Optical receiver characteristics analysis for GEPOF technical feasibility

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Agenda

- Objectives
- The optical receiver
- Characteristics of photodiodes used in POF communications
- Trans-impedance amplifier limits and performance
- Conclusions

Objectives

- The optical receiver is one of the key system blocks for technical feasibility assessment
  - The optical receiver is the main noise source (the floor of Shannon's capacity) for a well designed system
  - We are talking about -21 dBm sensitivity in [perezaranda_04_0514_linkbudget]. To give you an idea, this is equivalent to 2 uA average current from photodiode

- Main objective of this presentation is to provide the characteristics of the optical receiver in terms of maximum achievable trans-impedance, bandwidth, and minimum achievable noise, considering limiting factors of Si-PIN and CMOS technologies.

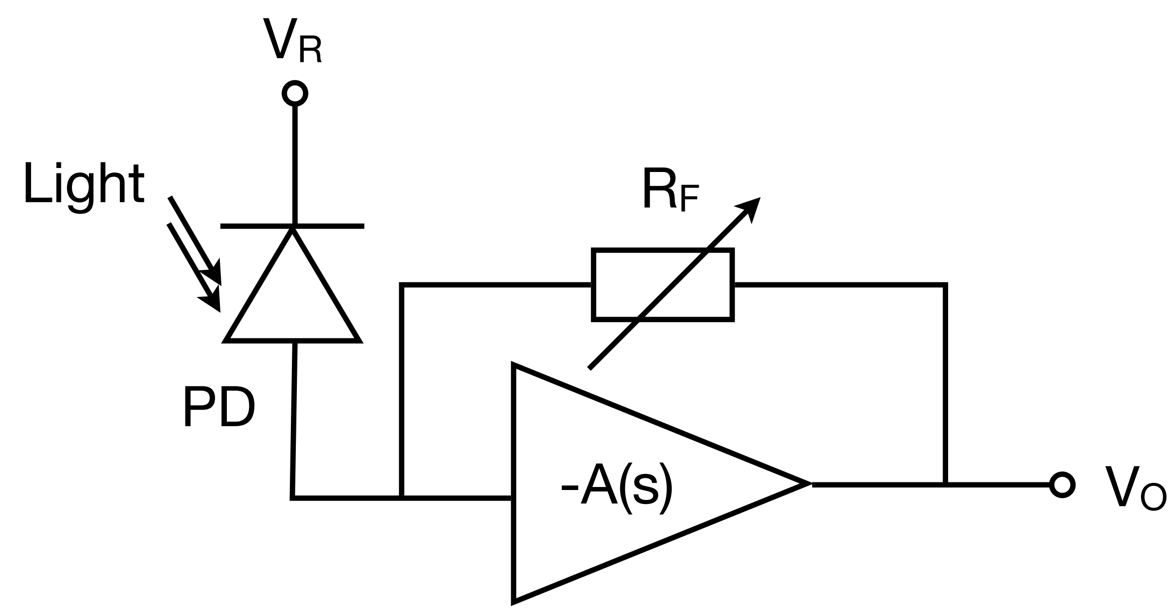
- The results presented here will be used for Shannon's capacity analysis in [perezaranda_02_0514_shannoncap]

Disclaimer

- Technical characteristics provided in this presentation are a collection of confidential information from several IC foundries, therefore sources will not be revealed.
- However, the characteristics of devices presented here are very common to several technology nodes from several years ago ➤ they are not in the state of art

The optical receiver

- Composed by photodetector and trans-impedance amplifier (TIA)
- The PD is in charge to convert photons into electrical current
- The TIA is in charge to convert the small electrical photo-current into an electrical voltage signal with amplitude high enough, so that the subsequents blocks in the signal path has not a relevant contribution in terms of noise



