EE 437/538B: Integrated Systems Capstone/Design of Analog Integrated Circuits and Systems

Lecture 7: Optical Rx (part 1)

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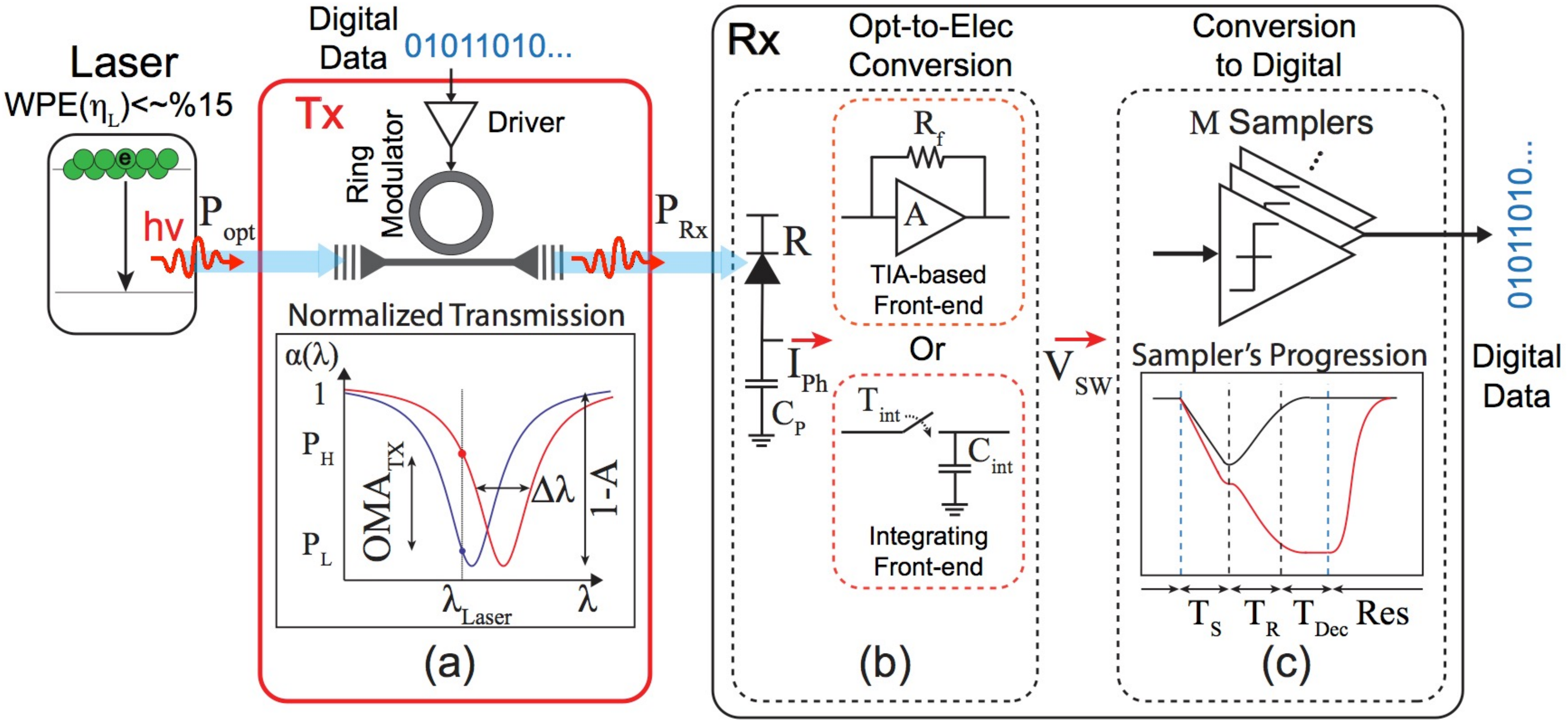
ELECTRICAL & COMPUTER ENGINEERING

A Full Photonic Link



- Receiver sensitivity: Min optical power for a certain data-rate & BER ($P_{Rx,in}$)

Photodetectors

- Photodetectors perform optical-to-electrical conversion and are the first elements in an optical receiver

