Department of Physics

PH963 **Advanced Photonics Devices**

Wednesday 26 April 2023 **09:30am-12:30pm – 3 hours**

Attempt ALL questions in Section A (40%) and
ALL questions from Section B (60%)

Calculators must not be used to store text and/or formulae nor be capable of communication.
Invigilators may require calculators to be reset.

Physical constants

Speed of light	$c = 3.00 \times 10^{8}\ \mathrm{m \cdot s^{-1}}$
Electron charge	$e = 1.60 \times 10^{-19}\ \mathrm{C}$
Electron mass	$m_0 = 9.11 \times 10^{-31}\ \mathrm{kg}$
Free space permittivity	$\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{C^2 \cdot J^{-1} \cdot m^{-1}}$
Planck's constant	$h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}$
Reduced Planck's constant	$\hbar = 1.05 \times 10^{-34}\ \mathrm{J \cdot s}$

Physical properties of some semiconductors

	InP	GaP	GaAs	AlAs
Lattice constant, a_0 (Å)	5.8688	5.4505	5.6533	
Electron effective mass, m_e^* $(1/m_0)$			0.067	0.15

The solution of Schrodinger's equation for a quantum well with infinite barriers

$$E_n = \frac{\hbar^2}{2m^*}\left(\frac{n\pi}{L}\right)^2 \quad n = 1,2,3 \ldots$$

where L is the thickness of the quantum well.

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Definitions for questions on waveguides and DFB laser

Normalised frequency:

$$V = \frac{2\pi}{\lambda_0} d \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{sub}}^2}$$

***b*-factor:**

$$b = \frac{n_{\mathrm{eff}}^2 - n_{\mathrm{sub}}^2}{n_{\mathrm{core}}^2 - n_{\mathrm{sub}}^2}$$

***a*-factor for TE polarisation:**

$$a = \frac{n_{\mathrm{sub}}^2 - n_{\mathrm{sup}}^2}{n_{\mathrm{core}}^2 - n_{\mathrm{sub}}^2}$$

Bragg relation for a DFB structure:

$$m\lambda_0 = 2n_{\mathrm{eff}}\Lambda$$

Cut-off frequency for planar waveguide modes:

$$V_{\mathrm{c}}^{m} = m\pi + \arctan\left(\sqrt{a}\right)$$

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Section A – Answer ALL questions

Q1.

a) Sketch the energy level diagrams for a four-level laser and a three-level laser. Identify the pump and laser transitions in each case.

[3]

b) In terms of the effect on laser threshold, what is the key difference between the energy level structures of a three-level laser and a four-level laser?

[1]

c) In order to achieve population inversion in a three-level laser, what fraction of the ground state population must be pumped into the upper laser level?

[1]

Q2.

a) Describe how a high-energy pulse can be obtained from a solid-state laser by means of Q-switching. Describe, in general terms, the effect Q-switching has on the population inversion and intracavity photon flux.

[3]

b) A pulse of pump light is incident on a laser gain material. After the pump pulse is complete, the time taken for the fluorescence from the laser gain material to decay to $1/e$ of its initial level is measured to be 230 μs. Is this material likely to be appropriate for generating high-energy laser pulses via Q-switching? Justify your answer.

[2]

Q3. The propagation of a non diffraction-limited laser beam with the distance z can be described as follows:

$$w = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

where

$$z_0 = \frac{\pi w_0^2}{M^2 \lambda}, \quad \theta = \frac{M^2 \lambda}{\pi w_0},$$

w is the beam radius, λ is the wavelength and θ is the divergence in the far field.

PLEASE TURN OVER

a) Explain the meaning of M^2 and w_0.

[2]

b) Explain how M^2 can be measured.

[3]

Q4. Consider the TE_0 mode in a symmetric planar waveguide where the core is made of an amplifying material. The propagation constant of the mode is given by:

$$\beta = \beta^{(0)} - i\Gamma \frac{g}{2}$$

a) Identify each of the parameters on the right side of the above relation.

[3]

b) A Fabry-Perot laser is obtained by polishing the facets of such a planar waveguide of length L and adding to the facets a coating with an intensity reflectivity R. Express the gain g needed to reach laser threshold as a function of L, R and Γ.

[2]

Q5. Consider a symmetric slab waveguide having a core of thickness d and refractive index n_1 sandwiched between two regions of refractive index n_2. The core is made of polyphosphonate (a high refractive-index polymer) with a refractive index $n_1 = 1.68$ at a wavelength of 630 nm and the cladding is an epoxy of refractive index $n_2 = 1.49$ at the same wavelength.

a) What is the critical angle for a wavelength of 630 nm?

[2]

b) If the core thickness is $d = 400$ nm, what is the wavelength above which only the fundamental modes (TE_0 and TM_0) are guided?

