Texas A&M University
Department of Electrical and Computer Engineering

ECEN 721 – Optical Interconnects

Spring 2024

Exam #2

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- Please write your name in the space provided below
- Please verify that there are 5 pages in your exam
- Good Luck!

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

Name: SAM PALERMO

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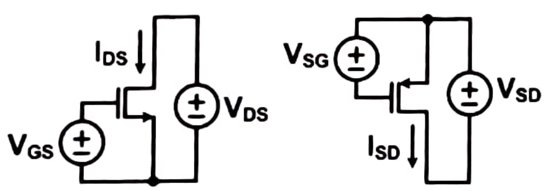
Table 4.1 Numerical relationship between Q and bit-error rate.

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	$0.564 \cdot B$	$0.639 \cdot B$

Key MOS Equations



$$\text{Saturation: } NMOS\ \ I_{DS} = \frac{1}{2} KP_N \frac{W}{L}(V_{GS} - V_{TN})^2$$

$$\text{Saturation: } PMOS\ \ I_{SD} = \frac{1}{2} KP_P \frac{W}{L}(V_{SG} - |V_{TP}|)^2$$

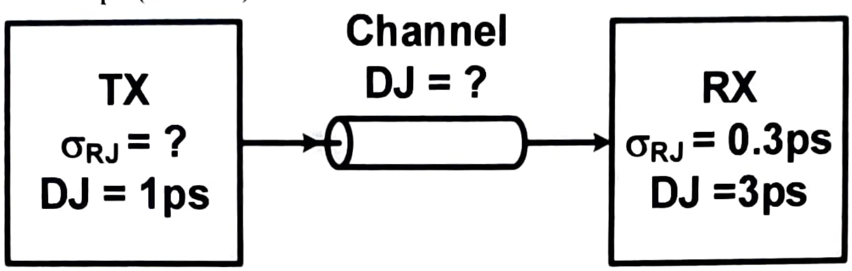
$$\text{Triode: NMOS } I_{DS} = KP_N \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right) V_{DS}$$

$$\text{Triode: } PMOS\ I_{SD} = KP_P \frac{W}{L}\left(V_{SG} - |V_{TP}| - \frac{V_{SD}}{2}\right) V_{SD}$$

$$NMOS\ g_m = \frac{\partial I_{DS}}{\partial V_{GS}},\ \ PMOS\ g_m = \frac{\partial I_{SD}}{\partial V_{SG}}$$

$$NMOS\ \ g_o = \frac{\partial I_{DS}}{\partial V_{DS}},\ \ PMOS\ \ g_o = \frac{\partial I_{SD}}{\partial V_{SD}}$$

Problem 1 (50 points)
The jitter budget of a 56Gb/s optical link operating at λ=1550nm can be modeled as having the random and deterministic jitter components shown in the figure below. The 2km single-mode fiber channel has D=17ps/(nm*km) and the transmit laser source has a 0.5nm 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?

$$\Delta T = D(\Delta\lambda)L = \left(17\frac{ps}{nm\,Km}\right)(0.5nm)(2Km) = 17ps$$

$$T_{OUT} = \sqrt{\left(\frac{1}{56G}\right)^2 + (17ps)^2} = 24.7ps$$

Channel DJ = 24.7ps - 17.9ps = 6.8ps

$DJ_{channel}$ = 6.8ps

b) What is the maximum RX random rms jitter, $\sigma_{RJ,TX}$, for a BER=10^{-15} at the 56Gb/s data rate?

$$\frac{1}{DR} = DJ_{TOT} + 2Q\sigma_{RJ_{TOT}} \Rightarrow \sigma_{RJ_{TOT}} = \frac{\frac{1}{DR} - DJ_{TOT}}{2Q}$$

$$= \frac{\left(\frac{1}{56G}\right) - (1ps + 6.8ps + 3ps)}{2(7.942)}$$

$\sigma_{RJTOT} = 0.444ps$

$$\sigma_{RJ,TX} = \sqrt{(\sigma_{RJ,TOT})^2 - (\sigma_{RJ,RX})^2} = \sqrt{(0.444ps)^2 - (0.3ps)^2} = 0.328ps$$

Max $\sigma_{RJ,TX}$ = 0.328ps

c) Now assume that we use employ FEC in the system which allows for an input BER=10^{-5}, what is the maximum RX random rms jitter, $\sigma_{RJ,TX}$, now?