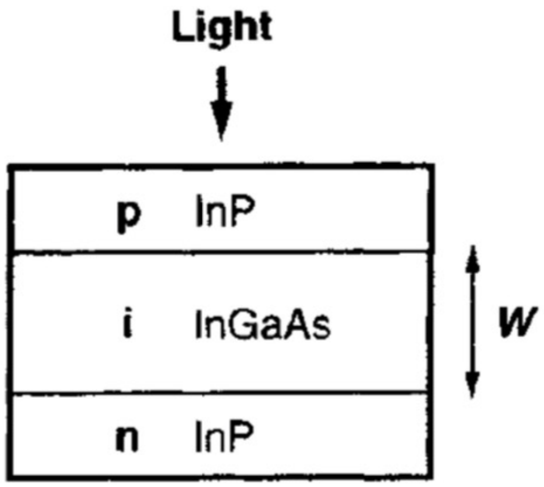
[Albis]

- Their responsivity and noise performance significantly impact receiver performance
- Common photodetector types
  - p-i-n photodetector
  - Avalanche photodetector (APD)
  - Optically preamplified p-i-n detector

[Sam Palermo]

p-i-n Photodetector

- A p-i-n photodetector has an intrinsic layer (undoped or lightly doped) sandwiched between p- and n-doped material
- This p-n junction operates in reverse bias to create a strong electric field in the intrinsic region



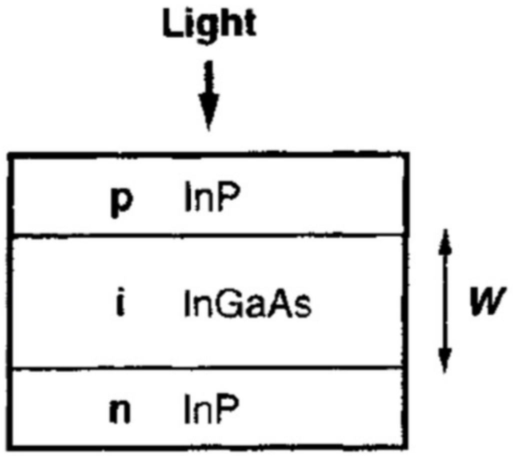
[Sackinger]

- Normally incident photons create electron-hole pairs in the intrinsic region which are separated by the electric drift field, and photocurrent appears at the terminals

[Sam Palermo]

p-i-n Photodetector Tradeoffs

- There is a tradeoff between efficiency and speed set by the intrinsic layer width W



[Sackinger]

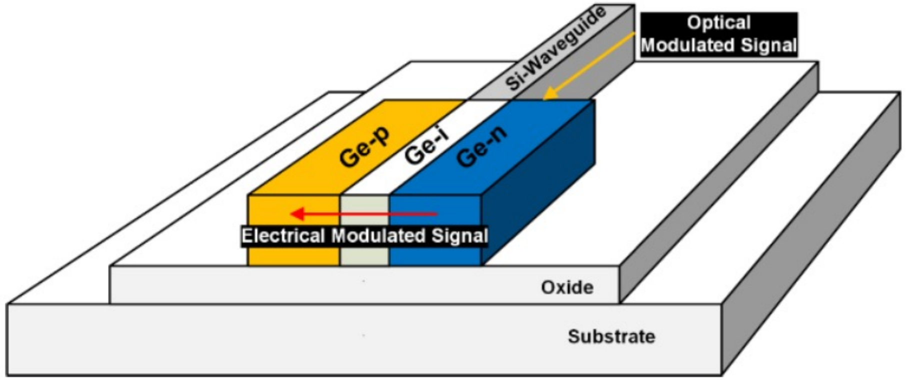
- The quantum efficiency η is the fraction of photons that create electron-hole pairs and is determined by W and detector's absorption coefficient α

$$\eta \approx 1 - e^{-\alpha W}$$

- A wider W allows for higher η, but also results in longer carrier transit times which reduces the detector bandwidth

[Sam Palermo]

Waveguide p-i-n Photodetector



- A waveguide p-i-n photodetector structure allows this efficiency-speed trade-off to be broken
- The light travels horizontally down the intrinsic region and the electric field is formed orthogonal
- Allows for both a thin i-region for short transit times and a sufficiently long i-region for high quantum efficiency

[Sam Palermo]

p-i-n Photodetector Responsivity

- The efficiency at which a photodetector converts optical power to electrical current is called responsivity *R*
- As each photon has energy of hc/λ,

