Texas A&M University
Department of Electrical and Computer Engineering

ECEN 689 – Optical Interconnects

Spring 2022

Exam #1

Instructor: Sam Palermo

- Please write your name in the space provided below
- Please verify that there are **6** pages in your exam
- You may use <u>one</u> double-sided page of notes and equations for the exam
- Good Luck!

Problem	Score	Max Score
1		35
2		35
3		30
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 (35 points)
This problem involves the design of a waveguide p-i-n detector and an estimation of the average transmit power for a 25Gb/s system operating at λ=1550nm.

a) A Ge waveguide p-i-n detector has 320nm intrinsic width and an absorption coefficient $\alpha=10^3 cm^{-1}$. The detector must have a 25GHz bandwidth to not limit the system. The device is biased to yield carrier velocities of 10^5m/s and electrical parasitics of R_{PD}=100Ω and C_{PD}=(1fF/µm)*L_{abs}. What is the maximum absorption length L_{abs} that allows for 25GHz bandwidth? What is the responsivity R with this maximum absorption length?

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

$$C_{PD} = \frac{\left(\frac{1}{2\pi BW} - \frac{W}{v_n}\right)}{R_{PD}} = \frac{\frac{1}{2\pi(25GHz)} - \frac{320nm}{10^5 m/s}}{100\Omega}$$

$$C_{PD} = 31.7fF \Rightarrow L_{abs} = \frac{C_{PD}}{1fF/\mu m} = 31.7\mu m$$

$$R = \eta\frac{q}{hc}\lambda \Rightarrow \eta = 1 - e^{-\alpha L_{abs}} = 1 - e^{-10^3 cm^{-1}(31.7\mu m)} = 0.958$$

$$R = 0.958\left(8\times10^5 \frac{A}{Wm}\right)(1550nm) = 1.19 A/W$$

Max L_{abs} = 31.7µm

R (Max L_{abs}) = 1.19 A/W

b) This detector is used in a 3km link with single-mode fiber that has a loss of 0.25dB/km. In addition to the fiber loss, the link must handle an additional 3dB loss due to coupling and waveguide losses. The receiver in the system has a sensitivity of $i_{sens}^{pp} = 100\mu A$. What is the required average transmit power?

$$\overline{P_{TX}} = \frac{\overline{P_{sens}}}{(\text{Fiber loss}/\text{length})(\text{length})(\text{Additional Loss})}$$

$$\overline{P_{sens}} = \frac{i_s^{pp}}{2R} = \frac{100\mu A}{2(1.19 A/W)} = 42.0\mu W = -13.8dBm$$

$$\overline{P_{TX}} = -13.8dBm - \left[-(0.25dB/km)(3km) - 3dB\right] = -10.05dBm$$

$\bar{P}_{TX}$ = −10.05dBm
= 98.9µW

Problem 2 (35 points)

A 25Gb/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 Bessel response with BW_{3dB}=18GHz. It has an input-noise spectrum described by

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

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

$\overline{i_n^2} = \alpha_0 BW_n + \frac{\alpha_2}{3} BW_n^3 = 10^{-22}\frac{A^2}{Hz}(1.15)(18GHz) + \frac{5\times10^{-43}\frac{A^2}{Hz^3}}{3}\left[(1.78)(18GHz)\right]^3$

$= 2.07\times10^{-12} + 5.48\times10^{-12} = 7.55\times10^{-12}\,A^2$

$i_n^{rms} = 2.75\mu A$

$i_{n,amp}^{rms} = 2.75\mu A$

b) Assuming an APD with R=0.9A/W, M=6, and F=3, 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.

$\overline{P}_{sens,APD} = \frac{1}{M}\frac{Q\, i_{n,amp}^{rms}}{R} + F\frac{Q^2 q\, BW_n}{R}$

$= \frac{1}{6}\frac{(7.942)(2.75\mu A)}{0.9} + 3\frac{(7.942)^2(1.6\times10^{-19})(1.15)(18GHz)}{0.9} = 4.04\mu + 0.7\mu$

$i_{n,0}^{rms} = i_{n,amp}^{rms} = 2.75\mu A$

$i_{n,1}^{rms} = \sqrt{FM^2 4qR\overline{P}_{sens}BW_n + (i_{n,amp}^{rms})^2} = \sqrt{3(6)^2(4)(1.6\times10^{-19})(0.9)(4.74\mu W)(1.15)(18GHz) + (2.75\mu)^2}$

$\overline{P}_{sens} = 4.74\mu W = -23.2dBm$

$i_{n,0}^{rms} = 2.75\mu A$

$i_{n,1}^{rms} = 3.89\mu A$

c) The comparator has a decision-threshold offset of 2mV. Assuming a TIA midband gain H_0=1kΩ, what is the power penalty associated with this decision-threshold offset?

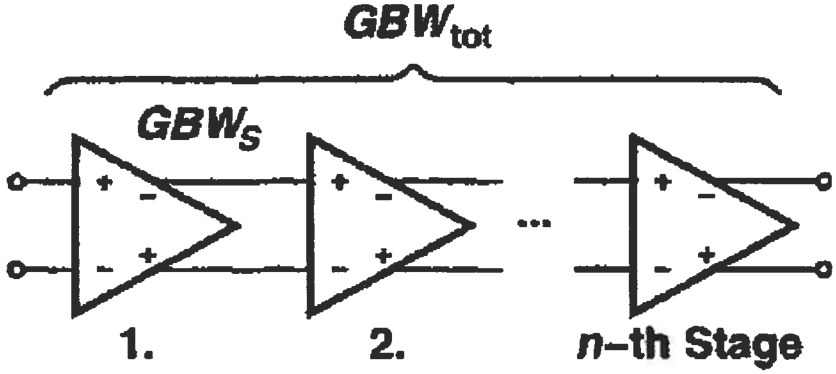
$V_{spp} = H_0 Q(i_{n,0}^{rms} + i_{n,1}^{rms}) = (1k)(7.942)(2.75\mu + 3.89\mu) = 51.2mV$

$\delta = \frac{2mV}{51.2mV} = 39.1\times10^{-3}$

$PP = 1+2\delta = 1.078 = 0.33dB$

PP_{offset} = 0.33dB

Problem 3 (30 points)
Assume that the limiting amplifier below consists of cascaded identical single-pole amplifier stages, with gain A_{vs} and bandwidth ω_{3dBs}.



Design the limiting amplifier to achieve a 37dB total gain and 25GHz total bandwidth with the minimum per-stage gain-bandwidth product. Give the stage number and the per-stage gain and bandwidth. Also compute the per-stage gain-bandwidth product.

$n_{opt} = 2\ln\left(10^{\frac{37}{20}}\right) = 8.52 \Rightarrow$ Use 9 stages

$A_{vs} = \sqrt[9]{10^{\frac{37}{20}}} = 1.61$

$\omega_{3dBtot} = \omega_{3dBs}\sqrt{2^{1/9}-1}$

$\omega_{3dBs} = \frac{\omega_{3dBtot}}{\sqrt{2^{1/9}-1}} = \frac{2\pi(25GHz)}{\sqrt{2^{1/9}-1}} = 555\ Grad/s = 88.4GHz$

$GBW_s = 894\ Grad/s = 142GHz$

n = 9

A_{vs} = 1.61

ω_{3dBs} = 555Grad/s = 88.4GHz

GBW_s = 894Grad/s = 142GHz

Scratch Paper