EE 5500 – Introduction to Photonics
Quiz II

60 minutes, 20 points, closed book

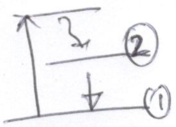
Remember…

- Make reasonable assumptions wherever necessary, but you should show all steps and justify assumptions for full credit. Use of figures may attract bonus points.
- Final answers will be graded ONLY if they are entered in the space provided.

Objective Type Questions (5 points)

1. Which of these is/are (maybe more than one) necessary condition(s) for laser operation?

   (a) Gain > loss (b) $N_2 > N_1$ (c) long T_2 (d) stimulated emission

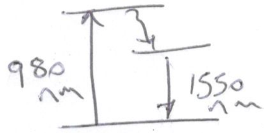


Gain need not be greater than loss
N_2 need not be greater than N_1
Long T_2 is desirable, not necessary

Stimulated emission is necessary for laser action

2. An Er-doped fiber laser pumped at 980 nm and operating at 1550 nm can be characterized as

   (a) 2-level (b) 3-level (c) 4-level (d) Cannot say



⇒ 3-level laser

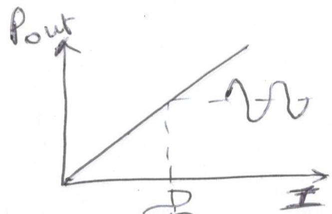
3. The average lifetime spent by a photon in a Fabry Perot laser cavity with loss=10 cm^{-1} & n=3

   (a) 1 ps (b) 10 ps (c) 100 ps (d) 1 ns

$$\tau_{ph} = \frac{1}{v_g \alpha_r} = \frac{1}{\frac{3\times10^8}{3}\times 10 \times 100} = 10^{11}\ s \quad \text{or} \quad \underline{10\ ps}$$

4. The modulation bandwidth of a LED does NOT depend on

   (a) drive current (b) heterostructure (c) recombination lifetime (d) any of these



$$\boxed{f_{3dB} \propto \frac{1}{\tau_c}}$$ ⇒ depends on recombination lifetime

NOT dependent on drive current

heterostructure helps to reduce recombination lifetime

5. For a given internal efficiency, the responsivity of a photodiode scales as

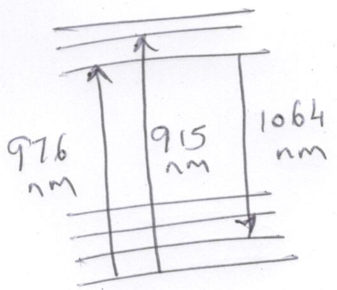
   (a) $1/\lambda$ (b) $\sqrt{\lambda}$ (c) λ^2 (d) λ

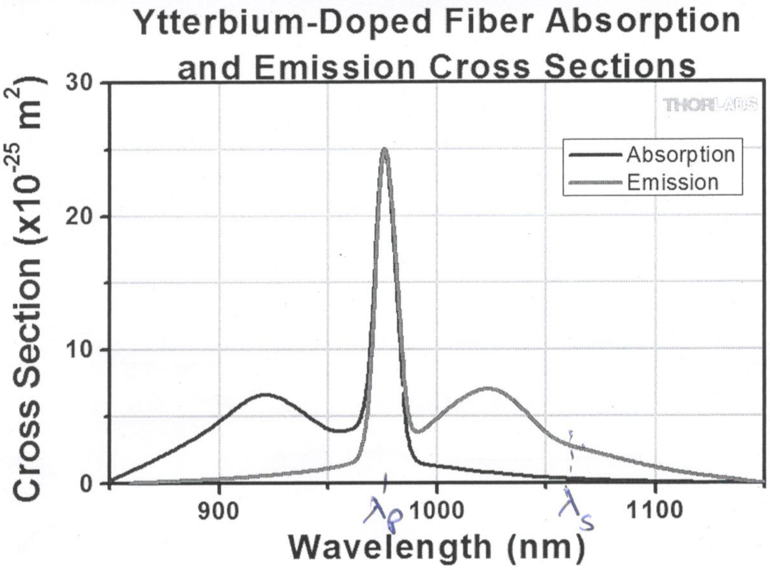
$$R = \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu} = \frac{\eta \lambda (\mu m)}{1.24}$$

$$\boxed{R \propto \lambda}$$

Quantitative Problems (2 questions, 15 points)

6. Suppose you are asked to design an optical amplifier at 1064 nm wavelength using a Yb-doped silica optical fiber, whose doping concentration is $3\text{x}10^{24}$ m^{-3} and its absorption and emission cross-sections are provided below.





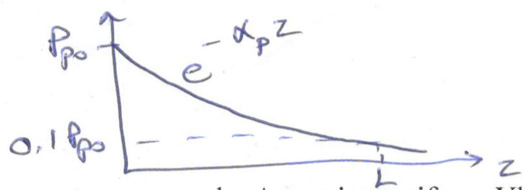
a. Based on the above graph, what are the possible pump wavelengths for the amplifier? Which one will you choose and why? (2 pts)

915 nm & 976 nm. The latter is preferred since the absorption cross-section is 3x higher.

b. Starting from appropriate rate equations, derive an expression for the small signal gain of the amplifier. (2 pts)

$$\frac{dP_s}{dz} = (N_2\sigma_e^s - N_1\sigma_a^s)P_s \Rightarrow G = \exp\left[\int_0^L (N_2\sigma_e^s - N_1\sigma_a^s)\,dz\right]$$

c. Estimate the length of Yb fiber required to absorb 90% of the launched pump radiation. (2 pts)



$$\alpha_p = N_a\sigma_a^p = 3\times10^{24}\times2.5\times10^{-24} = 7.5\ m^{-1}$$

$$e^{-\alpha_p L} = 0.9 \Rightarrow L = \frac{1}{7.5}\ln(0.9) = \underline{14\ mm}$$

d. Assuming uniform Yb ion excitation of 50% along the above length of fiber, what is the small-signal gain that could be achieved? (2 pts)