[3]

Q6. The bandgap of $\text{In}_{1-x}\text{Ga}_x\text{P}$ is given by:

$$E_\text{g}(x) = (1.35 + 0.668x + 0.758x^2)\ \text{eV}$$

a) Find the ground state transition wavelength of bulk $\text{In}_{1-x}\text{Ga}_x\text{P}$ lattice-matched to GaAs. You may assume a linear extrapolation from the binaries for the lattice constants.

[3]

PLEASE TURN OVER

b) Consider now using the material described in **a)** to build a quantum well with infinite barriers. Would the ground state transition wavelength increase or decrease compared to the bulk material? Justify your answer.

[2]

Q7. Explain three reasons why you would use semiconductor quantum wells instead of bulk material as the gain medium in a laser.

[6]

Q8. The probability of occupation of the conduction band of a semiconductor is described by the Fermi-Dirac statistics:

$$f_\mathrm{C}(E) = \frac{1}{1 + \exp\left(\left.(E - F_\mathrm{C})\middle/k_\mathrm{B}T\right.\right)}$$

where F_C is the quasi-Fermi level for the conduction band, k_B is Boltzmann's constant, and T is the temperature. The occupation of the valence band, $f_\mathrm{V}(E)$, is similarly described in terms of F_V.

The absorption spectrum of a bulk semiconductor is shown in Figure 1 below.

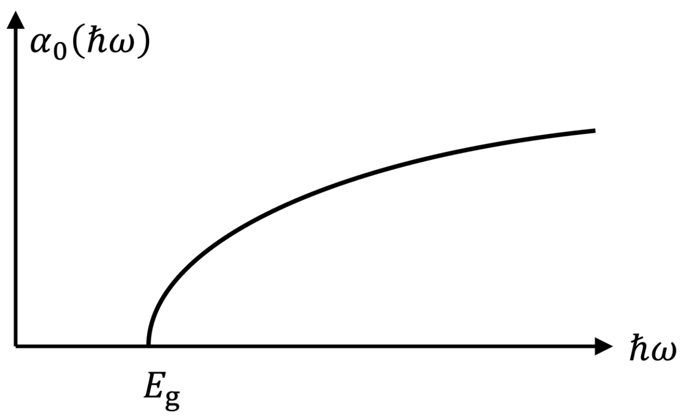

Figure 1: Absorption spectrum of a bulk semiconductor.

a) Give an expression for the gain spectrum, $g(\hbar\omega)$, of a bulk semiconductor in terms of the absorption spectrum $\alpha_0(\hbar\omega)$.

[1]

b) Consider the case when carriers are injected such that the separation of the quasi-Fermi levels is:

$$F_\mathrm{C} - F_\mathrm{V} = E_\mathrm{g} + 15\ \mathrm{meV}$$

Sketch the gain spectrum of the semiconductor, labelling any important features.

[3]

PLEASE TURN OVER

Section B – Answer ALL questions

Q9.

a) Ti:sapphire lasers and semiconductor disk lasers can both be used for spectroscopic applications. In terms of wavelength versatility, what is the principal advantage of each laser type for this application?

[2]

b) Good thermal management is vital to obtain high-power operation with both these laser types from **a)**. Assume that the quantum defect is the only significant heat source in the lasers described. On this basis, estimate the fraction of the absorbed pump power converted to heat in a Ti:sapphire laser operating at 800 nm and pumped at 532 nm.

[2]

c) Consider an end-pumped Ti:sapphire laser in a conventional rod geometry. In this scenario, which two thermally induced changes in the Ti:sapphire crystal contribute to thermal lensing?

[2]

d) Which properties of the laser crystal are most important in determining the strength of the thermal lens?

[3]

e) In Ti:sapphire lasers, it is often important to control the absolute temperature reached in the laser gain crystal to ensure good laser efficiency. Why is this the case?

[2]

f) Explain why pump-induced temperature rises limit the performance of semiconductor disk lasers. Diamond can be used to improve the thermal management of these lasers. Describe two ways in which diamond is used.

[4]

g) Ti:sapphire lasers have recently been demonstrated pumped by diode lasers rather than the more common route of pumping with a frequency doubled neodymium laser. Give two main benefits of direct diode laser pumping of Ti:sapphire lasers.

[2]

PLEASE TURN OVER

h) Diode laser pumping of Ti:sapphire has been demonstrated with diode lasers operating at 450 nm and at 520 nm. Consider the situation where a Ti:sapphire rod with undoped endcaps is used in such a laser, which operates at 800 nm. The focal length of the resulting thermal lens in the Ti:sapphire rod is measured to be 2 cm when pumped with a 520 nm diode. The 520 nm diode laser is then replaced by a 450 nm diode laser of the same power in such a way that the dimensions of the pumped region remain the same. Estimate the focal length of the thermal lens under 450 nm diode laser pumping.

[3]

Q10.

a) What are colloidal quantum dots? State what they are made of, their typical size and why they are called colloidal.

