University of Technology
Department of Laser & Opto-electronic Engineering
Final Examination 2011-2012

Subject: Laser Systems ***Class: 4^{th} year***
Division: Laser Engineering ***Time:3 hours***
Examiner: Dr. Hisham M. Ahmed ***Date: / /2012***

Answer five questions only

Q1: A- Draw and label a schematic diagram of Ar ion laser. Explain the function of segmented disks and the reasons for the presence of off-center holes. Why the pump efficiency of this laser increases by applying a magnetic field parallel to the laser tube? **(6 Marks)**

B- Why the N_2 laser is termed self-terminating? **(2 Marks)**

C- What are the main differences between different lasers? **(2 Marks)**

Q2: A- What is the role of two of the following: **(4 Marks)**
(i) A ballast resistor in HeNe laser.
(ii) The reservoir in CVL.
(iii) Cold trap in He-Cd laser.

B-What are the major constraints that influenced the design of CO_2 laser? **(3 Marks)**

C- On what parameters do the optimum mixing ratio depend in CO_2 lasers? **(3 Marks)**

Q3: A- Calculate the undulator period required in a free-electron laser (FEL) which has an undulator parameter K = 1 and operating at the emission wavelength =46.9nm when using a beam of electrons of energy 746 MeV and the electron rest energy is 0.511 MeV. Assuming a length of the magnets array L = 10 m, calculate the emission linewidth. **(6 Marks)**

B- Why the discharge tube diameter of a HeNe laser should be kept as narrow as possible? **(4 Marks)**

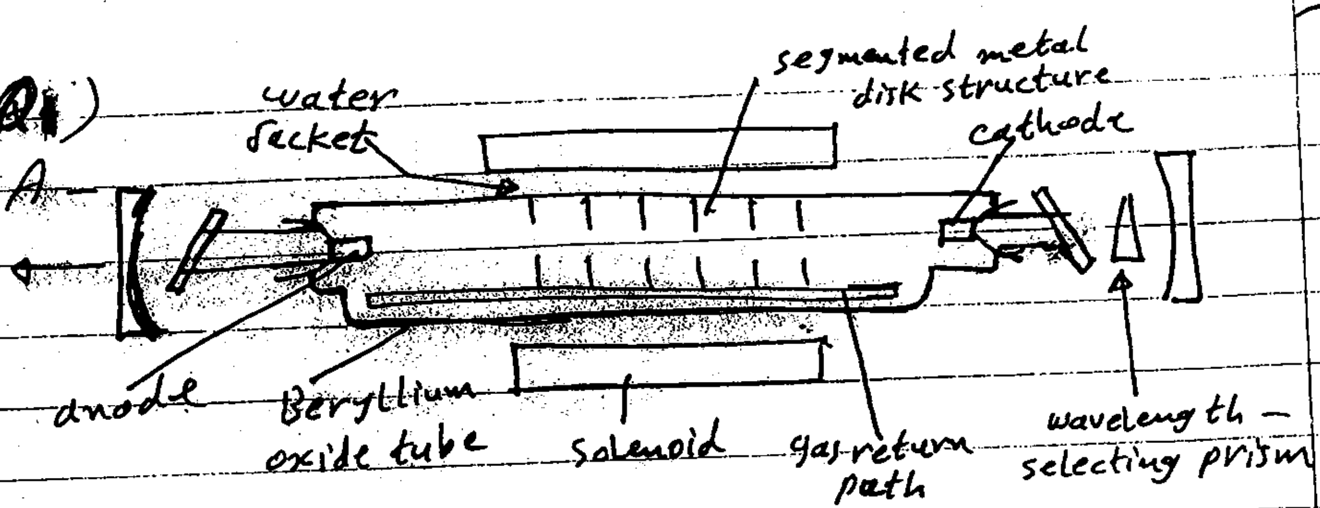
Q4: Explain the following terms: **(10 Marks)**
Pump efficiency, excitation efficiency, slope efficiency, overall system efficiency.

Q5: To estimate the internal losses in a high power diode pumped Nd:YLF laser, the threshold pump power was measured using two different output couplers with reflectivities R_1= 90% and R_2 =95%. The other cavity mirror has nominally 100% reflectivity at the laser wavelength .knowing that the measured threshold pump powers are p_{th1} = 1 w and P_{th2} = 600w .estimate the internal losses. **(10 Marks)**

Q6: Explain the principle of semiconductor laser operation and the difference between light emitting diode with laser diode. **(10 Marks)**

Q1)

A-



The segmented disks are placed at intervals along the tube with holes at their centers to define the active discharge. The disks serve to conduct heat away from the discharge to the tube walls. Also there are holes around the central holes (the off-center holes) to allow for gas return path. The pump efficiency is increased by applying a magnetic field since the ion spiral along the tube axis and kept away from the walls. This has the effect of confining the current near the center of the tube and increases the current density there.

B- Each laser differs from anothe laser in one or more of the following:

1- The output wavelength.

2- Time duration of the laser outputs (pulsed or CW).

