EE2003 – SEMICONDUCTOR FUNDAMENTALS (Part III)

Tutorial 11
Lasers

Q1:

For a two-level energy system, is it possible to achieve population inversion under thermal equilibrium? Please state your reasons.

No.

Because under thermal equilibrium, electron occupancy is determined by the Fermi-Dirac function.

The probability of finding an electron at a given energy E, $f(E) \propto \exp(-E/kT)$, which decreases exponentially as the energy level is increased. So, there are always fewer electrons at a higher energy level.

$$f(E) = \frac{1}{1 + \exp\left[\frac{E - E_F}{k_B T}\right]}$$

Q2:

For a two-level energy system,

(a) To achieve lasing action, what are the requirements?

- Population inversion (to make stimulated emission exceed spontaneous emission)
- Optical cavity (to trap the photons so as to enable them to further induce emission))
- Optical gain > optical loss (to sustain stimulated emission)

(b) What are the typical **pumping** mechanisms for a laser?

- Optical pumping
- Electrical pumping

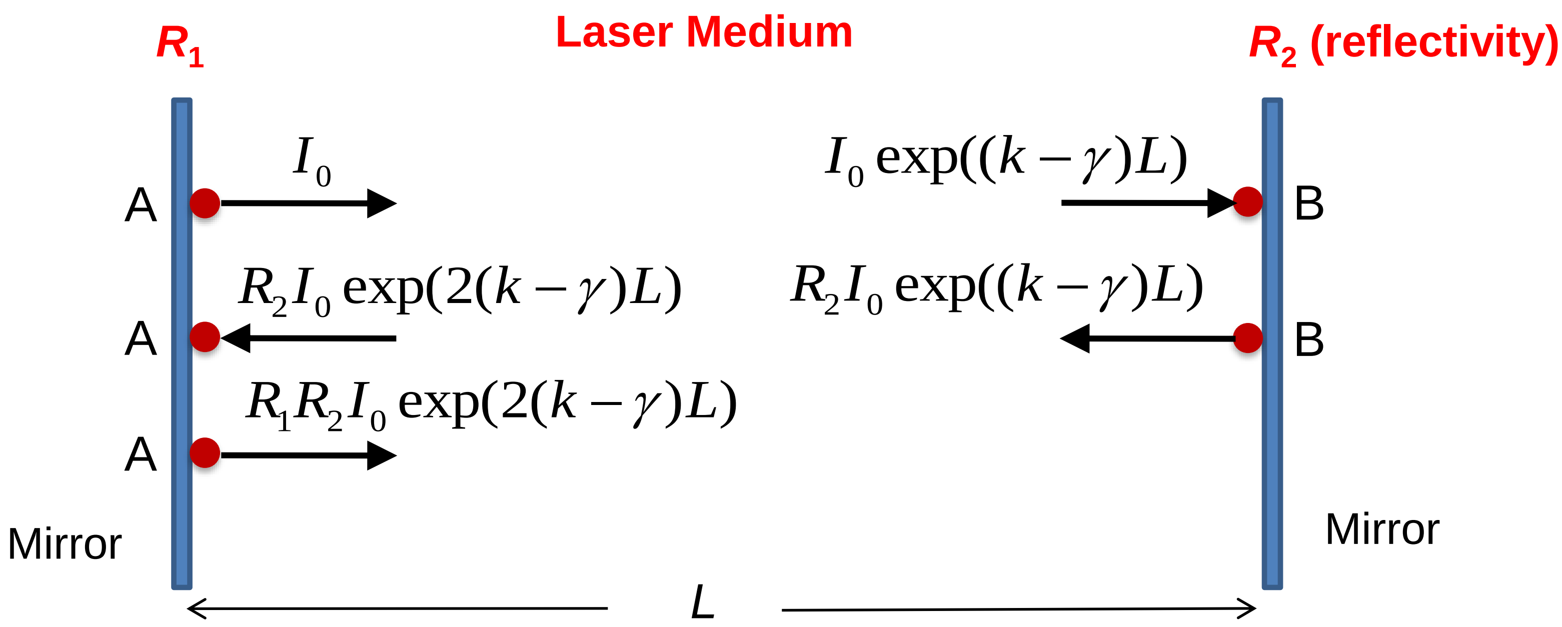
Q2:

(c) Explain the sources of optical losses in a laser.

