Exercise Chapter 4

Constants

Speed of light c : 2.9979×10^{8} m.s^{-1}

Planck's constant h : 6.6261×10^{-34} J.s

Electronic charge e : 1.60218×10^{-19} C

Boltzmann Constan k_B : 1.3807 x 10-23 J.K^{-1}

Thermal voltage @ 300K k_BT/e : 25.85 meV

1 **Photon concentration in a gas laser** The Ar ion laser has a strong lasing emission at 488 nm. The laser tube is 1 m in length, and the bore diameter is 3 mm. The output power is 1 W. Assume that most of the output power is in the 488 nm emission. Assume that the tube end has a transmittance T of 0.1. Calculate the photon output flow (number of lasing photons emitted from the tube per unit time), photon flux (number of lasing photons emitted per unit area per unit time), and estimate the order of magnitude of the steady state photon concentration (at 488 nm) in the tube (assume that the gas refractive index is approximately 1).

2 **He-Ne Laser and the photon cavity lifetime** A particular He-Ne laser operating at 632.8 nm has a tube that is 35 cm long and end mirrors with reflectances 98.0% and 99.9%. The tube diameter is 0.75 mm and the output power is 0.80 mW. The linewidth $\Delta\upsilon$ is 1.5 GHz, and the loss coefficient α_s is 0.05 m^{-1}. The spontaneous emission lifetime is 100 ns. (a) Calculate the threshold gain. (b) Calculate the threshold population inversion (c) Calculate the photon cavity lifetime. (d) Calculate the photon concentration in the cavity

3 **Threshold population Nd:YAG laser** Consider a Nd:YAG laser . The emission wavelength is 1064 nm, the optical gain linewidth is about 120 GHz, the spontaneous lifetime (τ_{sp}) of the upper laser level is 230 µs. The loss coefficient α_s is 0.1 m^{-1} and the refractive index n is 1.8. Suppose that the YAG rod is 10 cm in length, and has its ends coated to achieve reflectances of 1 and 0.90 (emission end). What is the threshold concentration of pumped Nd-ions (Nd^{3+})?

4 **Population inversion in a GaAs homojunction laser diode** Consider the energy diagram of a forward biased GaAs homojunction LD as shown in Figure 4.32(b) For simplicity we assume a symmetrical device ($n = p$) and we assume that population inversion has been just reached when the conduction band on the n^+ side overlaps the valence band on the p^+-side around the center of the depletion region, as illustrated in Figure 4.32(b), which results in $E_{Fn} - E_{Fp} = E_g$.

Estimate the minimum carrier concentration $n = p$ for population inversion in GaAs at 300K. The intrinsic carrier concentration in GaAs is of the order of 10^7 cm^{-3}. Assume for simplicity that

$n = n_i \exp[(E_{Fn} - E_{Fi})/k_BT)]$ and $p = n_i \exp[(E_{Fi} - E_{Fn})/k_BT)]$

(Note: The analysis will only be an order of magnitude as the above equations do not hold in degenerate semiconductors. A better approach is to use the Joyce-Dixon equations as can be found in advanced textbooks. The present analysis is an order of magnitude calculation.

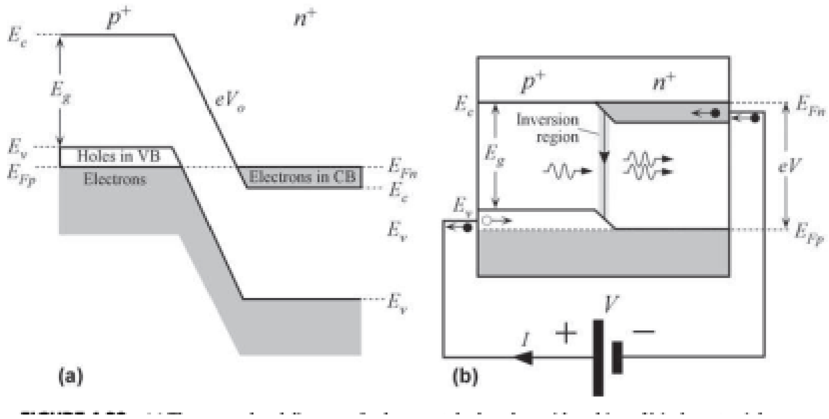

Figure 1 figure 4.32 (a) The energy band diagram of a degenerately doped pn with no bias. eVo is the potential energy barrier against electron diffusion from the n+-side to the p+-side. Note that (EFn - Ec) and (Ev - EFp) are small compared with eVo. (The diagram is exagerated)

