Exercise 1

Photons at a rate $10 \cdot 10^{10}\ /s$ are incident on an APD with responsivity of 6 A/W. Calculate the quantum efficiency and the photocurrent at the operating wavelength of 1550 nm for an APD gain of $M = 10$.

Exercise 2

A heterojunction a p-i-n photodiode is made of different materials to guarantee that all the light is absorbed in the intrinsic layer (i.e. the p and n layers are fully transparent to the light intended to be detected). We want to design such a photodiode to operate between 1064 nm and 1550 nm. The intrinsic layer is $2.5\ \mu\text{m}$ wide with electron drift velocity of $10^7\ \text{cm/s}$. The diode has a junction capacitance of 2 pF.

(a) Find the bound value for bandgap energy of the intrinsic region. Is this a maximum or minimum value?

(b) Find the bound value for the bandgap energy of the p, n region. Is this a maximum or minimum value?

(c) Given the quantum efficiency of the device being 0.92, what is the range of responsivity of the photodiode?

(d) If the detector dark current is $i_d = 3\ \text{nA}$, what is the minimum detectable optical power at 1550 nm?

(e) The photodiode is to be used with 10 Gb/s NRZ data. Find the maximum allowable value of load resistance, such that the photodiode bandwidth is adequate ($\Delta f = B/2$).

Exercise 3

You have a 10 Gbit/s NRZ transmitter at 1550 nm wavelength that outputs an average of 9 dBm of optical power. T The extinction ratio is ideal. The transmitter is connected to a fiber-optic link that has a total loss of 28 dB before reaching the receiver. At the receiving end, you have a p-i-n photodetector with a quantum efficiency of 80%, and negligible dark current. The photocurrent is amplified by an amplifier with a load resistance of 50 Ω, a noise equivalent bandwidth of $\Delta f = 5\ \text{GHz}$ and a noise figure of 3 dB.

Assume room temperature, that 1-bits and 0-bits are equally likely, and that the decision threshold is ideal.

(a) Calculate thermal noise and shot noise for ‘0’ and ‘1’ bits. Then determine the bit-error-rate (BER).

(b) Receiver sensitivity is defined as the average received optical power required for a BER of 10^{-9} ($Q = 6$). Determine the sensitivity of this receiver. (hint: what is the noise limit here?)

(c) If you replace the p-i-n with an APD, would the sensitivity improve? Why/why not?

Exercise 4

A PIN photodiode has a responsivity of 0.6 A/W at 0.8 µm, an amplifier noise figure F_n of 3 dB, a bandwidth Δf of 10 MHz, and a load resistance R_L of 100 Ω. Assume that thermal noise dominates.

(a) Calculate the thermal noise at a temperature of 300 K

(b) Calculate the noise equivalent power (NEP) in $\mathrm{pW}/\sqrt{\mathrm{Hz}}$, defined as the minimum optical power per unit bandwidth, required to produce SNR = 1.

(c) Calculate the minimum received power for BER of 10^{-9}.

(d) Calculate the shot noise for this value of received power. If we need at least 3dB between the 2 sources of noise to be considered in a limiting noise regime, verify if we are thermal noise limited.

(e) Calculate the signal to noise ratio for that value of received power

Exercise 5

We have an APD with a gain region of width $d = 0.5\ \mu\mathrm{m}$. Assume that the electron and hole ionization coefficients in silicon are approximated by the following equation:

$$\alpha = A\exp\left(-\frac{B}{E}\right)$$

With E the value of the field in the multiplication region. For electrons we have $A \approx 0.74 \cdot 10^6\ \mathrm{cm}^{-1}$,$B \approx 1.16 \cdot 10^6\ \mathrm{cm}^{-1}$, and for the holes $A \approx 0.725 \cdot 10^6\ \mathrm{cm}^{-1}$, $B \approx 2.2 \cdot 10^6\ \mathrm{cm}^{-1}$.

Recall that the multiplication factor of the APD is given by

$$M = \frac{1 - k_A}{\exp[-(1 - k_A)\alpha_e d] - k_A}$$

(a) Express M_e the multiplication factor of the APD if only the electron avalanche without holes ionizing (what would be $k_A$in this case…).

(b) Find the real multiplication factor M and the factor M_e in the case the applied field in the gain region reaches values of $4 \cdot 10^5\ \mathrm{Vcm}^{-1}$, $4.3 \cdot 10^5\ \mathrm{Vcm}^{-1}$, $4.38 \cdot 10^5\ \mathrm{Vcm}^{-1}$.

$E\ \mathrm{Vcm}^{-1}$	$4 \cdot 10^5$	$4.3 \cdot 10^5$	$4.38 \cdot 10^5$
α_e			
α_h			
k_a			
M			
M_e			

(c) What can you say about the evolution of k_A, M, M_e, as a function of the field ?

Graded Exercise

You have an RZ-transmitter at a wavelength of 1550 nm operating at 10 Gbit/s and a 40 km standard SMF with a loss of 0.2 dB/km and a dispersion coefficient of 16 ps/(nm km). The receiver consists of a p-i-n photodiode with a quantum efficiency of 0.7 and a negligible dark current, as well as an electrical amplifier with a load resistance of 50 Ω, noise figure of 3 dB and a bandwidth of 8 GHz.

Due to GVD, the pulses have broadened into neighboring bit slot after transmission. By looking at the eye-diagram with an oscilloscope at the output, the average optical power in 1-bits and 0-bits is measured to be -8 dBm and -13.5 dBm, respectively (i.e. the extinction ratio is degraded). Assume that 1-bits and 0-bits are equally likely.

(1) Make assumption on the noise limiting regime (thermal or shot). Based on this assumption, determine the sensitivity of the receiver (defined at BER = 10^{-9}) with the dispersion-degraded extinction ratio as above.

(2) Verify that your assumption is correct.

(3) What is the actual average power received? By how much (in dB) should you change the average transmitter power (up or down) from its current setting to operate the system at a BER of 10^{-9}?

(4) To avoid the problem of broadening due to GVD you are considering adding some DCF to the system. The DCF module compensates the dispersion perfectly, but has a loss of 3.5 dB. Find the power penalty due to the GVD, i.e. find how much the sensitivity has degraded compared to the case without GVD. Is adding the DCF a good idea?