4.3 Erbium doped fiber amplifier A fluorophosphate glass fiber has been doped with \(10^{19}\) Er\(^{3+}\) cm\(^{-3}\). At the wavelength of 1550 nm, the emission and absorption cross sections are \(4\times10^{-21}\) cm\(^2\) and \(3\times10^{-21}\) cm\(^2\) respectively. The Er\(^{3+}\)-doped fiber is pumped from a 1480 nm laser diode. Suppose that with strong pumping there is full population inversion \((N_i = 0)\), what is the maximum gain coefficient of the medium as dB m\(^{-1}\) at 1550 nm?

4.6 Erbium doped fiber amplifier Consider a 4 m long EDFA that has a core diameter of 5 \(\mu\)m, Er\(^{3+}\) doping concentration of \(8\times10^{18}\) cm\(^{-3}\); and \(\tau_p\) (the spontaneous decay time from \(E_2\) to \(E_1\)) is 10 ms. The fiber is pumped at 980 nm from a laser diode. The pump power coupled into the EDFA fiber is 30 mW. Assuming that the confinement factor \(\Gamma\) is 70%, what is the fiber length that will absorb the pump radiation? Find the small signal gain at 1550 nm for two cases corresponding to full population inversion and 80% inversion.

4.9 The Ar-ion laser The argon-ion laser can provide powerful CW visible coherent radiation of several watts. The laser operation is achieved as follows: The Ar atoms are ionized by electron collisions in a high current electrical discharge. Further multiple collisions with electrons excite the argon ion, \(\text{Ar}^+\), to a group of 4\(p\) energy levels \(\sim35\) eV above the atomic ground state as shown Figure 4.59. Thus a population inversion forms between the 4\(p\) levels and the 4\(s\) level which is about 33.5 eV above the Ar atom ground level. Consequently, the stimulated radiation from the 4\(p\) levels down to the 4\(s\) level contains a series of wavelengths ranging from 351.1 nm to 528.7 nm. Most of the power however is concentrated, approximately equally, in the 488 and 514.5 nm emissions. The \(\text{Ar}^+\) ion at the lower laser level \(4s\) returns to its neutral atomic ground state via a radiative decay to the \(\text{Ar}^+\) ion ground state, followed by recombination with an electron to form the neutral atom. The Ar atom is then ready for "pumping" again.

(a) Calculate the energy drop involved in the excited \(\text{Ar}^+\) ion when it is stimulated to emit the radiation at 514.5 nm.

(b) The Doppler broadened linewidth of the 514.5 nm radiation is about 3500 MHz (\(\Delta\nu\)) and is between the half-intensity points. Calculate the Doppler broadened width \(\Delta\lambda\) in the wavelength.

(c) Estimate the operation temperature of the argon ion gas; give the temperature in °C

(d) In a particular argon-ion laser the discharge tube, made of Beryllia (Beryllium Oxide), is 30 cm long and has a bore of 3 mm in diameter. When the laser is operated with a current of 40 A at 200 V dc, the total output power in the emitted radiation is 3 W. What is the efficiency of the laser?
4.12 Einstein coefficients and critical photon concentration $\rho(\nu)$ is the energy of the electromagnetic radiation per unit volume per unit frequency due to photons with energy $h\nu = E_2 - E_1$. Suppose that there are $N_{ph}$ photons per unit volume. Each has an energy $h\nu$. The frequency range of emission is $\Delta \nu$. Then, $\rho(\nu) = (N_{ph}h\nu)/\Delta \nu$. Consider the Ar-ion laser system. Given that the emission wavelength is at 488 nm and the linewidth in the output spectrum is roughly $5 \times 10^9$ Hz (between half intensity points), estimate the photon concentration necessary to achieve more stimulated emission than spontaneous emission.

4.17 Fabry-Perot optical resonator in gas lasers Consider an idealized He-Ne laser optical cavity. Taking $L = 0.5$ m, $R_1 = R_2 = 0.99$, calculate the separation $\Delta \lambda$ of the modes in wavelength and the spectral width $\delta \lambda$.

4.24 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

$$n = n_{e}\exp[(E_{Fn} - E_{Fp})/k_BT] \quad \text{and} \quad p = n_{e}\exp[(E_{Fn} - E_{Fp})/k_BT]$$

(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.)

4.26 SQW laser Consider a SQW (single quantum well) laser which has an ultrathin active InGaAs of bandgap 0.70 eV and thickness 10 nm between two layers of InAlAs which has a bandgap of 1.45 eV. Effective mass of conduction electrons in InGaAs is about 0.04$m_e$ and that of the holes in the valence band is $0.44m_e$, where $m_e$ is the mass of the electron in vacuum. Calculate the first and second electron energy levels above $E_c$ and the first hole energy level below $E_v$ in the QW. What is the lasing emission wavelength for this SQW laser? What is this wavelength if the transition were to occur in bulk InGaAs with the same bandgap?

4.29 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 $\alpha$, inside the cavity is 15 cm$^{-1}$. The radiative lifetime $\tau$, 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 $\eta_{slope}$. How would $\Gamma = 0.5$ affect the calculations?
4.31 **Laser diode efficiencies** The following specifications are provided for a particular commercial AlGaInP power laser diode (Hitachi HL6323MG) with an emission wavelength of 630 nm (red). The threshold current at 25 °C is 45 mA. Typical operating voltage for this device is 2.3 V. At \( I = 95 \) mA, the output optical power is 30 mW.

(a) Calculate the external QE, external differential QE, power conversion efficiency and the slope efficiency of the laser diode. What is the current required for an output of 20 mW?

(b) The threshold current at 50 °C is measured to be 70 mA. Assuming that \( I_{th} = A \exp(T/T_o) \) where \( T_o \) is a characteristic temperature, and given \( I_{th} \) at two temperatures, find the characteristic \( T_o \) temperature parameter. What is the threshold current at 0 °C? (The measured value is 31 mA)

4.34 **Laser diode extraction efficiency** Consider an optical cavity with end mirrors \( R_1 \) and \( R_2 \) and an internal loss coefficient of \( \alpha_i \). The total loss coefficient \( \alpha_t \) is given by

\[
\alpha_t = \alpha_i + (1/2L)\ln(1/R_1) + (1/2L)\ln(1/R_2)
\]

where the second term on the right represents the loss at the cavity end 1, associated with \( R_1 \), and the third is the loss at the cavity end 2 associated with \( R_2 \). Suppose that we are interested in how much light is coupled out from the cavity end 1. The extraction efficiency is then given by

\[
\eta_{EE} = (\text{Loss from cavity end 1}) / (\text{Total loss})
\]

i.e.

\[
\eta_{EE} = (1/2L)\ln(1/R_1) / \alpha_t
\]

Consider a GaAs active layer. The refractive index \( n \) is 3.6, the cavity length \( L \) is 250 \( \mu m \), and the internal loss coefficient \( \alpha_i = 10 \text{ cm}^{-1} \). (a) What is \( \eta_{EE} \)? (b) What would happen if you had no internal losses? (c) Suppose the end 2 had a perfect dielectric mirror and \( \alpha_i = 10 \text{ cm}^{-1} \). What is \( \eta_{EE} \)? (d) Suppose in (c) you set the internal losses to 1. What is \( \eta_{EE} \)? What is your conclusion?

(4.28 is a bonus question for EE130 students.)

4.28 **Fabry-Perot optical resonator in semiconductor lasers** Consider a semiconductor Fabry-Perot optical cavity of length 200 \( \mu m \) 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?

(4.13 is a bonus question for EE230 students.)

4.13 **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).