Assuming 50% excitation, $N_1 = N_2 = 0.5\,N_a$

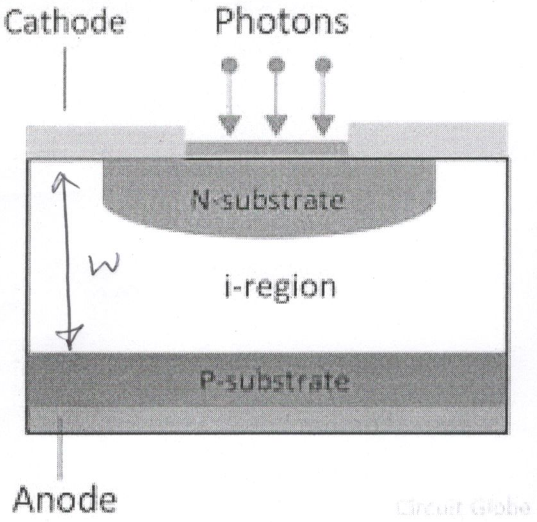
At 1064 nm (λ_s), $\sigma_e^s = 3\times10^{-25}\ m^2$

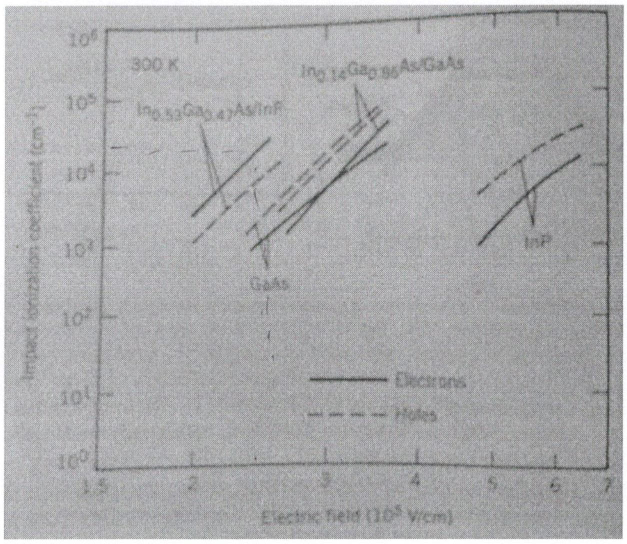
$\sigma_a^s = 0.1\times10^{-25}\ m^2$

$$G = \exp\left[0.5\times3\times10^{24}\times2.9\times10^{-25}\times14\times10^{-3}\right]$$

$$= \underline{1.006}$$

7. You have been asked to design a PIN photodiode with a bandwidth of 2.5 GHz for an optical fiber communication system using $In_{0.53}Ga_{0.47}As$ material (k = 0.5). The operation conditions include: photo-electron conversion efficiency of 0.8, anti-reflection coated facet, and an absorption coefficient of 0.5×10^5 cm^{-1} at 1550 nm.





a. Assuming negligible contribution from RC time constant and a saturation drift velocity of 10^5 m/s for 5 V reverse bias, what is the maximum width of the intrinsic region allowed to support the above bandwidth? (2 pts)

$$f_{3dB} = \frac{1}{2\pi(\tau_{tr} + \cancel{\tau_{RC}})} \quad \text{where } \tau_{tr} = \frac{W}{V_{dr}} = \frac{1}{2\pi . f_{3dB}} \Rightarrow W = \frac{V_{dr}}{2\pi \times f_{3dB}}$$

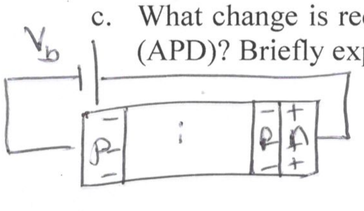
$= 6.4\ \mu m$

b. For the above structure, what is the expected responsivity? (2 pts)

$$\mathcal{R} = \frac{\eta\lambda}{1.24} \quad \text{where } \eta = (1-R_f)\zeta(1-e^{-\alpha W}) \simeq 0.8$$

$\Rightarrow \mathcal{R} = 1\ A/W$

c. What change is required in the above structure to realize an avalanche photodiode (APD)? Briefly explain with the help of appropriate schematic diagram. (1 pt)



Add p-layer between n & i layers

$\Rightarrow$ most of V_b drops across p-n junction

d. If the width of the multiplication region is 2 μm and the voltage drop across it is 50 V, what is the multiplicative gain (M) that could be achieved in the APD? (2 pts)

E-field in multiplication region $= \frac{50\ V}{2\ \mu m} = 2.5 \times 10^5$ V/cm

$\Rightarrow \alpha_e = 2 \times 10^4\ cm^{-1}$

Useful Constants:
Planck's constant (h) = 6.6256×10^{-34} J.s
Boltzmann's constant (k_B) = 1.38×10^{-23} J/K
Electric charge (q) = 1.602×10^{-19} C
Velocity of light (c) = 3×10^8 m/s

Useful Formulae
1. $M = (1-k) / \{\exp[-(1-k)\alpha_e W_m] - k\}$
2. $F = k.M + (1 - k).(2 - 1/M)$

$\alpha_e W_m = 4$

$$M = \frac{0.5}{e^{-2} - 0.5} = -1.37$$