The optical receiver

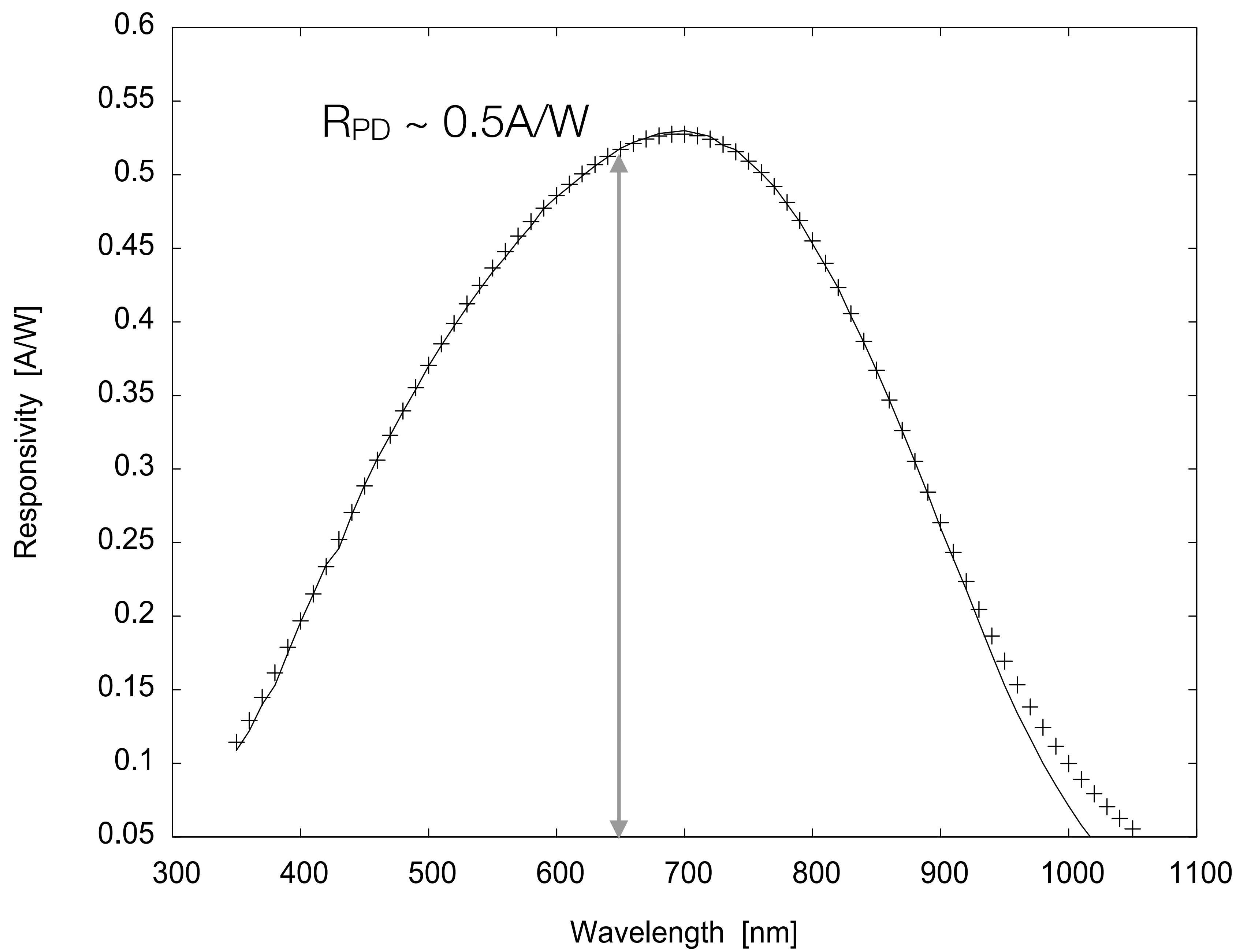
- Light to current conversion is linear, provided that the electrical current of the communication signal is higher enough than PD dark current characteristic
- In general, the TIA I-V conversion has to be linear to enable using advance modulation schemes ➤ for Shannon's capacity analysis can be considered linear
- Linear TIAs are implemented by integrating trans-impedance automatic control as a function of input photo-current to avoid transistors overloading
- For 650 nm POF applications, the PD is typically a Si-PIN
- 2 typical implementations:
    - PD and TIA are two separated ICs fabricated using different technology processes; both are connected in a lead-frame by using bonding wires
    - PD and TIA are fabricated in a single Opto-electronic IC (OEIC), improving SRR, EMI and ESD characteristics of optical RX and reducing manufacturing cost
    - Both implementations have been demonstrated to be good for MOST150 automotive applications

Photodiode characteristics

- Most relevant characteristics:
  - Electrical capacitance (C_D) between anode and cathode ➤ it is going to be a critical parameter for the minimum noise and maximum trans-impedance achievable by TIA
  - O/E Transition time (T_T) or bandwidth (BW) ➤ for a fast PIN design, almost part of the photo-current is drift current generated in depletion region, being slow diffusion currents small
  - Responsitivity (R_{PD}) ➤ the main link between optical power and current and directly related to achievable receiver sensitivity
  - Dark current (I_D) ➤ which can limit the linearity of O/E conversion and therefore the sensitivity (negligible for photo-currents considered here)
  - Quantum noise ($I_{n,Q}$) ➤ the main noise source from PD for communication applications, which is related to average photocurrent and represents the ultimate capacity lower bound
  - Coupling loss (C_L) ➤ how much power outgoing from POF is not coupled to PD; this will depend on the PD size and characteristics of the lens between POF and PD
- High speed, low capacitance, high responsitivity and low coupling loss are desired characteristics to maximize the sensitivity, but they are contradictory

