Texas A&M University
Department of Electrical and Computer Engineering

ECEN 689 – Optical Interconnects

Spring 2016

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 one double-sided page of notes and equations for the exam
- Good Luck!

Problem	Score	Max Score
1		35
2		45
3		20
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 56Gb/s system operating at λ=1310nm.

a) A Ge waveguide p-i-n detector has an absorption coefficient $\alpha=10^4 cm^{-1}$. What is the necessary absorption length for a responsivity of 1A/W?

$$R = \eta \frac{q}{hc}\lambda \Rightarrow \eta = R\frac{hc}{q\lambda} = (1\,A/W)\frac{1}{(8\times10^5\,A/Wm)(1310nm)}$$

$$\eta = 0.954$$

$$\eta = 1 - e^{-\alpha L_{abs}} \Rightarrow L_{abs} = -\frac{\ln(1-\eta)}{\alpha} = -\frac{\ln(1-0.954)}{10^4 cm^{-1}}$$

$$= 308\mu m = 3.08\mu m$$

L_{abs} = $3.08\mu m$

b) The detector must have a 56GHz bandwidth to not limit the system. The device is biased to yield carrier velocities of 10^5m/s and electrical parasitics of $R_{PD}=50\Omega$ and $C_{PD}=(1fF/\mu m)*L_{abs}$. Using the L_{abs} calculated in (a), what is the necessary intrinsic width to achieve the 56GHz bandwidth?

$$C_{PD} = (1fF/\mu m)(3.08\mu m) = 3.08fF$$

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

$$W = \left(\frac{1}{2\pi BW} - R_{PD}C_{PD}\right)V_n = \left[\frac{1}{2\pi(56GHz)} - (50\Omega)(3.08fF)\right]10^5\,m/s$$

W_{int} = $269nm$

c) This detector is used in a 5km link with single-mode fiber that has a loss of 0.4dB/km. In addition to the fiber loss, the link must handle an additional 6dB loss due to coupling and waveguide losses. The receiver in the system has a sensitivity of $i_{sens}^{pp} = 200\mu A$ and R=1A/W. What is the required average transmit power?

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

$$\overline{P}_{sens} = \frac{i_s^{pp}}{2R} = \frac{200\mu A}{2(1A/W)} = 100\mu W = -10dBm$$

$$\overline{P}_{TX} = -10dBm - [(-0.4dB/km)(5km) - 6dB]$$

$$= -2dBm$$

$\bar{P}_{TX}$ = $-2dBm$

Problem 2 (45 points)

A 56Gb/s optical receiver consists of a TIA followed by a comparator acting as the decision circuit.

a) The TIA is designed to yield a 2nd-order low-pass Butterworth response with BW_{3dB}=40GHz. 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.

$$\overline{i_n^2} = \alpha_0 BW_{n} + \frac{\alpha_2}{3}BW_{n2}^3 = 10^{-22}\frac{A^2}{Hz}(1.11)(40GHz) + \frac{5\times10^{-43}\frac{A^2}{Hz^3}}{3}\left[(1.49)(40GHz)\right]^3$$

$$\overline{i_n^2} = 39.7\times10^{-12}A^2 \Rightarrow i_n^{rms} = 6.30\mu A$$

$i_{n,amp}^{rms} = 6.30\mu A$

b) Assuming a photodetector with R=0.8A/W, what is the receiver sensitivity at a $BER=10^{-12}$ 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.

$$\bar{P}_{sens} = \frac{Q\, i_{n,amp}^{rms}}{R} + \frac{Q^2 q BW_n}{R} = \frac{(7.035)(6.3\mu)}{0.8} + \frac{(7.035)^2(1.6\times10^{-19})(1.11)(40GHz)}{0.8}$$

$$= 55.8\mu W = -12.5dBm$$

$\bar{P}_{sens} = -12.5dBm$

$$i_{n,0}^{rms} = i_{n,amp}^{rms} = 6.3\mu A$$

$$i_{n,1}^{rms} = \sqrt{4qR\bar{P}_{sens}BW_n + (i_{n,amp}^{rms})^2} = \sqrt{4(1.6\times10^{-19})(0.8)(55.8\mu)(1.11)(40G) + (6.3\mu)^2}$$