- Absorption loss (photons emitted can be reabsorbed by the laser medium)
- Scattering loss (due to optical inhomogeneities in the laser medium)
- Transmission loss (photons that are let out through one of the mirrors to become useful output)
- Losses related to the mirrors
  - Absorption
  - Scattering
  - Diffraction

Q3:

(a) Derive the round trip gain in a laser cavity.



Roundtrip gain: $G = \dfrac{I}{I_0} = R_1 R_2 \exp(2(k-\gamma)L)$

k is gain coefficient and γ Is cavity loss coefficient.

Q3:

(b) State the condition for net amplification.

For net amplification, $I > I_0 \Rightarrow G > 1$

(c) State the condition that would lead to the dying out of the laser

The laser would eventually die out when $I < I_0 \Rightarrow G < 1$

(d) State the threshold condition and derive an expression for the threshold gain coefficient.

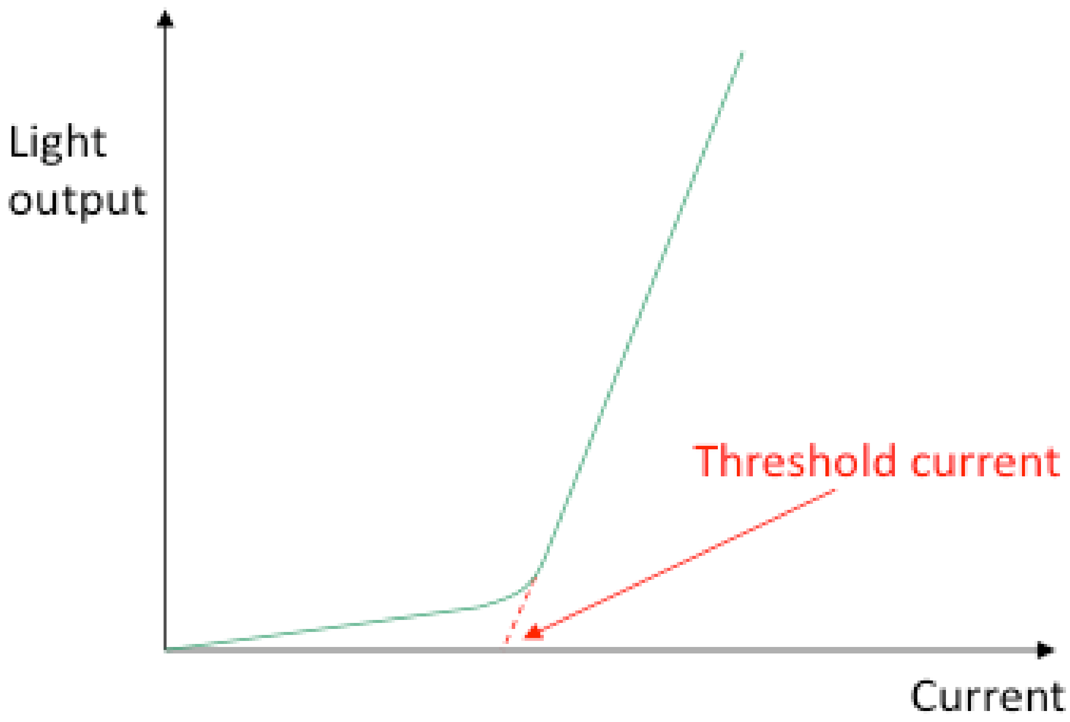
At threshold, $G = 1$.

$$R_1 R_2 \exp(2(k_{th} - \gamma)L) = 1$$

$$k_{th} = \gamma + \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

Q3:

(e) Show the threshold point in the light output vs. current plot of a laser diode.



Q4:

For a Fabry Perot laser cavity, the reflection coefficient of two mirrors both are 50%. The threshold gain coefficient is 5 cm^{-1}. When one of the mirrors is coated with a layer of metal providing 100% reflection, the threshold gain coefficient is 3 cm^{-1}. Calculate the loss coefficient γ cm^{-1} of the laser system.