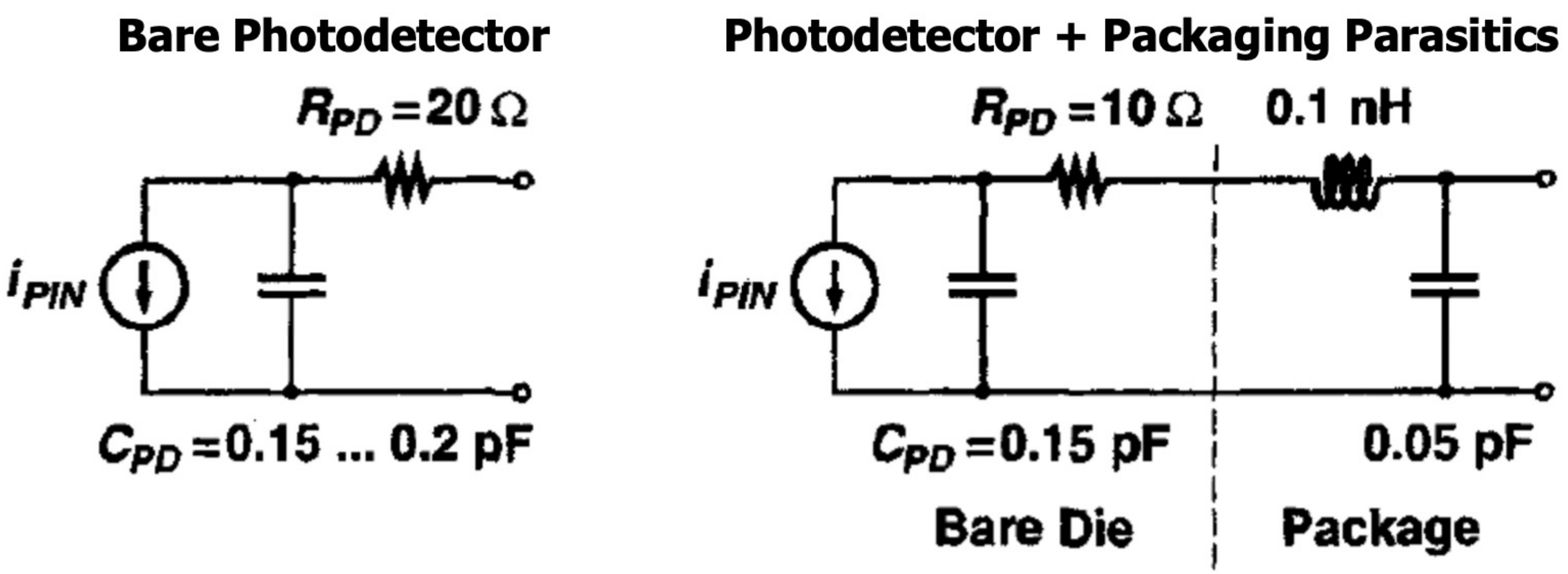
$$I_{PIN} = \eta \cdot \frac{\lambda q}{hc} \cdot P = R \cdot P$$

$$\text{where} \quad \mathrm{R} = \eta \cdot \frac{\lambda q}{hc} = \left(8 \times 10^{5}\right)\eta\lambda \ \ (\mathrm{A/W})$$

- Example: A photodetector with η=0.6 operating at 1310nm has *R*=0.63 A/W
- There is the potential for *R*>1, with η=1 and 1550nm operation $\Rightarrow$ *R*=1.24

[Sam Palermo]

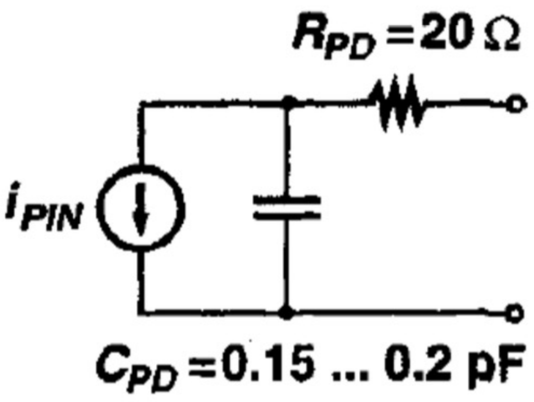
p-i-n Photodetector Equivalent AC Circuits

