Exercise 1

Let's consider an optically pumped amplifier that amplifies light between levels E_1 and E_2. The population at ground level, level 1, and level 2 are denoted N_g, N_1, N_2, respectively. No signal is at the input.

Assume that $R_1 = 0$ and that R_1 is realized by exciting atoms from the ground level to level 2 using photons of frequency E_2/h. These photons are absorbed with a transition probability W_p (i.e. probability between ground level and level 2)

Assume also that $\tau_2 \approx \tau_{sp}$ and $\tau_1 \ll \tau_{sp}$. In steady state we have $N_1 \approx 0$ and $N_0 \approx R_2\tau_{sp}$.

If N_a is the total population distributed over levels 0,1 and 2:

(a) Write the steady state equation for population N_2.

(b) Write the rate equation for the pumping rate R_2 as a function of W_p and show that $R_2 \approx (N_a - 2N_0)W_p$. (hint: R_2 will depend on the population N_g and N_2)

(c) Show that $N_0 \approx N_a\tau_{sp}\frac{W_p}{(1+2\tau_{sp}W_p)}$

Exercise 2

We are building and EDFA with a fiber length of 30 m. The stimulated emission cross section for this specific doped fiber is $\sigma(\nu) = 5 \cdot 10^{-25}\ \mathrm{m}^2$.

What population difference $(N_2 - N_1)$ is necessary for the amplifier gain to reach 30 dB?

Exercise 3

In a DWDM system using PSK modulation one wishes to transport data over $L_T = 1000$ km with as few as possible wavelength channels. In the system one also wishes to minimize the number of in-line EDFAs (N_A) used in the link. The fiber loss is α =0.2 dB/km.

The required OSNR for a given total bit rate scales approximately linearly with the number of bits/symbols, e.g. QPSK (2 bits/symbol) needs twice the OSNR required for binary PSK (1 bit/symbol).

(a) The binary PSK system needs ten amplifiers to satisfy the OSNR requirement at the end of the link. What is in this case the distance L_A between amplifiers ? What is the gain G_1 required of the EDFA in this case?

(b) Show that the number of amplifiers N_A can be expressed as $N_A = (\alpha L_T)/(\ln G)$ and that the ONSR at the end of the link can be written as :

$$OSNR_{end} = \frac{P_{in}\ln G}{2n_{sp}h\nu\Delta\nu_0\alpha L_T(G-1)}$$

(c) Using this expression of OSNR and assuming that the optical filter bandwidth is the same in all cases, what should be the gain G_1 and G_4 required of the EDFA if the linked used QPSK (2 bits/symbol) or 16-QAM (4 bits/symbol), respectively? (HINT: start by expressing the ratio of the required OSNR compared to the PSK case, which simplifies many of the terms in common …)

(d) How many amplifiers would be needed for the link if QPSK or 16-QAM was used?

Exercise 4

We want to set up a 200 km link at 1550 nm operating at 1 Gb/s using RZ format. The transmitter has a given rise time of 100 ps. The receiver is RC limited and has a capacitance of 2 pF and a load resistance of 80 Ω. Dispersion is 17 ps/km.nm. The source has a spectral width of 0.016 nm.

From the rise time budget, can such link operate correctly? What are the possible solutions ?

Exercise 5

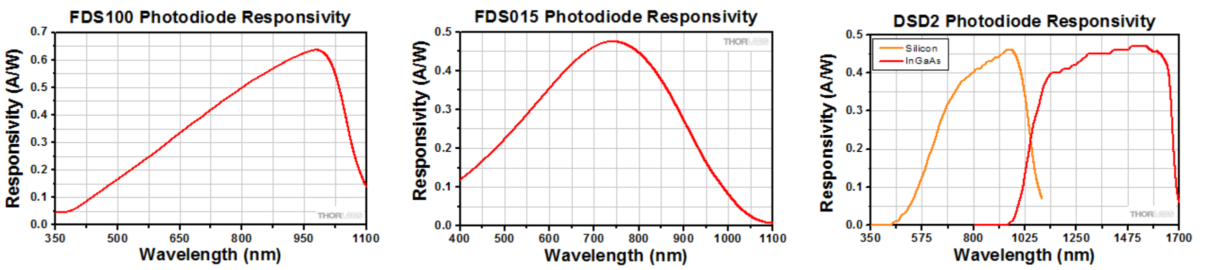
We are designing a typical digital fiber optic link. The data to be transmitted is operating at a data rate of 18 Mb/s with NRZ and we must guarantee a BER of 10^{-9}.

We are using an AlGaAs LED emitting at 850 nm and 100 mW of power can be coupled into a multimode GRIN fiber with a core of 50 µm. The source including its drive circuit has a rise time of 12 ns. The GRIN has a loss of 2.5 dB/km and given the spectral bandwidth of the source induces a combined material/intermodal-group-delay dispersion of 4 ns/km.

The fiber requires splicing every 1 km with a 0.5 dB/splice of loss. We also need 2 connectors, one at the transmitter and one at receiver end, each with 1 dB of loss.