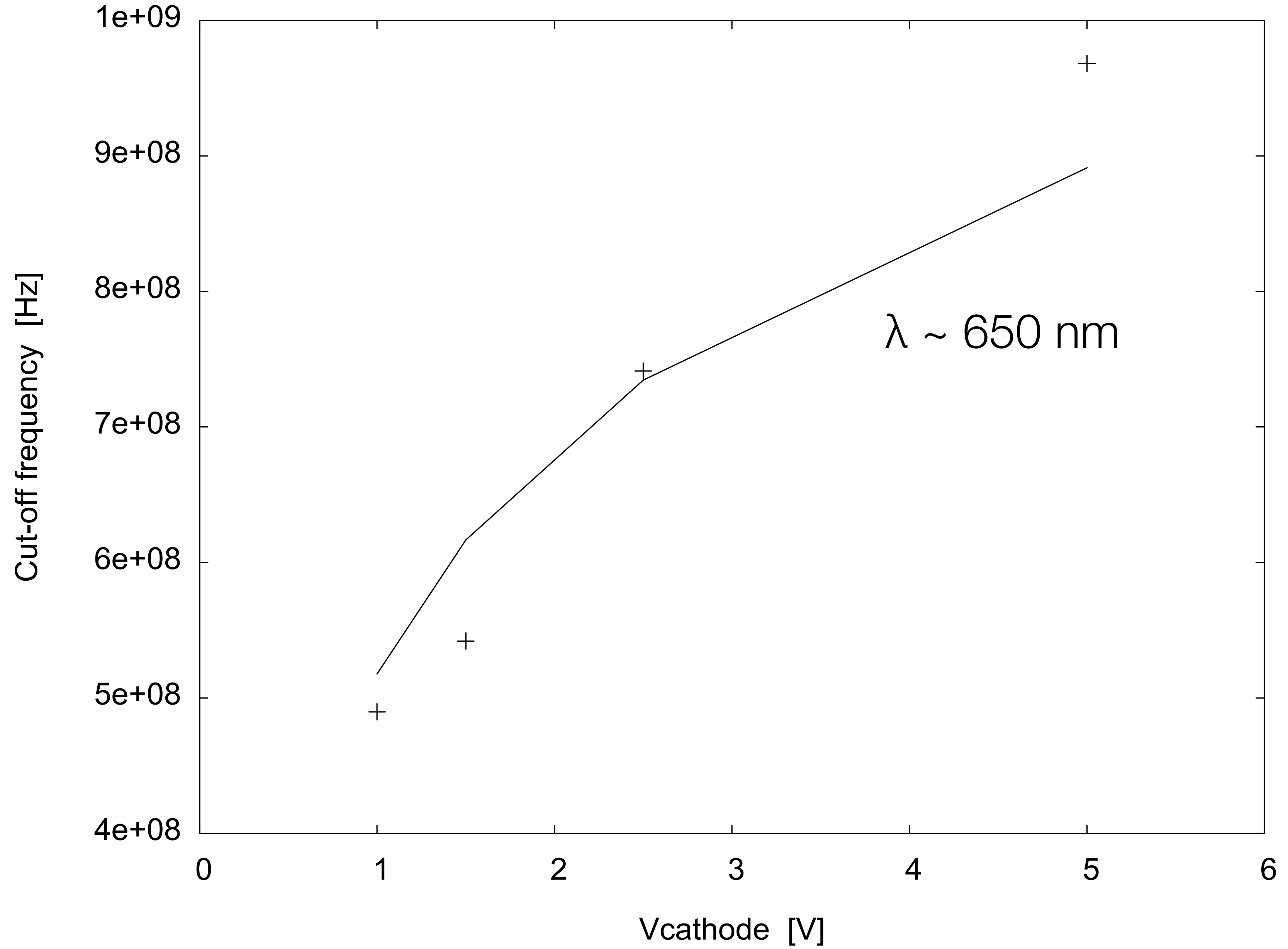
Photodiode characteristics

- Responsivity of a Si-PIN PD optimized for red light



Photodiode characteristics

- Bandwidth of a Si-PIN PD optimized for red light



Photodiode characteristics

- Manufacturer 1: photodiodes optimized for speed

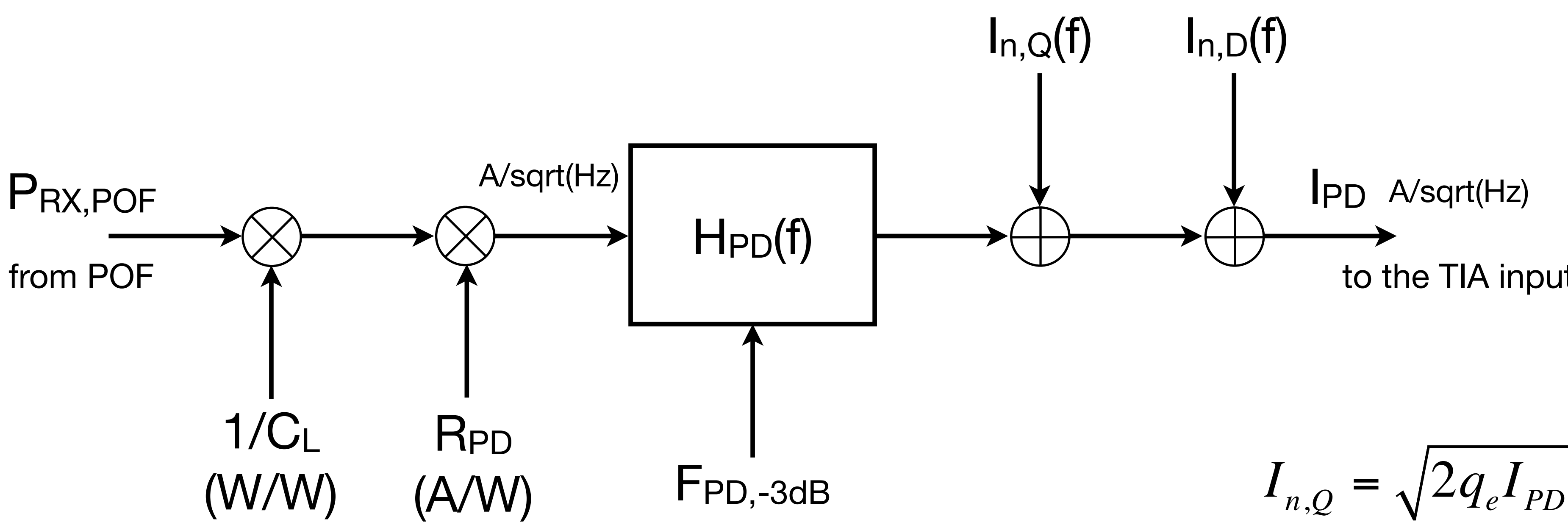
Φ_{PD} (um)	C_D (pF)	I_D (nA) @ 100 ºC	Transition BW_{-3dB} (MHz) @ V_R = 1V	C_L (dBo)
200	0,52	0,74		5,5
400	1,9	2,8		3,0
600	4,2	6,1	480	2,0
800	7,3	10,6		1,0
1000	11,4	16,5		0,0