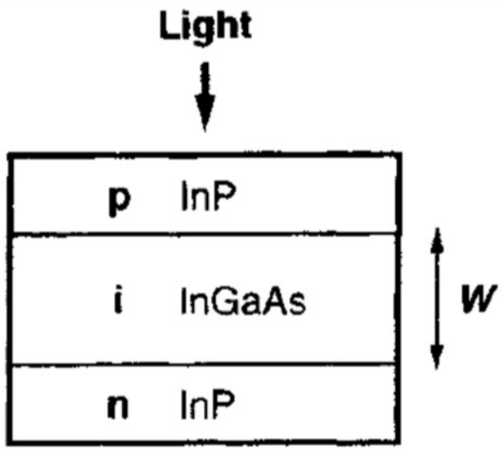


- The photodetectors main parasitics are the junction capacitance C_{PD} and contact/spreading resistance R_{PD}
- Additional LC parasitics are present in packaged devices due to wirebonds, etc…

[Sam Palermo]

p-i-n Photodetector Bandwidth





- Two time constants set the bare photodetector bandwidth

Transit Time: $\tau_{TR} = \dfrac{W}{v_n}$ where v_n is the carrier veloicty

R - C Time Constant: $\tau_{RC} = R_{PD} C_{PD}$

The bandwidth in Hz can be approximated by

$$BW = \frac{1}{2\pi} \cdot \frac{1}{W/v_n + R_{PD} C_{PD}}$$

[Sam Palermo]

p-i-n Photodetector Shot Noise

- p-i-n photodetectors also produce a noise current, known as shot noise
- This noise is due to the photocurrent being comprised of a large number of short pulses distributed randomly in time
- It is modelled as having a white spectrum and a mean-square value of

$$\overline{i^2_{n,PIN}} = 2qI_{PIN} \cdot BW_n$$

where I_{PIN} is the signal current and BW_n is the bandwidth which we measure the noise current (receiver bandwidth)

Example: Average received optical power $= 1\text{mW}$, $R = 0.8A/W$, and a 10GHz receiver bandwidth

$$i_{n,PIN,rms} = 1.6\mu A_{rms}$$

$$SNR = 10\log_{10}(0.8mA/1.6\mu A)^2 = 54dB$$

13

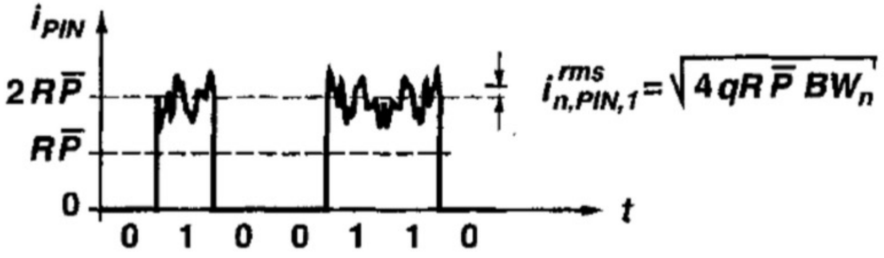
[Sam Palermo]

Shot Noise Signal Dependency

- The shot noise is signal dependent, with the rms value growing with the square root of the optical power
- If we double the optical power, the SNR improves by 3dB
- The noise can vary on a per-bit basis
- Assuming a large extinction ratio (P_1/P_0)

$$\overline{i_{n,PIN,0}^2} \approx 0$$

$$i_{n,PIN,1}^2 = 2qR\left(2\overline{P}\right)BW_n$$



[Sam Palermo]

p-i-n Photodetector Dark Current

- The p-i-n photodetector produces current even when no light is present, called **dark current**

- Generally this dark current is only a few nA and not an issue, as long as it is less than 10% of the signal current