$i_{n,0}^{rms} = 6.30\mu A$

$i_{n,1}^{rms} = 6.40\mu A$

c) The comparator has a decision-threshold offset of 1mV. Assuming a TIA midband gain H_0=500Ω, what is the power penalty associated with this decision-threshold offset?

$$V_{spp} = H_0 Q\left(i_{n,0}^{rms} + i_{n,1}^{rms}\right) = 500(7.035)(6.3\mu + 6.4\mu) = 44.7mV$$

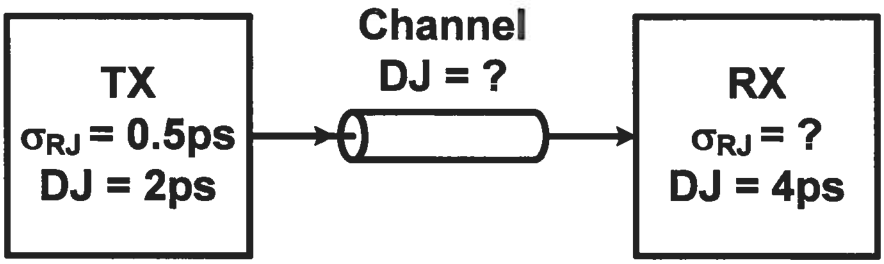
$$\delta = \frac{1mV}{44.7mV} = 22.4\times10^{-3}$$

$$PP = 1 + 2\delta = 1.045 = 0.19dB$$

PP_{offset} = 0.19dB

Problem 3 (20 points)

The jitter budget of a 56Gb/s optical link operating at λ=1310nm can be modeled as having the random and deterministic jitter components shown in the figure below. The 5km single-mode fiber channel has D=0.5ps/(nm*km) and the transmit laser source has a 1nm linewidth.



a) Assuming Gaussian pulse inputs, the SMF channel's DJ can be modeled as the difference between the output pulse width and the ideal 56Gb/s pulse width. What is the channel's DJ?

$$\Delta T = D|\Delta\lambda|L = \left(0.5\frac{ps}{nm\,km}\right)(1nm)(5km) = 2.5ps$$

$$T_{out} = \sqrt{\left(\frac{1}{56G}\right)^2 + (2.5p)^2} = 18.03ps$$

$$\text{Channel } DJ = 18.03ps - \frac{1}{56G} = 0.174ps$$

$DJ_{channel}$ = 0.174ps

b) What is the maximum RX random rms jitter, $\sigma_{RJ,RX}$, for a BER=10^{-12} at the 56Gb/s data rate?

$$\frac{1}{DR} = DJ_{tot} + 2Q\sigma_{RJ,tot}$$

$$\sigma_{RJ,tot} = \frac{\frac{1}{DR} - DJ_{tot}}{2Q} = \frac{\frac{1}{56G} - (2ps + 0.174ps + 4ps)}{2(7.035)} = 0.830ps$$

$$\sigma_{RJ,RX} = \sqrt{\sigma_{RJ,tot}^2 - \sigma_{RJ,TX}^2} = \sqrt{(0.83)^2 - (0.5)^2}$$

Max $\sigma_{RJ,RX}$ = 0.662ps

c) Now assume that we use employ FEC in the system which allows for an input BER=10^{-4}, what is the maximum RX random rms jitter, $\sigma_{RJ,RX}$, now?

$$\text{Now } \sigma_{RJ,tot} = \frac{\frac{1}{56G} - (2ps + 0.174ps + 4ps)}{2(3.719)} = 1.57ps$$

$$\sigma_{RJ,RX} = \sqrt{(1.57)^2 - (0.5)^2}$$

Max $\sigma_{RJ,RX}$ (w/ FEC) = 1.49ps

Scratch Paper