- Manufacturer 2: photodiodes optimized for capacitance

Φ_{PD} (um)	C_D (pF)	Transition BW_{-3dB} (MHz) @ V_R = 1V	C_L (dBo)
500	2,0	240	2,5
800	5,0	150	0,0

Photodiode model

- q_e stands for electron charge
- Both noise sources are incorrelated
- $I_{n,Q}$ depends on average photocurrent, therefore the SNR at the PD output finally will depend on the optical extinction ratio for a given average optical power (i.e. higher ER translates into higher SNR)



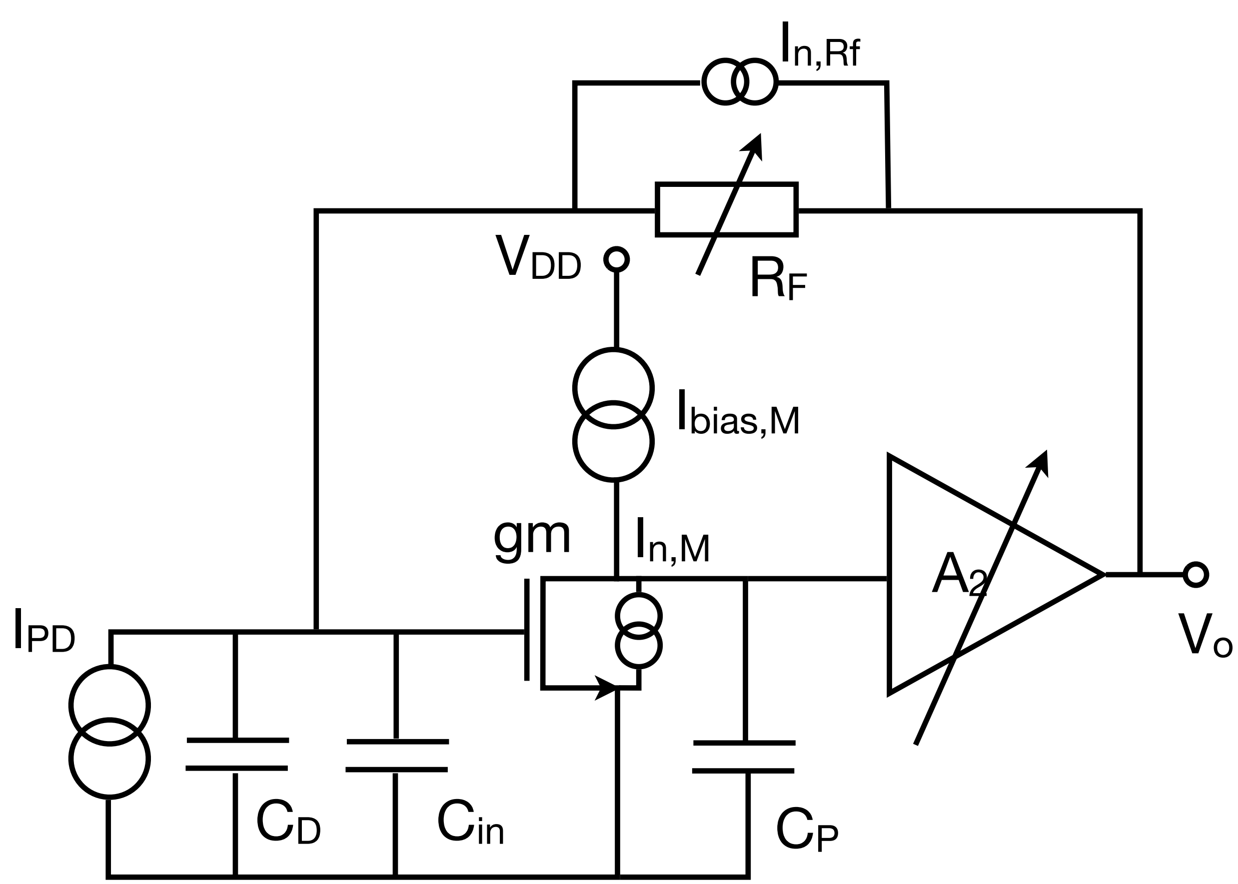
$$I_{n,Q} = \sqrt{2 q_e I_{PD,Avg}} \quad A/\sqrt{Hz}$$

$$I_{n,D} = \sqrt{2 q_e I_D} \quad A/\sqrt{Hz}$$

$$H_{PD}(f) = \left| \sqrt{1 + \frac{f^2}{F^2_{PD,-3dB}}} \right|^{-1}$$

$$I_{n,PD} = \sqrt{I^2_{n,Q} + I^2_{n,D}} \quad A/\sqrt{Hz}$$

Trans-Impedance Amplifier characteristics



- I_{PD}: photocurrent from PD
- C_D: PD capacitance
- C_{in}: input amplifier capacitance
- R_F: feedback resistor (i.e. trans-impedance)
- gm: transconductance of first transistor in the chain
- $I_{n,Rf}$ and $I_{n,M}$: main noise sources for a good design
- V_O: output voltage signal
- Output impedance is considered negligible compared to feedback, which simplifies the analysis