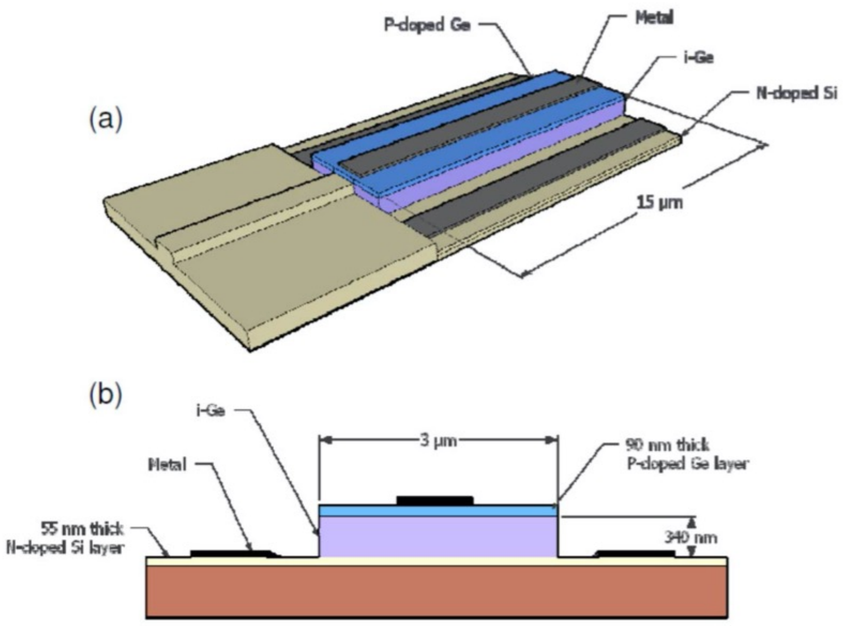
$$\overline{P} > 10 \cdot \frac{I_{DK}(\max)}{R}$$

[Sam Palermo]

Waveguide p-i-n Photodetector Example

42 GHz p.i.n Germanium photodetector integrated in a silicon-on-insulator waveguide

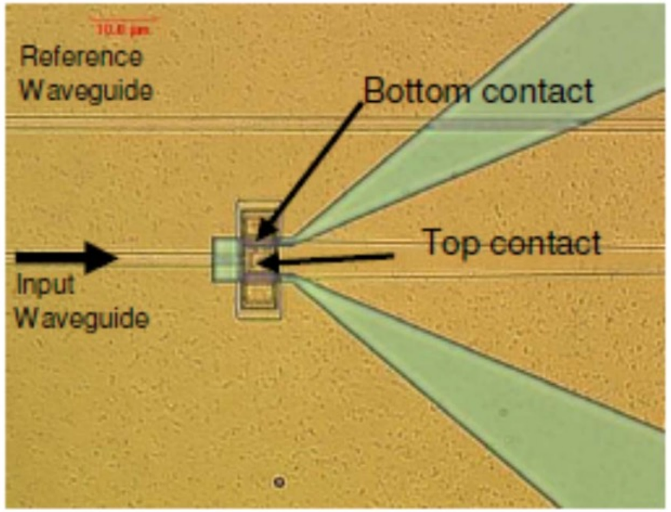
Laurent Vivien[1], Johann Osmond[1], Jean-Marc Fédéli[2], Delphine Marris-Morini[1], Paul Crozat[1], Jean-François Damlencourt[2], Eric Cassan[1], Y.Lecunff[2], Suzanne Laval[1]