The receiver uses a p-i-n photodiode with a load resistance of 1 kΩ, a noise figure f_n= 3 dB and with a bandwidth assumed to be exactly matched for 20 Mb/s NRZ data. Assume a temperature of 300 K and that the system is in the thermal limit

(a) You have a choice between the p-i-ns shown below. Assume they all have a response time of 10 ns Which one do you use and why?



(b) Based on the photodiode you picked, what is the receiver sensitivity for BER $=10^{-9}$?

(c) Verify that your assumption of thermal limit is correct.

(d) What is the possible maximum loss limited link length without repeaters if a 1 dB margin is required?

(e) Based on rise time budget, is this system viable?

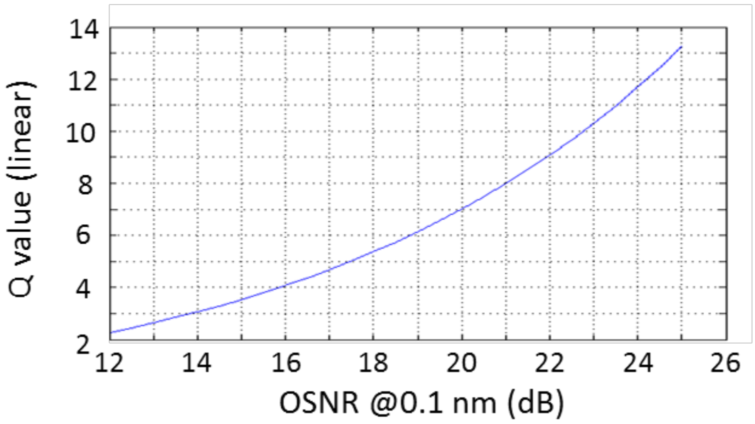
(f) If the system is viable, how much further could you actually go? in this case what would be the BER at the end of your link ?

Exercise 6

You are designing a 1550 nm 3000 km long fully dispersion-compensated fiber-optic link. The link is periodically amplified, and you are considering either 50 km or 75 km spacing between amplifiers. The dilemma is that while an increased span length saves you a lot of money on EDFAs, the OSNR will be worse. The fiber average loss is 0.3 dB/km because of dispersion compensation. Each span is followed by an EDFA with gain equal to span loss. The EDFA noise figure is 5 dB and the average input signal power into each span is 1 mW.

(a) Calculate the OSNR (at the receiver) in the two cases. Assume 0.1 nm of optical filter bandwidth is sufficient.

(b) Use the figure below, which shows the relation between OSNR and Q-value and determine the BER with the two span lengths.



(c) Given that you need -22.5 dBm of power at the receiver, what could be the maximum length of an additional last fiber span, after the last EDFA (Reuse the fact that the input power in the last span is 1 mW).

(d) You want to increase the reach by adding backward Raman pumping on the last span. You have a 1 W Raman pump available. The loss at the pump wavelength is 0.25 dB/km. The fiber has $a_p = 50\ \mu\text{m}^2$ and $g_r = 6 \cdot 10^{-14}\ \text{m/W}$. How long could this last span be? Assume the length of the last span is much longer than the effective length.

Graded Exercise

Part 1:

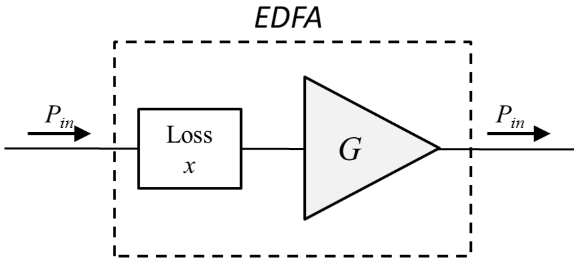
An Erbium doped fiber amplifier built from a co-doped silicate L22 fiber could be used to amplify a 940 nm signal, where the spontaneous life time is 0.001 ms, or in the C-band, where the spontaneous lifetime is 14.5 ms. You can either pump at 800 nm or 980 nm, where the absorption cross sections are $4 \cdot 10^{-22}$ cm² and $10 \cdot 10^{-22}$ cm², respectively. The fiber has a radius of 4 μm.

(a) What pump wavelength would you use to amplify 940 nm? What minimum pump power would it require? Is such amplifier practical? What is the limiting factor?

(b) What pump wavelength would you use to amplify in the C-band? What would be the minimum pump power required in this case?

Part 2:

A 25 dB gain C-band EDFA is used as a preamplifier but due to a bad design, it suffers from an optical loss at the input port as shown below. The power entering the EDFA is therefore xP_{in}.



Without the loss section (that is when x = 1) the EDFA has a noise figure of $NF = 2n_{sp} = 5$ dB. When installed the loss is actually of 3 dB (x = 0.5). We want to calculate the noise figure of the lossy amplifier (the relation $NF = 2n_{sp}$ does not hold anymore).

(a) Does the loss impact the input signal to noise ratio $(SNR)_{in}$? Assuming that shot noise dominate at the input, find the expression for $(SNR)_{in}$.

(b) Assuming that signal-ASE beat noise dominates after the EDFA, find the expression for $(SNR)_{out}$.

(c) Find the expression for the new NF. Estimate its value in the limit $G \gg 1$ and η = 100%.