Trans-Impedance Amplifier characteristics

- Let's consider a first order core amplifier, composed by the first transistor and subsequent amplification stages required to get the correct gain:

$$A(s) = \frac{A_0}{1 + s/\omega_0}$$

- First order approximation is considered, neglecting higher frequency poles, which is quite realistic
- The transition frequency (f_T) of the technology node is going to limit the achievable gain-bandwidth product provided by the core amplifier
- Let's define the transition frequency of technology as:

$$\omega_T = 2\pi f_T \propto \omega_0 \sqrt{A_0^2 - 1} \approx \omega_0 A_0$$

Trans-Impedance Amplifier characteristics

- The input-output trans-impedance transfer function is given by

$$\frac{V_O}{I_{PD}} = -\frac{A(s)R_F}{1 + A(s) + sR_F C_T} = -\frac{\dfrac{A_0\omega_0}{C_T}}{s^2 + \dfrac{R_F C_T + 1/\omega_0}{R_F C_T/\omega_0} s + \dfrac{(A_0 + 1)\omega_0}{R_F C_T}}$$

which is a 2nd order system and where $C_T = C_D + C_{in}$.

- The transfer functions of the current noise densities to the TIA output are given by:

$$\frac{V_O}{I_{n,M}} = -\frac{A(s)}{1 + A(s) + sR_F C_T}\frac{1 + sR_F C_T}{gm}$$

$$\frac{V_O}{I_{n,R_F}} = -\frac{A(s)}{1 + A(s) + sR_F C_T} R_F$$

Trans-Impedance Amplifier limits

- The closed loop stability, as well as ripple, are going to depend on the core amplifier gain and bandwidth, the input capacitance and the trans-impedance
- A conservative criteria, considering temperature and process variation, is to design to ensure a critically-damped response

$$\varsigma = \frac{1}{2}\frac{R_F C_T \omega_0 + 1}{\sqrt{\left(A_0 + 1\right) R_F C_T \omega_0}} = \frac{1}{\sqrt{2}}$$

- Under this condition, the next equations relates the design parameters:

$$\omega_0 = \frac{A_0 + \sqrt{A_0^2 + 1}}{R_F C_T} \approx \frac{2A_0}{R_F C_T} \qquad \omega_{-3dB} = \sqrt{\frac{\left(A_0 + 1\right)\omega_0}{R_F C_T}} \approx \frac{\sqrt{2}A_0}{R_F C_T}$$

where we have assumed A_0>>1 for approximations and ω_{-3dB} stands for the closed loop TIA bandwidth.

Trans-Impedance Amplifier limits

- The current noise densities are given by:

$$I_{n,R_F} = \sqrt{\frac{4KT}{R_F}} \qquad\qquad I_{n,M} = \sqrt{4KT\cdot\gamma\cdot gm}$$

where, K is the Boltzman’s constant, T is the absolute temperature and γ denotes the excess noise coefficient, typically equal to ⅔ for long-channel MOS transistors, although it can increase for deep submicron technologies.

- We are ready to calculate the input referred noise of the TIA:

$$NEP = \sqrt{4KT\left(\frac{1}{R_F}\left(1+\frac{\gamma}{gm\cdot R_F}\right)+\frac{\gamma}{gm}\left(2\pi C_T f\right)^2\right)} \quad A/\sqrt{Hz}$$

which indicates that R_F determines the noise for frequencies below a critical f_C, and C_T and gm for frequencies bove that.

- This critical frequency is given by:

