SK2411, IO2659 Second Examination tasks

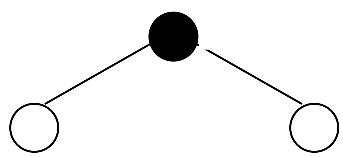
VT11, 2011 May 23

Task 1

(a) N_2 molecular gas comprises 78% of the atmosphere by volume. CO_2 gas, for comparison, comprises only 0.033% of the atmosphere. Nevertheless, unlike CO_2, the N_2 gas is not considered as a "greenhouse gas", contributing to the changes in the temperature of the Earth surface. What is the physical reason behind it?

Hint: the greenhouse effect is related to long-wavelength radiation trapping. (2 points)

(b) Vapour of heavy water D_2O is used as a gain medium for far-infrared lasers emitting wavelengths around 385 µm. Which degrees of freedom are used in these lasers: electronic, vibrational or rotational? How many vibrational and rotational modes contain D_2O molecule, whose structure is given below? (1 point)



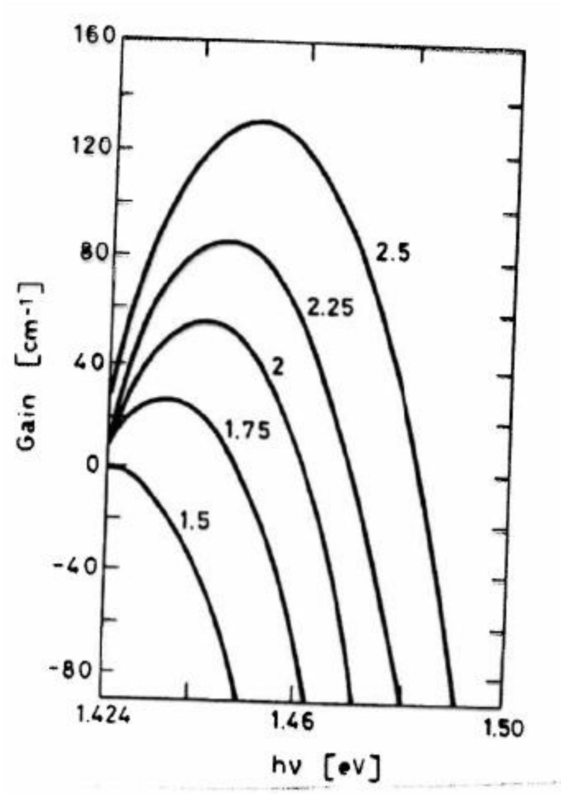
(c) Considering that the light water molecule H_2O has the same structure as in the picture above predict the wavelength emitted by H_2O laser. Reminder: hydrogen contains one proton, while deuterium contains one proton and one neutron in the nucleus and heavy water laser emits light with the wavelength of 385 µm. (1 point).

Task 2

(a) Spectral hole burning. In which gain media you would expect to observe it: Nd:YAG, Nd:glass, He-Cd? Explain briefly the physics behind it. (1 point).

(b) Spatial hole burning. In which gain media you would expect to observe it: Nd:YAG, Nd:glass, He-Cd? Explain briefly the physics behind it. (1 point).

(c) In the figure below gain spectra in the semiconductor GaAs are given for different injection carrier densities (given in units of 10^{18} cm^{-3} by the numbers at respective curves). Explain these dependencies. Specifically, pay attention why the gain maxima are shifting; why at the photon energy of 1.424 eV, the gain is always very close to zero even at high carrier densities; why the gain spectra are broadening with increasing carrier density. (2 points).



Task 3

(a) Organic dye molecules such as RhD6 can be used as laser gain medium as well as in bio-microscopy as fluorescent markers of different biologically significant molecules. Depending on surroundings of the molecules the fluorescence yield changes due to influence of nonradiative decay of the excited state. You know that the transition emitting fluorescence is dipole-allowed with the emission cross-section of $7x10^{-16}$ cm^2, the index of refraction of the medium surrounding the molecule is equal to 1.5, the central emission wavelength is 600 nm and the emission bandwidth (assume as being homogeneously broadened) is 3 THz. The fluorescence yield measured at the wavelength of 600 nm is 30%. Derive formula for calculating nonradiative relaxation time. Calculate the values of the radiative and the nonradiative relaxation times. Speed of light is $2.9979x10^8$ m/s. (3 points).

(b) What is natural linewidth? (1 point).

Task 4:

(a) Consider a resonator formed by two planar mirrors placed in parallel. What is the frequency spacing between two neighboring resonant modes if the cavity has a length of *L*? Explain how you came to the answer. If a laser has a gain line-width $\Delta\nu_0$, write out the condition imposed on *L* in order to have single-mode operation. (1 pt)

(b) Consider a resonator made of two concave mirrors (R_1>0, R_2>0) separated by a distance of L. Find the range(s) of *L* for which the resonator is stable. You may assume R_2>R_1. (1 pt)

(c) Does the TEM_{00} mode in a laser correspond to a lowest-order Gaussian beam? Indicate its beam profile in the transverse plane (say *xy* plane), preferably with equation and illustration. Show schematically how the beam evolves in free space in the longitudinal direction (say *z* direction). Indicate the beam waist and the Rayleigh range. (1 pt)

(d) What are the main advantages of a laser light source compared to natural light sources? Name at least three applications of lasers which cannot be done with natural light. (1 pt)

Task 5:

(a) State the rate equations for a four-level laser system. Assume single-mode operation and uniform lasing mode and pump. Explain each symbol and each term. (1 pt)

(b) Derive the expressions for the critical population inversion N_c and the critical pump rate R_{cp} under continuously-wave (CW) operation based on the above rate equations. Hint: The stimulated emission rate per photon per mode is $B = \frac{\sigma c}{V} = \frac{\sigma l c}{V_a L_e}$ and the cavity photon life-time is $\tau_c = \frac{L_e}{\gamma c}$, where V is mode volume, V_a is the mode volume in the active medium, L_e is the optical length of the cavity, l is the length of the active medium (other symbols have their standard meanings as used during the lectures). (1 pt)

(c) What is the population inversion if the pump rate is increased from R_{cp} to some larger value while the laser is still in CW operation? How about cavity photon number? Explain your answers. (1 pt)

(d) For pumping by incoherent light, describe the pump efficiency η_p by dividing the pumping process into four steps. Apart from the pump efficiency, what are the other factors which decide the overall slope efficiency η_s of a laser? Remember that

$\eta_s = \frac{dP_{out}}{dP_p}$, which is the amount of laser output power gained from a unit increase in pump power. (1 pt)

Task 6:

(a) What is the effect of spatial hole-burning on the number of longitudinal modes in a laser system? Repeat the question for spectral hole-burning. (1 pt).

(b) A Fabry-Perot etalon can help to reduce the number of longitudinal modes in a laser cavity; in turn it allows to increase the cavity length while keeping the single-longitudinal-mode laser operation. Explain the principle. Deduce the condition imposed on cavity length *L* in terms of gain line-width $\Delta\nu_0$ and finesse of the etalon *F* for getting a single-longitudinal-mode operation. Compare with the case without an etalon, i.e. task 4a. (1 pt)

(c) Consider a quasi-three-level laser. Draw schematically the time variations of population inversion (N) and cavity photon number (ϕ) just after the laser is suddenly switched on (R_p changes from 0 to a constant value at t=0). Show at least the first two cycles. Indicate specifically how the two curves are cross-related (synchronized) by qualitative arguments. (1 pt).

(d) Describe briefly the principles of Q-switching and mode-locking. Which approach has been used for generating the shortest pulse ever achieved? (1 pt)