At the laser threshold,

$$k_{th} = \gamma + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$$

$$5 = \gamma + \frac{1}{2L}\ln\left(\frac{1}{0.5\times 0.5}\right)$$

$$3 = \gamma + \frac{1}{2L}\ln\left(\frac{1}{1\times 0.5}\right)$$

Thus, $\gamma = 1\ \text{cm}^{-1}$

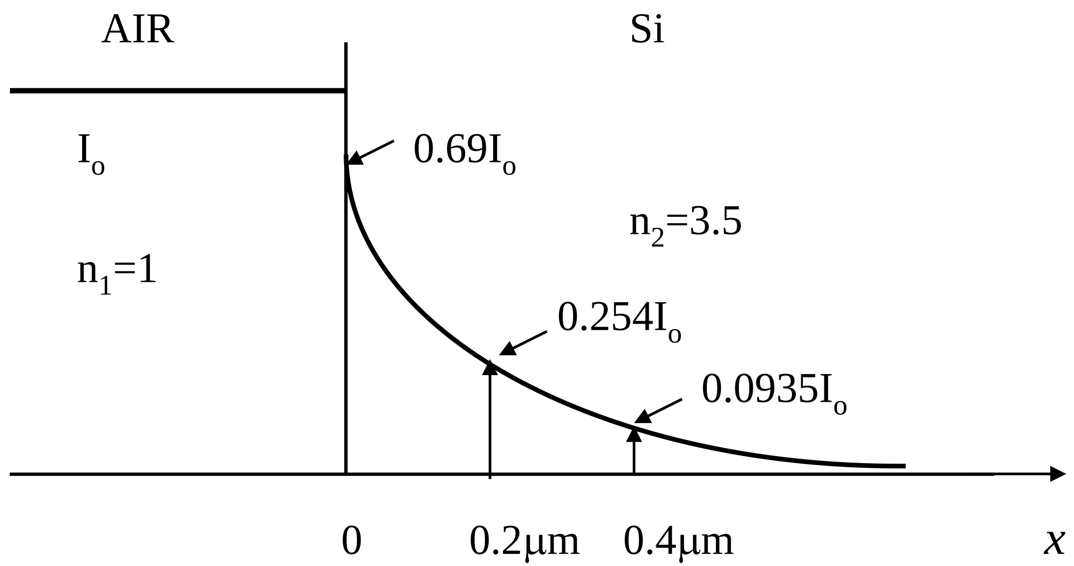
Q5:

A 300 μm thick single crystal Si wafer is subjected to incident surface-normal light with a total power of 20 mW. The absorption coefficient of Si is 5×10^{4} cm^{-1} and its refractive index is 3.5 at the light frequency.

(a) Determine the power absorbed within the first 0.2 μm and then the next 0.2 μm by the Si crystal.

(b) Explain why it is unlikely that the energy absorbed in the Si wafer can be converted into optical energy output through photon emission.

(a)



$$\text{Reflectivity, r} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = \left(\frac{1-3.5}{1+3.5}\right)^2 = 0.309$$

$$\text{Transmitted intensity, } I_t = (1\text{-}r)\,I_0 = 0.691\,I_0$$

$$\text{Intensity in Si: } I(x) = 0.691\,I_0 \exp(-\alpha x)$$

$$I(x = 0.2\ \mu\text{m}) = 0.691\,I_0 \exp\left(-5\times10^4 \times 0.2\times10^{-4}\right) = 0.254\,I_0$$

$$\text{I(x} = 0.4\ \mu\text{m}) = 0.691\,I_0 \exp\left(-5\times10^4 \times 0.4\times10^{-4}\right) = 0.0935\,I_0$$

Determine the power absorbed within the first 0.2 μm and then the next 0.2 μm by the Si crystal.

$$\underline{\text{Power absorbed in:}}$$

$$0.2\ \mu\text{m} = (0.691 - 0.254)\ I_0 = 0.437 \times 20\ \text{mW} = 8.74\ \text{mW}$$

$$0.4\ \mu\text{m} = (0.691 - 0.0935)\ I_0 = 0.597 \times 20\ \text{mW} = 11.95\ \text{mW}$$

$$\Rightarrow \textit{power}\ \text{absorbed between 0.2 to 0.4}\ \mu\text{m:}$$

$$= 11.95 - 8.74 = 3.21\ \text{mW}$$

Absorption is more at the surface and decreases exponentially through the material.

(b) Explain why it is unlikely that the energy absorbed in the Si wafer can be converted into optical energy output through photon emission.

This is because

Si is an indirect bandgap semiconductor.

Recombination between electrons and holes requires a change in the crystal momentum.

The momentum change is facilitated by lattice vibrations (phonons).

Interaction between electrons and phonons results in the electron energy being converted into thermal energy (heat).