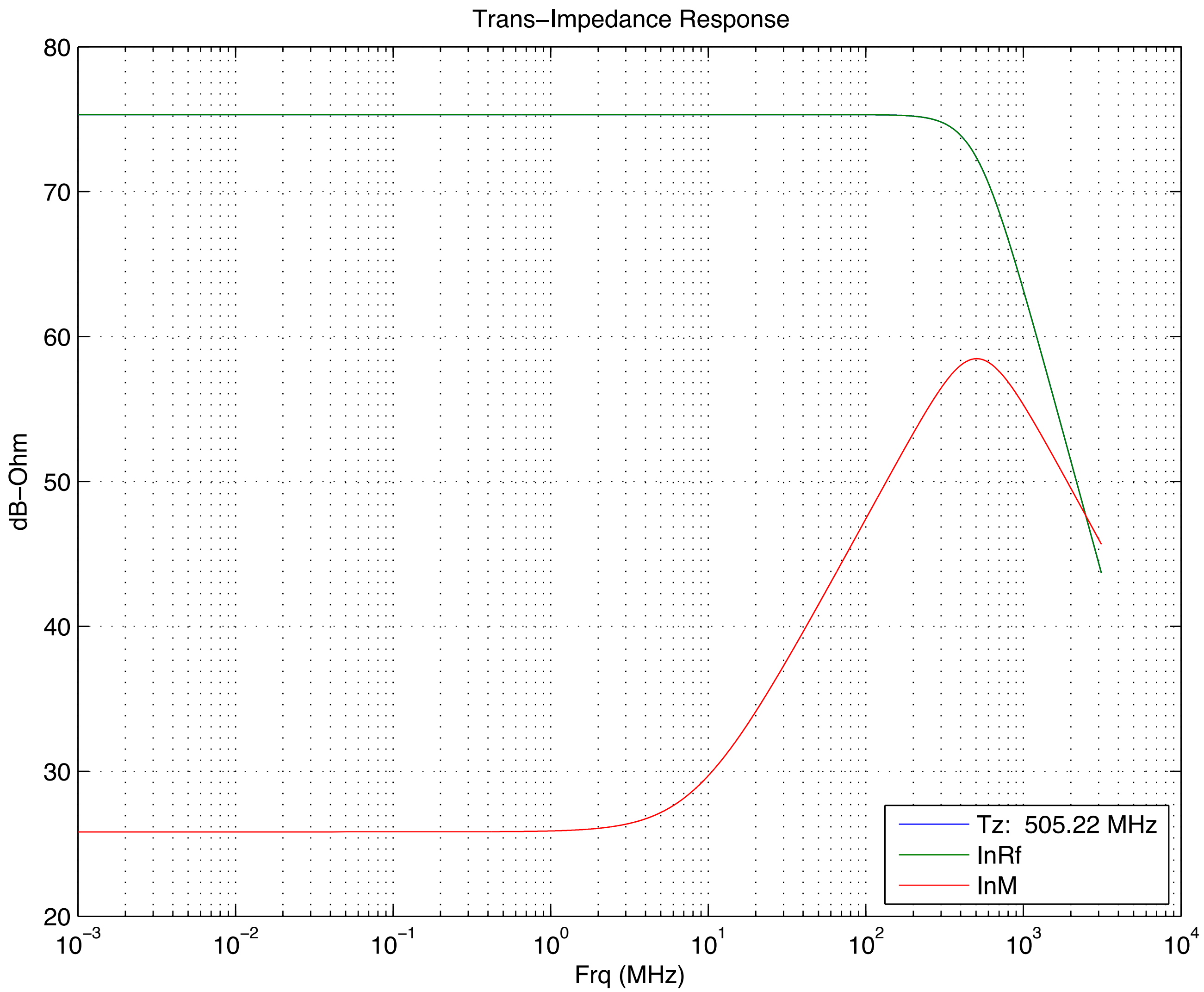
$$f_C = \frac{1}{2\pi R_F C_T}\sqrt{\frac{gm\cdot R_F+\gamma}{\gamma}}$$

Trans-Impedance Amplifier limits

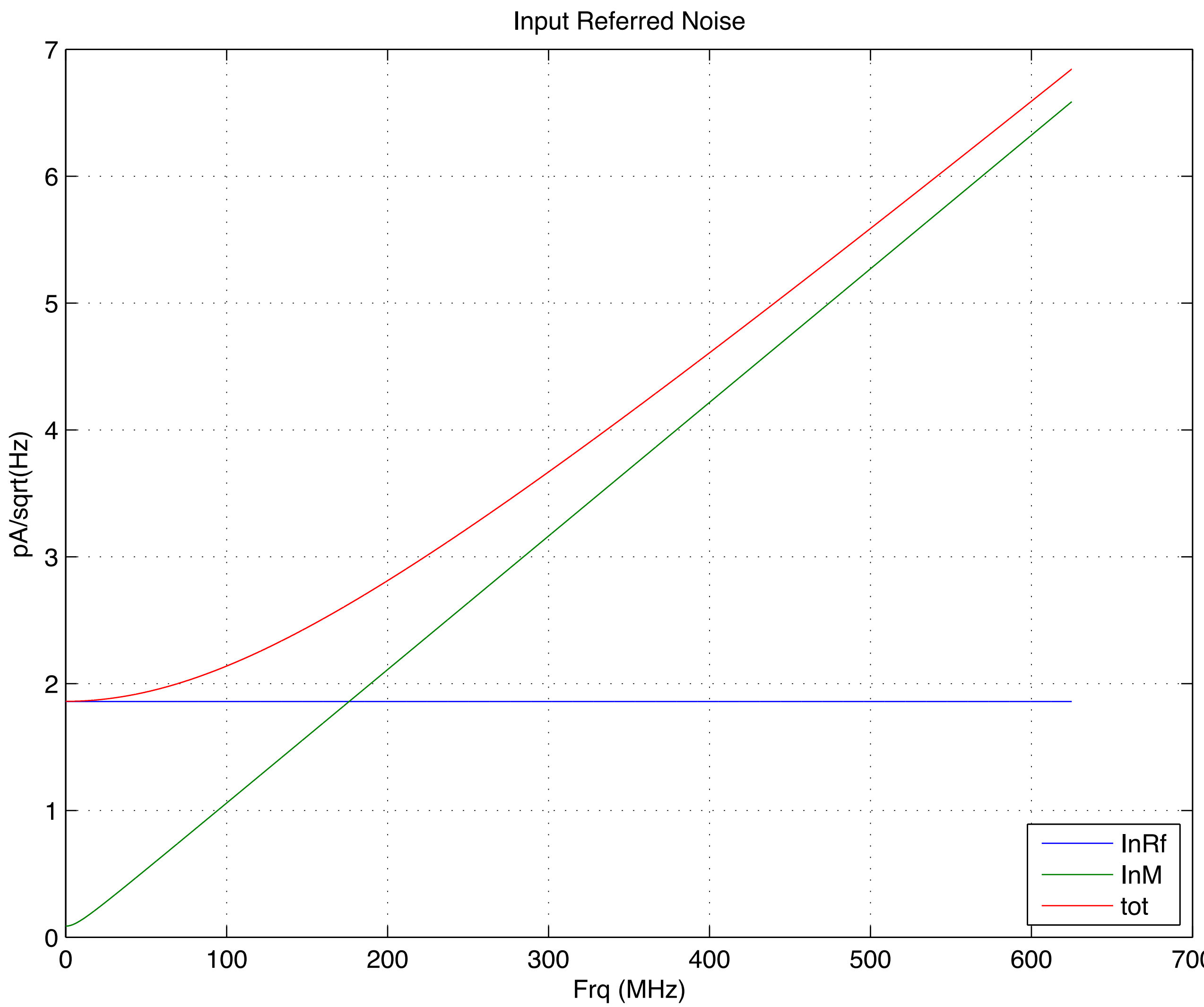
- In order to obtain the best sensitivity in the receiver, the TIA has to provide maximum R_F, maximum gm and minimum C_T, preserving critically dumped stable response
- However:
  - The TIA has to provide high enough BW for the communication signal, let say $\omega_{-3dB} = \alpha \cdot \pi \cdot F_S$ where F_S is the symbol frequency and α is a high factor of the Nyquist frequency.
  - Maximum R_F is limited by the maximum gain-bandwidth product of the technology, the required ω_{-3dB} and the input capacitance

