# Texas A&M University
## Department of Electrical and Computer Engineering

## ECEN 689 – Optical Interconnects

## Spring 2020

## Exam #2

**Instructor: Sam Palermo**

- 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** |

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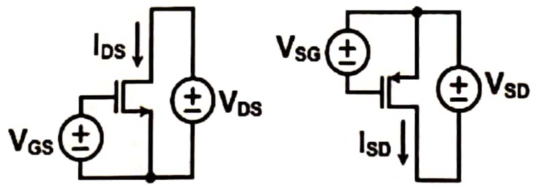
**Table 4.1** Numerical relationship between $Q$ and bit-error rate.

| $Q$ | $BER$ | $Q$ | $BER$ |
|---|---|---|---|
| 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 | $1.57 \cdot BW_{3dB}$ | $\infty$ |
| 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 | $0.500 \cdot B$ | $\infty$ |
| NRZ to full raised-cosine filter | $0.564 \cdot B$ | $0.639 \cdot B$ |

## Key MOS Equations




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

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

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

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

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

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

Problem 1 (50 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 2nd-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.

$$\overline{i_n^2} = \alpha_0 BW_n + \frac{\alpha_2}{3} BW_{n2}^3 = 10^{-22}\left(\frac{A^2}{Hz}\right)(1.15)(18GHz) + \frac{5\times10^{-43}\frac{A^2}{Hz^3}}{3}\left[(1.78)(18GHz)\right]^3$$

$$\overline{i_n^2} = 7.55\times10^{-12} A^2 \Rightarrow i_n^{rms} = 2.75\mu A$$

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

b) Assuming an avalanche photodetector (APD) with R=0.8A/W, M=10, and F=3, 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.

$$\overline{P}_{sens,APD} = \frac{1}{M}\frac{Q i_{n,amp}^{rms}}{R} + F\frac{Q^2 q BW_n}{R} = \frac{7.035(2.75\mu A)}{10(0.8)} + \frac{3(7.035)^2(1.6\times10^{-19})(1.15)(18GHz)}{0.8}$$

$$= 3.03\mu W = -25.2dBm$$

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

$$i_{n,1}^{rms} = \sqrt{FM^2 4qR\overline{P}_{sens}BW_n + (i_{n,amp}^{rms})^2} = \sqrt{3(10)^2 4(1.6\times10^{-19})(0.8)(3.03\mu)(1.15)(18GHz) + (2.75\mu)^2}$$

$\overline{P}_{sens}$ = $-25.2dBm$

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

$i_{n,1}^{rms}$ = $4.15\mu A$

c) The APD also has a dark current of 100nA. What is the power penalty associated with this dark current. Here we can assume that the receiver noise is dominated by amplifier noise for this calculation.

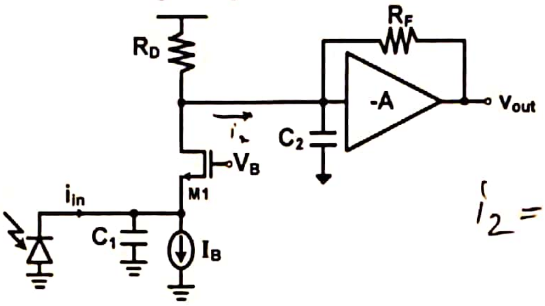
$$PP = \sqrt{1 + \frac{FM^2 2q I_{DK} BW_n}{i_{n,amp}^2}} = \sqrt{1 + \frac{3(10)^2(2)(1.6\times10^{-19})(100n)(1.15)(18GHz)}{(2.75\mu)^2}}$$

$$PP = 1.013 = 0.056 dB$$

$PP_{IDK}$ = $0.056dB$

Problem 2 (50 points)

For the TIA shown below, assume that all transistors are operating in saturation with $r_o=\infty$. Also assume that the voltage amplifier has infinite bandwidth, but finite open-loop gain $A$.




$$V_{OUT} = -i_2 R_F \left(\frac{A}{A+1}\right)$$

$$i_2 = i_{in}\left(\frac{R_D}{R_{in2}+R_D}\right) = \frac{i_{in} R_D}{\frac{R_F}{A+1}+R_D}$$

Obtain expressions for the following:

a) Low-Frequency Transimpedance ($v_{out}/i_{in}$). Note, don't neglect the impact of $R_D$.

b) The TIA's two poles. Note, it's OK to neglect the transistor capacitors here.

$$V_{OUT} = -i_{in}\left(\frac{R_D R_F}{\frac{R_F}{A+1}+R_D}\right)\left(\frac{A}{A+1}\right)$$

$$\boxed{R_T = \frac{V_{OUT}}{i_{in}} = \frac{-R_D R_F}{\frac{R_F}{A+1}+R_D}\left(\frac{A}{A+1}\right)}$$

Input Pole: $\omega_1 = \frac{g_{m1}}{C_1}$

Middle-Node Pole: $\omega_2 = \frac{1}{C_2(R_D \| R_{in2})}$ where $R_{in2} = \frac{R_F}{A+1}$

c) Now assume that $R_D$ is relatively large. What does the low-frequency transimpedance expression simplify to? What benefit does this topology offer over just using an input feedback TIA?

$$R_T \simeq -R_F\left(\frac{A}{A+1}\right)$$

This is the same as an input feedback TIA, but we have the ability to set the input pole w/ $g_{m1}$ without impacting the TIA stability.