[3]

b) In core/shell colloidal quantum dot heterostructures, what effect does the shell have on the photoluminescence and why?

[2]

c) Colloidal quantum dots (CQD) with spectral gain centred at 600 nm (the gain spectrum is considered flat in the range 590 nm-610 nm and nil outside of this range) are dispersed in a polymer matrix to form a composite. Two CQD-to-matrix volume ratios are used: 2% and 20%, with a refractive index at 600 nm of, respectively, 1.506 and 1.558. Consider planar waveguides made with these nanocomposites as the core material, epoxy as the substrate ($n_{\text{epoxy}} = 1.480$) and air as the superstrate ($n = 1$). Calculate the cut-off thickness of the TE_0 mode at a wavelength of 600 nm in both cases - detail your calculation.

[4]

d) You have been tasked with designing a surface-emitting distributed feedback (DFB) laser. The gain medium will be made of a film of colloidal quantum dots ($n_{\text{CQD}} = 1.558$). The material for the substrate will be an epoxy ($\text{n}_{\text{epoxy}} = 1.480$). The dispersion plots for the first few modes of the equivalent planar waveguide are represented in Figure 2 below (next page). You have two silicon master gratings at your disposal (the surface of the silicon is corrugated with a periodic grating structure) with respective periodicity of 100 nm and 400 nm. You need to select one of these master gratings to imprint the surface of the epoxy substrate onto which the colloidal quantum dot film will be deposited in order to form the DFB laser. Which grating periodicity do you choose and what thickness does the colloidal quantum dot film need to be for a surface-emitting laser oscillating in the TE_0 mode at 600 nm?

[5]

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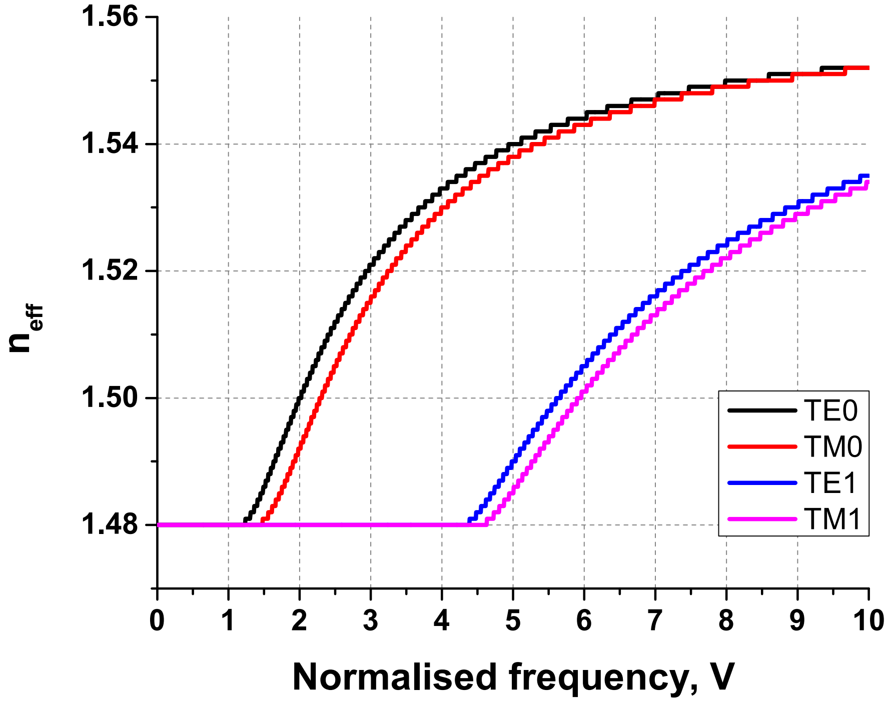

Figure 2: Effective refractive index versus the normalised frequency.

e) Using the materials and gratings outlined in **d)**, describe your design for a purely edge-emitting DFB laser.

[2]

f) Will the surface emitting or the purely edge-emitting laser design have the lower oscillation threshold? Justify your answer.

[2]

g) For the laser structure described in part **d)**, can the TM_0 mode oscillate (i.e. lase) in principle? Justify your answer.

[2]

Q11.

a) Find the wavelength of the first intersubband transition in a 6-nm-thick $Al_{0.37}Ga_{0.63}As$ quantum well, assuming the approximation of infinite barriers. You may assume a linear extrapolation from the binaries for the effective mass.

[7]

PLEASE TURN OVER

b) Explain the principle of operation of the 'quantum cascade' in a quantum cascade laser. To illustrate your explanation, sketch adjacent quantum wells and label all important features, including the optical transitions.

[11]

c) What is the polarisation of the emission of a quantum cascade laser? Explain your answer.

[2]

END OF PAPER

(Examiners: Nicolas Laurand, Lucia Caspani)