Trans-impedance limit based on conservative technology parameters						
α	C_D (pF)	C_{in} (pF)	gm_{M1} (mS)	f_T (GHz)	F_S (MHz)	Max. R_F (Kohm)
0,8	2,0	1,2	50	30	1250	6
					625	24
					312,5	96

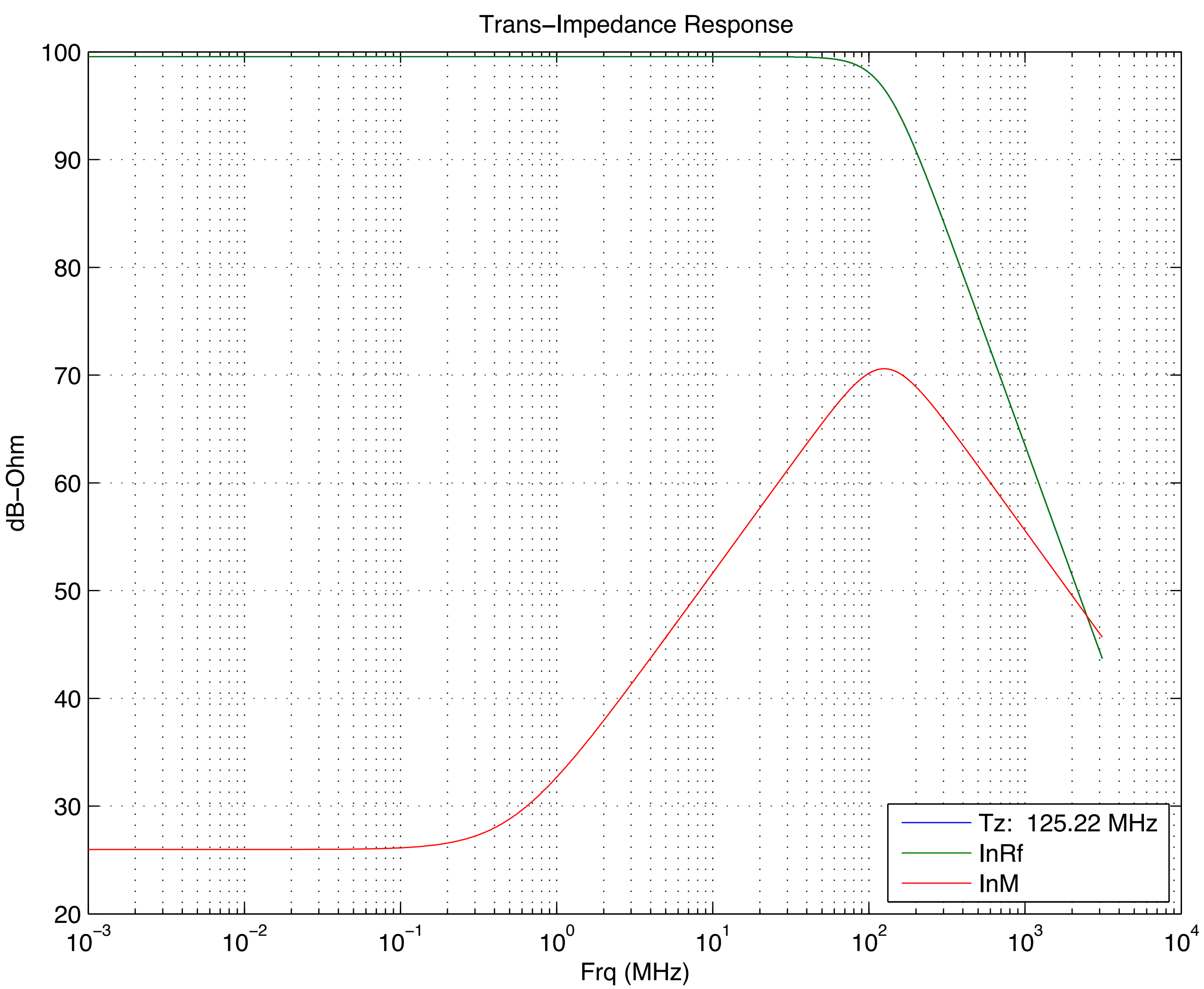
Trans-Impedance Amplifier performance



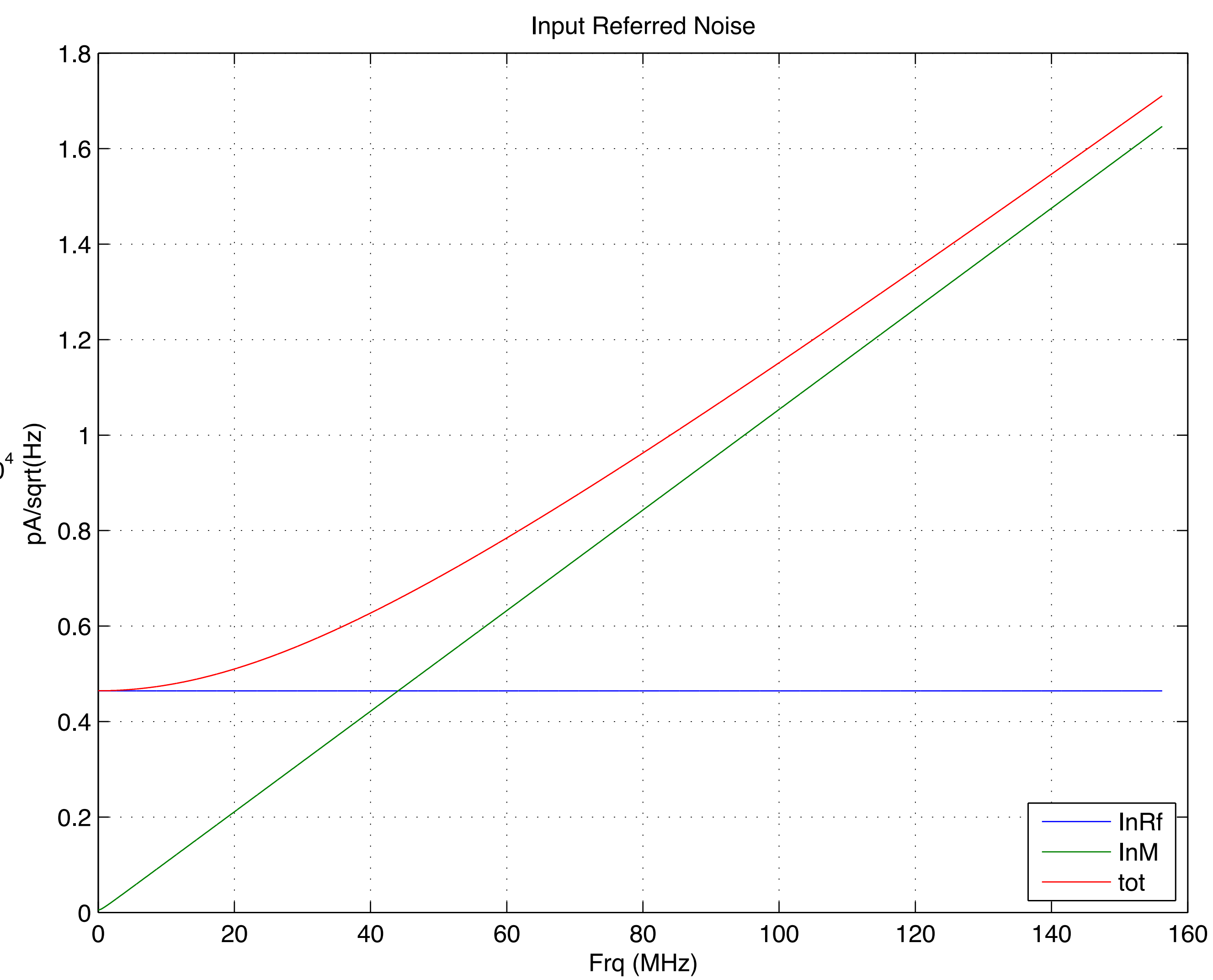
Fs = 1.25 GHz
T = 100°C



Trans-Impedance Amplifier performance



F_S = 312.5 MHz
T = 100ºC



Conclusions

- Main characteristics of the optical receiver have been provided in terms of maximum achievable trans-impedance, bandwidth, and minimum achievable noise, considering limiting factors of Si-PIN and CMOS technologies.
- The results presented here will be used for Shannon's capacity analysis in [perezaranda_02_0514_shannoncap]

Questions?