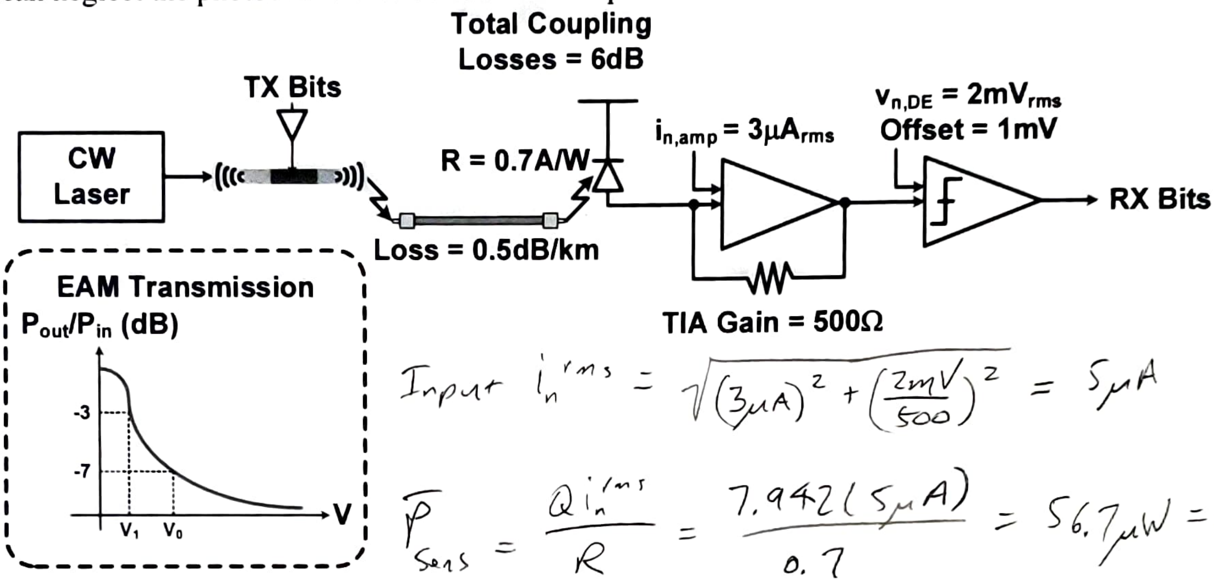
$$\sigma_{RJ,TOT} = \frac{\left(\frac{1}{56G}\right) - (1ps + 6.8ps + 3ps)}{2(4.265)} = 0.827ps$$

$$\sigma_{RJ,TX} = \sqrt{(0.827ps)^2 - (0.3ps)^2} = 0.771ps$$

Max $\sigma_{RJ,TX}$ (w/ FEC) = 0.771ps

Problem 2 (50 points)

A 56Gb/s optical interconnect system uses a electroabsorption modulator transmitter to transmit data over a 2km fiber. The optical receiver has 500Ω gain and the following noise/offset components shown below. The link has an additional total coupling loss of 6dB. Assume that we can neglect the photodetector noise and fiber dispersion.



$$\text{Input } i_n^{rms} = \sqrt{(3\mu A)^2 + \left(\frac{2mV}{500}\right)^2} = 5\mu A$$

$$\bar{P}_{sens} = \frac{Q i_n^{rms}}{R} = \frac{7.942(5\mu A)}{0.7} = 56.7\mu W = -12.5dBm$$

What is the required CW Laser output power to achieve a BER=10^{-15}?

Loss / Penalties: 1. offset → $V_{spp} = 500(2)(7.942)(5\mu A) = 39.7mV$

$$\delta = \frac{1mV}{39.7mV} = 25.2\times10^{-3} \quad PP_{offset} = 1+2\delta = 1.05 = 0.213dB$$

2. Fiber Loss = $(0.5dB/km)(2km) = 1dB$ 3. Coupling Loss = 6dB

4. EAM ER = $-3dB-(-7dB) = 4dB \Rightarrow 2.51$ 5. EAM Insertion Loss = 3dB

$$PP_{ER} = \frac{2.51+1}{2.51-1} = 2.32 = 3.66dB$$

Total Loss/Penalties = 13.87dB

$$\bar{P}_{TX} = \frac{\bar{P}_{sens}}{\text{Loss/Penalties}} = -12.5dBm - (-13.87dB) = 1.37dBm = 1.37mW$$

CW Power: $$\frac{P_1 + \frac{P_1}{2.51}}{2} = 1.37mW \Rightarrow P_{CW} = 1.96mW = 2.93dBm$$