3- power output levels.
4- operating efficiency.
5- coupling between the active medium and the pumping source.
6- Cooling system.

Q2) A-
(i) The role of the ballast resistor is to limit the current through the tube when the tube resistance falls.

A(ii)- The reservoir is located in the middle of the tube, and it's function is to replenish the reducing amount of Cu metal.

(iii) The cold trap is incorporated just before the cathode to protect it from Cd contamination and to prevent coating of the Brewster windows or end mirrors with cadmium.

Q2) B-
1- The removal of heat from the discharge tube
2- Operation of discharge at high electrical input powers.

C- 1- Laser system.
2- excitation mechanism.

Q3 2 A - $\lambda = \frac{\lambda_W}{2\gamma^2}(1+K^2)$

$$\gamma = \frac{E}{m_0c^2} = \frac{746\,MeV}{0.511\,MeV} = 1.46\times10^3$$

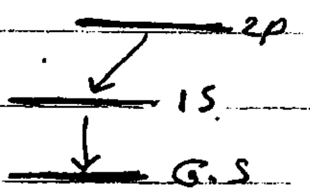
$$\therefore\ 46.9\times10^{-7}\,cm = \frac{\lambda_W}{2(1.46\times10^3)^2}(1+1^2)$$

$$\lambda_W = 10\ cm$$

$$\Delta\nu = \frac{\nu}{2N} = \frac{c/\lambda}{2L/L_W} = \frac{c\lambda_W}{2L\lambda} = \frac{3\times10^8\times10\times10^{-2}}{2\times10\times46.9\times10^{-9}} = 32\times10^{12}\,Hz$$
$$= 32\ THz$$

Q3: B - Two reasons:

1- The electrons in the terminal level (its population should be kept as low as possible) should decay as rapidly as possible back to the ground state. In neon this is a two step process, the first, 2p to 1s, is a rapid transition, but the second, 1s to the ground state, is not so rapid.



The latter transition rate is enhanced by collisions with the walls of the discharge tube.

2- The gain of the laser is found to be inversely proportional to the tube radius.

[illegible]

حلول المنزجب (النسخة الثالثة)

Q4:

① pump efficiency : $\eta_r \eta_t \eta_\alpha$

2.5

α : absorption coefficient

l : length of the active medium

$$\eta_\alpha = 1 - e^{-\alpha l}$$

② Excitation efficiency η.

2.5

$$\eta = \eta_p \eta_\phi \eta_B$$

$$\eta_\phi = \frac{h\nu}{h\nu_p} = \frac{\lambda_p}{\lambda}$$

③ Slope efficiency η_s

2.5

$$\eta_s = \eta \cdot \eta_c$$ (η_c) output coupling efficiency

④ overall system efficiency η_{sys}

2.5

$$\eta_{sys} = \frac{P_{out}}{P_p} = \eta_c \eta$$

$$\eta_E = \frac{P_{out}}{P_{avail}}$$

Q5 i)

$$\frac{P_{th1}}{P_{th2}} = \frac{\gamma^{(1)}}{\gamma^{(2)}} = \frac{\gamma_i + \frac{1}{2}\ln\frac{1}{R_1}}{\gamma_i + \frac{1}{2}\ln\frac{1}{R_2}}$$

$$\frac{1}{0.6W} = \frac{\gamma_i + 0.053}{\gamma_i + 0.026}$$

$$\gamma_i + 0.026 = 0.6\gamma_i + 0.032$$

$$\gamma_i = 0.015$$

$2\gamma_i = 0.03$ round trip internal losses.

9.4. SEMICONDUCTOR LASERS[31,32]

Semiconductor lasers represent one of the most important class of lasers in use today, not only because of the large variety of direct applications in which they are involved but also because they have found a widespread use as pumps for solid state lasers. These lasers will therefore be considered at some length here.

Semiconductor lasers require, for the active medium, a direct gap material and, accordingly, the normal elemental semiconductors (e.g., Si or Ge) cannot be used. The majority of semiconductor-laser materials are based on a combination of elements belonging to the third group of the periodic table (such as Al, Ga, In) with elements of the fifth group (such as N, P, As, Sb) (*III–V compounds*). Examples include the best known, GaAs, as well as some ternary (e.g. AlGaAs, InGaAs) and quaternary (e.g., InGaAsP) alloys. The cw laser emission wavelength of these III–V compounds generally ranges between 630–1,600 nm. Quite recently, however, very interesting InGaN semiconductor lasers, providing cw room-temperature emission in the blue (~410 nm), have been developed and promise to become the best candidates for semiconductor laser emission in the very important blue-green spectral region. Semiconductor laser materials are not limited to III–V compounds, however. For the blue-green end of the spectrum we note that there are wide-gap semiconductors using a combination between elements of the second group (such as Cd and Zn) and of the sixth group (S, Se) (*II–VI compounds*). For the other end of the e.m. spectrum, we mention semiconductors based on some *IV–VI compounds* such as Pb salts of S, Se, and Te, all oscillating in the mid-infrared (4 μm–29 μm). Due to the small band gap, these last lasers reuire cryogenic temperatures, however. In the same wavelength range, we thus mention the recent invention of the *quantum cascade* laser,[33] which promises efficient mid infrared sources without requiring cryogenic temperatures.

