University of Bath
Department of Physics

Year 3/4
PH30032 Laser Physics

Tuesday, 16th January 2018, 09:30 to 11:30

Answer ALL questions from Section A
and
TWO questions from Section B

The only calculators that may be used are those supplied by the University.

Please fill in your name and sign the section on the right of your answer cover, peel away adhesive strip and seal.

Take care to enter the correct candidate number as detailed on your desk label.

CANDIDATES MUST NOT TURN OVER THE PAGE AND READ THE EXAMINATION PAPER UNTIL THE CHIEF INVIGILATOR GIVES PERMISSION TO DO SO.

SECTION A

1. A helium-neon laser has an optical cavity with two mirrors separated by 0.15 m and an emission wavelength of 632.8 nm. If the mirrors have reflectivities of 85 % and 100 % and the gain medium fills the cavity, calculate the following:

   (a) The population inversion at threshold if losses between the mirrors can be neglected and the gain cross section is 5.8×10^{-13} cm^2. (2)

   (b) The empty cavity lifetime. (2)

   (c) The linewidth of a single longitudinal mode and empty cavity Q-factor. (2)

2. Describe the differences between spontaneous and stimulated emission and write down expressions for the transition rates of the two processes in terms of the excited state population N, spontaneous lifetime τ, gain cross section σ, laser frequency ν and intensity, I, of light at the optical transition frequency. (4)

3. An InGaN 'blu ray' semiconductor laser has an output power of 10 mW at an injection current of 40 mA. If the threshold current is 30 mA and the wavelength is 400 nm, what is the quantum efficiency if each injected electron-hole pair creates one photon? (2)

4. A TEM_{00} Gaussian beam emerging from an InGaAsP quantum well surface emitting laser has a complex radius of curvature $q = 0.2 + 0.01\mathrm{i}$ m at a point P on the optical axis.

If the wavelength is 1300 nm, how far is P from the surface of the laser and what is the size in mm of the beam waist at the laser and at the point P? (3)

5. A diode-pumped modelocked laser is based on the material Cr^{3+}:$LiSrAlF_6$ and has a laser output centred at 842 nm. A diode-pumped CW laser is based on the material Yb^{3+}:YVO_4 (Yb:Yttrium Aluminium Garnet) and has a laser transition at 1030 nm. State with reasons whether either ion might also work in a $KGd(WO_4)_2$ (potassium gadolinium tungstate) crystal host and, if so, what laser wavelength might be expected. (2)

(ytterbium (Yb) is a rare earth and chromium (Cr) is a transition metal)

6. A laser produces pulses with a duration of 375 fs and with a spectral width of 5 nm centred on 1060 nm at a pulse repetition rate of 10 MHz.

   (a) If a filter were placed in the output of the laser which reduced the bandwidth to 2 nm, what else would change in the laser pulses? (2)

   (b) Without the filter, the laser pulses are transmitted down an optical fibre which has a group velocity dispersion of D = -50 ps/(nm.km) at 1060 nm. Estimate the maximum length of the fibre before the pulse width is increased by a factor of two. (2)

7. (a) Explain briefly what is meant by Q-switching, including two ways in which it may be achieved. (4)

(b) A Q-switched laser is required with a pulse duration of 1 ns at 1064 nm using a gain medium with a gain bandwidth of 20 nm and an excited state lifetime of 300 μs. In building the laser what parameter is important for achieving this pulse duration? (2)

8. Explain the importance of phasematching in nonlinear optical processes, including one way in which it may be achieved in a real crystal. (3)

SECTION B

9. (a) Explain what is meant by a ray matrix and state the approximation used in deriving the matrix elements. (2)

(b) The ray matrix for a dielectric interface with radius of curvature R between two dielectric media of refractive index n_1 and n_2 is

$$\underline{\underline{O_d}} = \begin{pmatrix} 1 & 0 \\ \dfrac{(n_1/n_2)-1}{R} & \dfrac{n_1}{n_2} \end{pmatrix}.$$

Use this result to derive the 'lens makers' formula for the focal length of a thin lens made from glass of refractive index n with spherical surfaces of radii of curvature R_1 and R_2: (4)

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

You may assume that the ray matrix for a thin lens is $\underline{\underline{O_l}} = \begin{pmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{pmatrix}$.

(c) Explain what is meant by the terms unstable and stable when describing an optical cavity and state the minimum conditions that the complex radius of curvature must satisfy for stability. (3)

(d) Show that a laser cavity with round trip matrix $\begin{pmatrix} A & B \\ C & D \end{pmatrix}$ is stable if $(A+D)^2 < 4$.

(3)

(e) A laser cavity is constructed from two concave mirrors with equal radii of curvature $R = 2$ m separated by a distance of L=1 m. Show that the cavity is stable. You may assume that the ray matrix for a concave mirror is $\underline{\underline{O}}_m = \begin{pmatrix} 1 & 0 \\ -2/R & 1 \end{pmatrix}$.

