HW #10 due 4/26/18 5PM
no later than 4/29/18 5PM

1. A shot-noise-limited 500 Mbps PCM system operates with a BER Better than 2×10^{-11}. The wavelength is $1.3\mu m$ and the photodetector's quantum efficiency is 0.9. The dark current is negligible.
a) How much optical power must reach the receiver?
b) Compute the number of incident photons per bit at this power level.
c) Compare the results of this problem with those in HW 9 problem 3.
d) You should have found that the quantum-limited system required much less power than the thermal-limited one. How can the system be designed to approach the quantum-limited results? (Note: look at various expressions for SNR for various detectors in the handout.)

2. a) Compare the maximum theoretical PCE for 980nm and 1475nm pumping in an EDFA for a 1545nm signal. Contrast this with actual measured results of PCE=50.0 percent and 75.6 percent for 980nm and 1475nm pumping, respectively.
b) Using the actual results for PCE given in a), plot the maximum output power as a function of pump power for $0 \le P_{p,in} \le 200$ mW for pump wavelength of 980nm and 1475nm.

3. Assume we have an EDFA power amplifier that produces $P_{out} = 30$ dBm for an input level of 2dBm at 1582nm.
a) Find the amplifier gain.
b) What is the minimum pump power power required? (hint: choose an appropriate pump wavelength to achieve minimum pump power)

4. a) To see the relative contributions of the various noise mechanisms in an optical amplifier, calculate the values of the five noise terms in Eq. (11-29) of the handout for operational gains of G=28dB and 38dB. Assume the optical bandwidth is equal to the spontaneous emission bandwidth (30nm linewidth) and use the following parameter values:
quantum efficiency $\eta = 0.6$, responsivity $R = 0.7$A/W, input optical power $P_{in} = 1\mu W$, wavelength $\lambda = 1560$nm, optical bandwidth $\Delta\nu_{opt} = 3.77 \times 10^{12}$Hz, receiver bandwidth $\Delta f = 2 \times 10^{9}$Hz, spontaneous emission factor $n_{sp} = 2$, receiver load resistor $R_L = 1000\Omega$.
b) To see the effect of using a narrowband optical filter at the receiver, let $\Delta\nu_{opt} = 1.25 \times 10^{11}$ Hz and find the same five noise term values for G=25dB and 35dB.

Extra-credit for undergraduate (regular for graduate)
5. Consider the use of a EDFA of gain 22dB for a receiver with a PIN diode that has a responsivity of 0.7A/W and NEP of $5 \times 10^{-11} W/\sqrt{Hz}$. Find the input power below which the beat noise of the signal with the ASE is smaller than the signal independent noise power. Assume $n_{sp} = 8$ and wavelength $\lambda = 1540$nm. (Hint: Which noise is independent of input? Thermal or Shot noise?)

Extra-credit
6. a) Consider the WGR described in section 3.3.8 and in particular equation (3.15) which gives the phase different between input port i and output port j through waveguide k. Now assume $d_{ik}^{in} = R(1 - ik\alpha^2)$ and $d_{kj}^{out} = R(1 - kj\alpha^2)$ where R is the separation between input/output fiber array and WGR and α is the incremental change in angle from one port to adjacent waveguides measured in radian. Similar to MZ interferometer, the phase difference between adjacent waveguide paths must satisfy constructive interference condition, i.e. $\phi_{i\,j\,k} - \phi_{i\,j\,k-1} = 2\pi$, to have output. We call the wavelength that satisfy such condition λ_{i+j}. Carry out the above procedure and show that $\lambda_{i+j} = \lambda_0 - (i + j)\,\Delta\lambda$ where $\lambda_0 = n_2\Delta L$ and $\Delta\lambda = n_1\alpha^2 R$.
b) Consider multiple wavelength laser in April 17 summary (last item). Follow the same

wavelength assignment in a) and the example diagram, design a multiple wavelength laser that generate λ_{14}, λ_{10} and λ_9. If $n_1 = n_2 = 1.5$, $\Delta L = 1.033\mu m$, $R = 10mm$ and $\alpha = 5 \times 10^{-4}$, find numerical values for λ_{14}, λ_{10} and λ_9.