9.4.1. Principle of Semiconductor Laser Operation

The principle of operation of a semiconductor laser can be simply explained with the help of Fig. 9.18, where the semiconductor valence band, V, and conduction band, C, separated by the energy gap, E_g, are indicated. For simplicity, let us first assume that the semiconductor is held at $T = 0$ K. Then, for a non-degenerate semiconductor, the valence band will be completely filled with electrons while the conduction band will be completely empty (see Fig. 9.18a, in which the energy states belonging to the hatched area are completely filled by

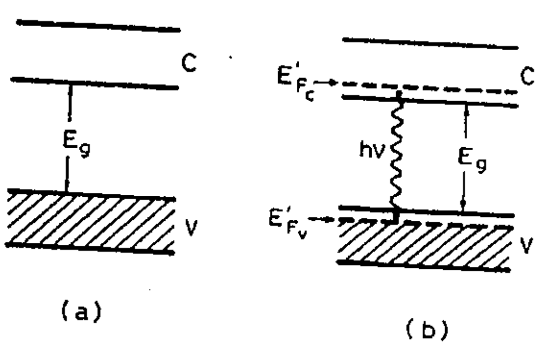


FIG. 9.18. Principle of operation of a semiconductor laser.

electrons). Suppose now that some electrons are raised from the valence band to the conduction band by a suitable pumping mechanism. After a very short time (~1 ps), the electrons in the conduction band drop to the lowest unoccupied levels of this band, and, meanwhile, any electron near the top of the valence band also drops to the lowest unoccupied levels of this band, thus leaving holes at the top of the valence band (Fig. 9.18b). This situation can be described by introducing the quasi-Fermi levels, E'_{F_c}, for the conduction band and, E'_{F_v}, for the valence band (see Sect. 3.2.3.). At $T = 0$ K they define, for each band, the energy below which states are fully occupied by electrons and above which, states are empty. Light emission can now occur when an electron, of the conduction band, falls back to the valence band recombining with a hole. This, so-called recombination-radiation process, is the process by which radiation is emitted in light emitting diodes (LED). Given the appropriate conditions, however, a process of stimulated emission of this recombination radiation, thus leading to laser action, can occur. It was shown in Sect. 3.2.5. that the condition for a photon to be amplified rather than absorbed by the semiconductor is simply given by [see Eq. (3.2.39)]

$$E_g \leq h\nu \leq E'_{F_c} - E'_{F_v} \tag{9.4.1}$$

In the simple case where $T = 0$ K, this condition can be readily understood from Fig. 9.18b, since the non-hatched area in the valence band corresponds to states which are empty, and a conduction band electron can only fall into an empty state of the valence band. However, the detailed treatment of Sect. 3.2.5. shows that condition of Eq. (9.4.1) in fact holds for any temperature and simply means that, for the range of transition energy $h\nu$ defined by Eq. (9.4.1), the gain arising from stimulated emission exceeds the absorption. To achieve condition of Eq. (9.4.1) one must, of course, have $E'_{F_c} - E'_{F_v} \geq E_g$. It is important at this point to realize that the values of both E'_{F_c} and E'_{F_v} depend on the intensity of the pumping process, i.e. on the number density, N, of electrons raised to the conduction band (see Fig. 3.15). Actually $E'_{F_c} = E'_{F_c}(N)$ increases while $E'_{F_v} = E'_{F_v}(N)$ decreases as N is increased. Thus, to obtain $E'_{F_c} - E'_{F_v} \geq E_g$ i.e., to have gain exceeding absorption losses, the electron density N must exceed some critical value established by the condition

$$E'_{F_c}(N) - E'_{F_v}(N) = E_g \tag{9.4.2}$$

The value of the injected carrier density which satisfies Eq. (9.4.2) is referred to as the carrier density at transparency*, N_{tr}. If now the injected carrier density is larger than N_{tr}, the semiconductor will exhibit a net gain and, if this active medium is placed in a suitable cavity, laser action can occur if this net gain is sufficient to overcome the cavity losses. Thus, to obtain laser action, the injected carriers must reach some threshold value, N_{th}, larger than N_{tr} by a sufficient margin to allow the net gain to overcome the cavity losses.

Semiconductor laser pumping can in principle be achieved, and indeed has been achieved, in a number of ways, e.g., by using either the beam of another laser, or an auxiliary electron beam, to transversely or longitudinally excite a bulk semiconductor. By far the most convenient way of excitation is, however, to use the semiconductor laser in the form of a diode with excitation produced by current flowing in the forward direction of the junction.[34] Laser action in a semiconductor was in fact first observed in 1962 by using a p-n junction

* Condition (9.4.2) is thus equivalent to the condition $N_2 = N_1$ under which a non-degenerate two level system becomes transparent