(3)

10. (a) Explain the terms homogeneous and inhomogeneous broadening and give an example of how each can arise. (3)

(b) The gain of the inhomogeneously broadened gain medium in a laser can be written as

$$\gamma(I) = \frac{\gamma_0}{\sqrt{1 + I / I_s}}$$

where I is the intensity of light at the laser frequency and the constants γ_0 and I_s are the small signal gain and saturation intensity respectively. Use this result to explain why the gain of the laser cannot rise significantly above the threshold gain when the pump power is increased. (2)

(c) Explain why a laser with an inhomogeneously broadened gain medium is intrinsically multimode, *i.e.* it normally lases on many longitudinal cavity modes, and sketch the gain as a function of frequency for the case that 3 modes are lasing, taking care to show the threshold gain level. (3)

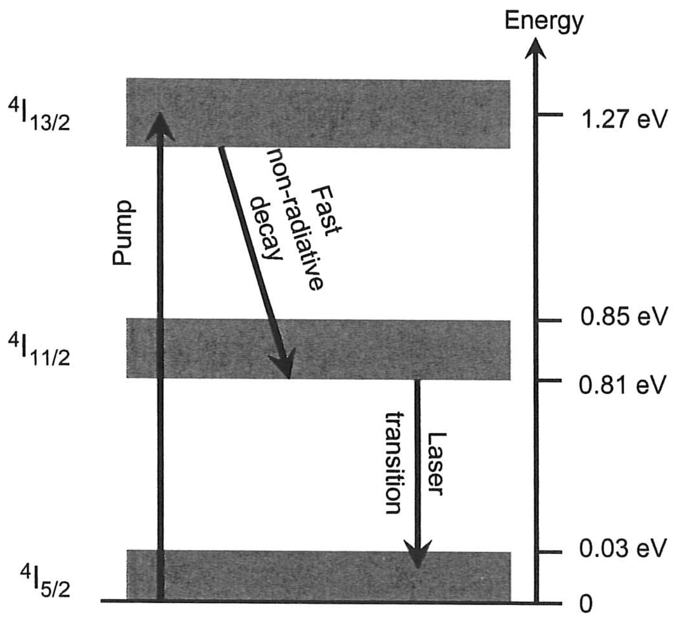
(d) A tunable laser is to be designed with a linear cavity for single frequency operation using a homogeneously broadened gain medium.

(i) Briefly describe how spatial holeburning may be a limiting factor in the laser operation. (3)

(ii) How may the laser wavelength be selected and tuned? (3)

(iii) Suggest, with reasons, a use for a tunable single frequency laser. (1)

11. A schematic of the energy level structure and pumping scheme for an erbium doped glass laser is shown below.



(a) Why are transition metal ions and rare earth ions (such as erbium) suitable for solid-state lasers? (3)

(b) By considering the energy level diagram for erbium doped glass shown above, explain why the laser operates as a three level laser at room temperature. (2)

(c) With the aid of a diagram describe the operation of a double clad fibre laser. You should include the pumping mechanism, the range of available laser materials, typical dimensions, required pump laser beam quality and output laser beam quality. (7)

(d) What range of laser wavelengths are available from an erbium-doped fibre laser? (1)

(e) If the erbium-doped fibre laser is operated as a modelocked laser, what minimum pulse duration would be available? (2)

SRA/WJW

UNIVERSITY OF BATH – DEPARTMENT OF PHYSICS

FUNDAMENTAL CONSTANTS

Note: Numerical values have been rounded to four significant figures.

Quantity	Symbol	Value	Unit	Dimensions
Atomic mass unit	u	1.661×10^{-27}	kg	M
Avogadro constant	N_A	6.022×10^{23}	mol^{-1}	
Bohr magneton ($e\hbar/2m_e$)	μ_B	9.274×10^{-24}	JT^{-1}	$I\,L^2$
Bohr radius ($4\pi\hbar^2/\mu_o c^2 e^2 m_e$)	a_o	5.292×10^{-11}	m	L
Boltzmann constant	k	1.381×10^{-23}	$J\,K^{-1}$	$ML^2T^{-2}\theta^{-1}$
Charge of electron (magnitude)	e	1.602×10^{-19}	C	I T
Charge (magnitude)/rest mass ratio (electron)	e/m_e	1.759×10^{11}	$C\,kg^{-1}$	$I\,M^{-1}T$
Fine–structure constant ($\mu_o ce^2/2h$)	α	7.292×10^{-3}		
	$1/\alpha$	137.0		
Gravitational constant	G	6.672×10^{-11}	$Nm^2\,kg^{-2}$	$M^{-1}\,L^3\,T^{-2}$
Mass ratio, m_p/m_e	m_p/m_e	1836		
Molar gas constant	R	8.314	$J\,mol^{-1}K^{-1}$	$ML^2T^{-2}\theta^{-1}$
Molar volume (ideal gas, STP)	V_m	2.241×10^{-2}	m^3	L^3
Permeability of vacuum	μ_o	$4\pi \times 10^{-7}$	Hm^{-1}	$I^{-2}MLT^{-2}$
Permittivity of vacuum ($1/\mu_o c^2$)	ε_o	8.854×10^{-12}	Fm^{-1}	$I^2M^{-1}L^{-3}T^4$
	$4\pi\varepsilon_o$	1.113×10^{-10}	Fm^{-1}	$I^2M^{-1}L^{-3}T^4$
Planck constant	h	6.626×10^{-34}	Js	ML^2T^{-1}
	$\hbar$	1.055×10^{-34}	Js	ML^2T^{-1}
Rest mass of electron	m_e	9.110×10^{-31}	kg	M
Rest mass of proton	m_p	1.673×10^{-27}	kg	M
Speed of light in vacuum	c	2.998×10^8	ms^{-1}	LT^{-1}
Stefan-Boltzmann constant ($2\pi^5k^4/15h^3c^2$)	σ	5.670×10^{-8}	$Wm^{-2}K^{-4}$	$MT^{-3}\theta^{-4}$