Texas A&M University
Department of Electrical and Computer Engineering

ECEN 721 – Optical Interconnects

Spring 2024

Exam #1

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- Please write your name in the space provided below
- Please verify that there are 5 pages in your exam
- You may use one double-sided page of notes and equations for the exam
- Good Luck!

Problem	Score	Max Score
1		50
2		50
Total		**100**

Name: SAM PALERMO

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Table 4.1 Numerical relationship between Q and bit-error rate.

Q	BER	Q	BER
0.0	1/2	5.998	10^{-9}
3.090	10^{-3}	6.361	10^{-10}
3.719	10^{-4}	6.706	10^{-11}
4.265	10^{-5}	7.035	10^{-12}
4.753	10^{-6}	7.349	10^{-13}
5.199	10^{-7}	7.651	10^{-14}
5.612	10^{-8}	7.942	10^{-15}

Table 4.6 Numerical values for BW_n and BW_{n2}.

$H(f)$	BW_n	BW_{n2}
1st-order low pass	$1.57 \cdot BW_{3dB}$	∞
2nd-order low pass, crit. damped ($Q = 0.500$)	$1.22 \cdot BW_{3dB}$	$2.07 \cdot BW_{3dB}$
2nd-order low pass, Bessel ($Q = 0.577$)	$1.15 \cdot BW_{3dB}$	$1.78 \cdot BW_{3dB}$
2nd-order low pass, Butterworth ($Q = 0.707$)	$1.11 \cdot BW_{3dB}$	$1.49 \cdot BW_{3dB}$
Brick wall low pass	$1.00 \cdot BW_{3dB}$	$1.00 \cdot BW_{3dB}$
Rectangular (impulse response) filter	$0.500 \cdot B$	∞
NRZ to full raised-cosine filter	$0.564 \cdot B$	$0.639 \cdot B$

Problem 1 (50 points)

A 32Gb/s optical receiver utilizes an GaAs vertical p-i-n detector that has a 0.5μm intrinsic layer width when operating at λ=850nm.

a) What is the necessary detector absorption coefficient α to achieve a responsivity R=0.5A/W?

$$R = \left(1-e^{-\alpha W}\right)\frac{q}{hc}\lambda$$

$$\alpha = \frac{-\ln\left(1-\frac{Rhc}{q\lambda}\right)}{W} = \frac{-\ln\left[1-\frac{0.5}{(8\times10^{5})(850nm)}\right]}{0.5\mu m}$$

$$\alpha = 2.66\times10^{6}\,m^{-1} = 2.66\times10^{4}\,cm^{-1}$$

α = $2.66\times10^{4}\,cm^{-1}$

b) The detector must have a 32GHz bandwidth to not limit the system. The device is biased to yield carrier velocities of 2×10^{5}m/s and has C_{PD}=50fF. What is the maximum parasitic R_{PD} to achieve 32GHz bandwidth?

$$BW = \left(\frac{1}{2\pi}\right)\frac{1}{\frac{W}{V_n}+R_{PD}C_{PD}}$$

$$R_{PD} = \frac{\frac{1}{2\pi BW}-\frac{W}{V_n}}{C_{PD}} = \frac{\frac{1}{2\pi(32G)}-\frac{0.5\mu m}{2\times10^{5}\,m/s}}{50fF} = 49.5\Omega$$

Max R_{PD} = 49.5Ω

c) An optical amplifier with G=20 and ηF=3 is added to the receiver before the p-i-n detector. This is followed by a simple front-end that consists of a 40Ω resistor and has a noise bandwidth BW_n=32GHz. Give the optical average power sensitivity for a BER=10^{-15} considering both amplifier and detector noise. Assume T=300K and the detector responsivity is 0.5A/W.

$$\bar{P}_{sens,oA} = \frac{1}{G}\frac{Q\,i_{n,amp}^{rms}}{R} + \eta F\frac{Q^2 q BW_n}{R}$$

$$i_{n,amp}^{rms} = \sqrt{\frac{4KT}{R}BW_n} = \sqrt{\frac{4(1.38\times10^{-23})(300)}{40}(32GHz)} = 3.64\mu A_{rms}$$

$$\bar{P}_{sens,oA} = \frac{1}{20}\frac{(7.942)(3.64\mu)}{0.5} + (3)\frac{(7.942)^2(1.6\times10^{-19})(32G)}{0.5}$$

$\bar{P}_{sens}$ = $4.83\mu W$ = $-23.2dBm$

Problem 2 (50 points)
A 32Gb/s optical receiver consists of a TIA followed by a comparator acting as the decision circuit.

a) The TIA is designed to yield a 2^{nd}-order low-pass Butterworth response with BW_{3dB}=22GHz. It has an input-noise spectrum described by

$$I_n^2(f) = \alpha_0 + \alpha_2 f^2 = 10^{-22}\frac{A^2}{Hz} + \left(5\times10^{-43}\frac{A^2}{Hz^3}\right) f^2.$$

What is the input rms noise current? Refer to the Page 2 table for relevant noise bandwidths.

$$\overline{I_n^2} = \alpha_0 BW_n + \frac{\alpha_2}{3} BW_{n2}^3 = 10^{-22}\frac{A^2}{Hz}(1.11)(22G) + \frac{5\times10^{-43}\frac{A^2}{Hz^3}}{3}\left[(1.49)(22G)\right]^3$$

$$\overline{I_n^2} = 8.31\times10^{-12} A^2 \Rightarrow I_n^{rms} = 2.88\mu A$$

$i_{n,amp}^{rms} = 2.88\mu A$

b) Assuming a photodetector with R=1A/W, what is the receiver sensitivity at a BER=10^{-15}, including both amplifier and detector noise? You can assume an ideal extinction ratio and zero dark current. Also calculate the total low-level and high-level rms noise currents.

$$\overline{P}_{sens} = \frac{Q\, i_{n,amp}^{rms}}{R} + \frac{Q^2 q BW_n}{R} = \frac{7.942(2.88\mu)}{1} + \frac{(7.942)^2(1.6\times10^{-19})(1.11)(22G)}{1}$$

$$= 23.1\mu W = -16.4\,dBm$$

$$I_{n,0}^{rms} = i_{n,amp}^{rms} = 2.88\mu A$$

$$I_{n,1}^{rms} = \sqrt{4qR\overline{P}_{sens}BW_n + (i_{n,amp}^{rms})^2} = \sqrt{4(1.6\times10^{-19})(1)(23.1\mu)(1.11)(22G) + (2.88\mu)^2} = 2.94\mu A$$

$\overline{P}_{sens} = 23.1\mu W$

$i_{n,0}^{rms} = 2.88\mu A$

$i_{n,1}^{rms} = 2.94\mu A$

c) The comparator has a decision-threshold offset of 1mV. Assuming a TIA midband gain H_0=800Ω, what is the power penalty associated with this decision-threshold offset?

$$V_{spp} = H_0 Q\left(i_{n,0}^{rms} + i_{n,1}^{rms}\right) = 800(7.942)(2.88\mu + 2.94\mu)$$

$$= 37.0\,mV$$

$$\delta = \frac{1mV}{37.0mV} = 27.0\times10^{-3}$$

$$PP = 1 + 2\delta = 1.054 = 0.23dB$$

$PP_{offset} = 1.054$
$= 0.23dB$