5 **InGaAsP-InP Laser** Consider a FP InGaAsP-InP laser diode that has an optical cavity of length 250 microns. The peak radiation is at 1550 nm and the refractive index of InGaAsP is 3.8. The internal cavity losses (α_s) is 20 cm^{-1}. The optical gain bandwidth (as measured between half intensity points) will normally depend on the pumping current (diode current) but for this problem assume that it is 2 nm. (a) What is the mode integer m of the peak radiation? (b) What is the separation between the modes of the cavity? (c) How many modes are there in the cavity? (d) What is the reflectance at the ends of the optical cavity (faces of the InGaAsP crystal)?

6 **Fabry-Perot optical resonator in semiconductor lasers** Consider a semiconductor Fabry-Perot optical cavity of length 200 µm with end-mirrors that have a reflectance of R. If the semiconductor refractive index is 3.6, calculate the cavity mode nearest to the free space wavelength of 1300 nm. Calculate the separation of the modes. Calculate the spectral width for R = 0.9 and 0.8. What is your conclusion?

7 **GaAs DH laser diode** Consider GaAs DH laser diode that lases at 860 nm. It has an active layer (cavity) length L of 300 µm. The active layer thickness d is 0.1 µm and the width is (W) is 4 µm. The refractive index is 3.6, and the attenuation coefficient α_s inside the cavity is 15 cm^{-1}. The radiative lifetime τ_r in the active region is 2.5 ns. Find the threshold gain g_{th}, carrier concentration n_{th}, current density J_{th} and current I_{th}. Find the output optical power at $I = 1.5I_{th}$, and the external slope efficiency η_{slope}. How would $\Gamma = 0.5$ affect the calculations?

8 **Threshold current and power output from a 1310 nm FP laser diode** Consider a double heterostructure InGaAsP semiconductor laser operating at 1310 nm. The cavity length $L \approx 100$ µm,

width $W \approx 10$ μm, and $d \approx 0.1$ μm. The refractive index $n \approx 3.7$. The loss coefficient $\alpha_s \approx 20$ cm^{-1} and the direct recombination coefficient $B \approx 1\times10^{-16}$ m^3 s^{-1}. Assume that the optical confinement factor is 1. Find the threshold gain g_{th}, carrier concentration n_{th}, current density J_{th} and the threshold current I_{th}. Find the output optical power at $I = 1.3I_{th}$, and the external slope efficiency η_{slope}. What would I_{th} be if Γ were 0.3 (a more realistic value)?

9 **UV laser diode** Consider GaN-based MQW UV LD that emits at a peak wavelength of 370 nm. What is the transition energy ΔE in eV that corresponds to 370 nm? The threshold current is 45 mA and the emitted power is 20 mW at a forward current of 60 mA and a voltage of 4.5 V. Find the slope efficiency, EQE, EDQE, PCE. What is the power emitted at 50 mA?

10 **Laser diode modulation** Consider a GaAs LD, that has the following typical properties. The radiative lifetime, $\tau_r \approx 2$ ns, nonradiative lifetime $\tau_{nr} \approx 50$ ns, total attenuation coefficient $\alpha_t \approx 6000$ m^{-1} (this is basically the threshold gain for GaAs active layer of length of about 250 μm), refractive index n of 3.6. What is the relaxation oscillation frequency and hence the bandwidth at bias currents $I_1 = 2I_{th}$ and $3I_{th}$? What is the delay time if the LD is biased at $0.9I_{th}$ and switched by a current to $2I_{th}$? What is this delay time if the LD is not biased at all?