 + (\Delta\nu/4\pi)^2} \qquad I(\nu) = \frac{a}{\Delta\nu^D}\exp\{-[\frac{b(\nu-\theta_0)^2}{(\Delta\nu^D)^2}]\}$$

$$\sigma(\nu) = \frac{\lambda^2}{n^2 8\pi\ t_{sp}} G_l(\nu) \qquad N_l/N_u = \exp(E_u\text{-}E_l)/kT \qquad (N_u - N_l) = \frac{(N_u - N_l)_0}{1 + \frac{I}{I_{sat}}}$$

$$E_n = \frac{h^2}{8m^*\pi^2}(\frac{\pi n}{d})^2 \qquad \frac{I_t(\nu)}{I_0} = \frac{1}{1 + (2F/\pi)^2 \sin^2(\pi\nu/\Delta\nu)}$$

$$R= [(n_1\text{-}n_2)/(n_1+ n_2)]^2$$

$$I(z) = I(0)e^{gz} \qquad F = \frac{\pi(R_1R_2)^{1/4}}{1-(R_1R_2)^{1/2}} \qquad F=\Delta\nu/\delta\nu$$

$$g_i=1+ d/\rho_i \qquad \alpha_{eff} = \alpha_0 + (1/2d)\ln(1/R_1R_2) \qquad G(\nu_0) = 2/\pi\Delta\nu$$

$$\tau_p = 1/\alpha_{eff}c \qquad \Delta t_{sep} = 2nd/c \qquad \Delta t_p = 2nd / Nc$$

1. **(10 Marks)** Discuss briefly the following concepts using words, sketches and/or formulae:
    a. stability of a laser resonator
    b. mode locked laser
    c. vertical cavity surface emitting laser (VCSEL)

2. **(10 Marks)**
    a. Explain what is meant by photon lifetime.
    b. Given that a cavity has an effective loss coefficient of $\alpha_{eff} = 0.1\text{cm}^{-1}$, calculate the photon lifetime in this cavity.
    c. Calculate the time it takes for the optical energy stored in the cavity discussed in (b) above to decay to one half of its initial value.

3. **(10 Marks)** Assume a laser operating at $\lambda = 633$nm having two mirrors with reflectivity $R_1=0.6$ and $R_2=0.98$ separated by a distance 20cm. The refractive index of the medium in the cavity is n=1.5. Other losses are negligible. Calculate:
    a. The frequency spacing of the modes
    b. The finesse of this cavity
    c. The linewidth of the modes

4. **(15 Marks)** The relationship between gain (G) and amplified intensity (I) is given by the following equation:

$$\ln\left(\frac{I}{I_0}\right) + \frac{I - I_0}{I_{sat}} = Gz$$

where I_0 is the incident intensity, z is the amplifier length, $I_{sat} = h\upsilon / \sigma(\upsilon)\tau_u$ is the saturation intensity, τ_u is the upper lifetime and $\sigma(\upsilon)$ is the gain cross-section.

    a. Explain why gain saturation occurs in optical amplifiers.
    b. Make a plot of the amplified intensity as a function of gain indicating the important limiting cases of $I \ll I_{sat}$ and $I > I_{sat}$.
    c. How does gain saturation affect the operation of a laser?
    d. What role does gain saturation play in spectral hole-burning?

5. **(20 Marks)** You have discovered a new type of gain material made from a pi-conjugated (plastic) ***organic semiconductor*** which emits in the yellow (580nm), which you've dubbed Mellow Yellow! This new plastic light emitting material will be of great importance for future flexible display technologies. To turn your great discovery into an important technological breakthrough, all you need to do is build a laser with it. Let's see how you go:
    a. You can make Mellow Yellow into a strip length of 1mm and you measure its small-signal gain coefficient to be 6.4cm^{-1}. Given that the loss-coefficient of Mellow Yellow due to Rayleigh scattering is 3.8cm^{-1}

and that it has a refractive index $n = 1.5$, can you use the reflections from the end facets of the gain medium to achieve lasing? How might you modify the reflectivity at the ends?

b. If you make one mirror of your optical resonator 100% reflecting, what is the minimum reflectivity of the second mirror required to achieve lasing? What is the finesse of this resonator?

c. Your new laser needs a pump source and because your material is a semiconductor, you can use electrical injection. Given that the internal quantum efficiency of Mellow Yellow is 0.1, what is the external differential quantum efficiency of your laser?

d. Oh dear, your new plastic laser is not very thermally stable and will melt when it reaches an operating temperature of 60 degrees! Mellow Yellow is essentially a homojunction-type diode laser. Discuss some methods which you can use to improve the efficiency of your laser.

6. **(15 Marks)**

   a. Explain the role and benefits of quantum-wells in diode lasers

   b. Assume an AlGaAs/GaAs/AlGaAs quantum well laser diode with a GaAs quantum well layer whose thickness is L = 8nm. Take the effective mass of electrons and holes in GaAs to be $m_e^* = 0.07m_0$ and $m_h^* = 0.47m_0$ respectively, where m_0 is the mass of the electron in vacuum.

      (i) Calculate the first energy levels in the quantum well for electrons and for holes

      (ii) Calculate the change in the emission wavelength with respect to bulk GaAs which has an energy bandgap of 1.42eV

      (iii) Draw the typical energy-band diagram of a AlGaAs/GaAs/AlGaAs quantum-well indicating the GaAs and the AlGaAs regions

      (iv) Explain why GaAs and AlGaAs are often used together in quantum well structures.

7. **(20 Marks)** Describe each of the five characteristic optical properties unique to lasers. Give separate examples (with explanation) where each of these properties has been used to initiate or advance a technological application. Where appropriate, use quantitative data to back up your claims.