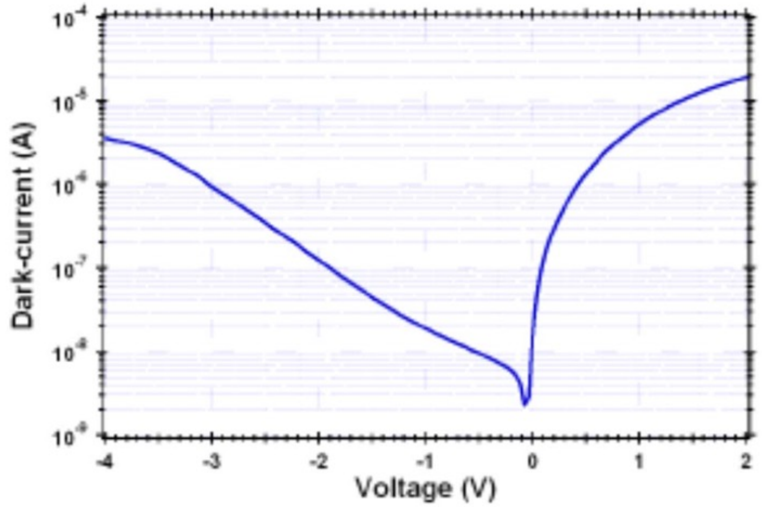


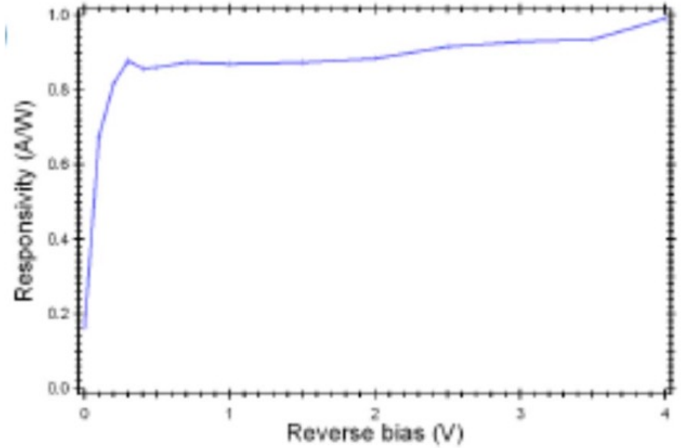
- Key performance metrics
  - 15μm detector length
  - 42GHz bandwidth at 4V bias
  - 1A/W responsivity at 0.5V bias

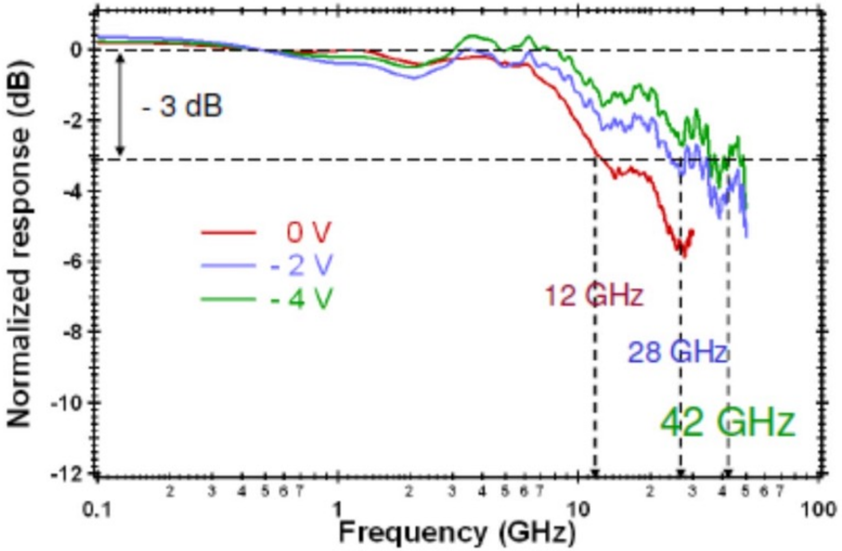
17 [Sam Palermo]

Waveguide p-i-n Photodetector Example







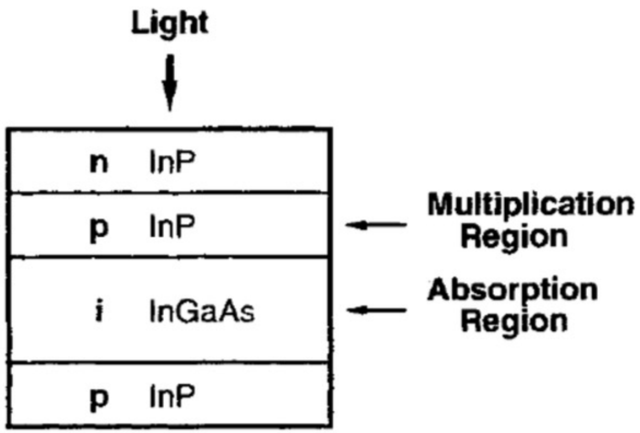


18

[Sam Palermo]

Avalanche Photodetector (APD)

- An avalanche photodetector adds a multiplication region to the p-i-n structure
- Electron-hole pairs generated in the intrinsic or absorption region experience avalanche multiplication



[Sackinger]

- A relatively high reverse bias (>10V) is necessary for to avalanche process to occur
- InP is often introduced to allow for higher electric fields

[Sam Palermo]

Avalanche Photodetector Responsivity

- APD gain is called avalanche gain or multiplication factor *M*

$$I_{APD} = M \cdot RP$$

where R is the responsivity without avalanche gain, which is similar to a p - i - n photodetector.

Example: with $R = 0.8 A/W$ and $M = 10$, the APD generates 8A/W

[Sam Palermo]

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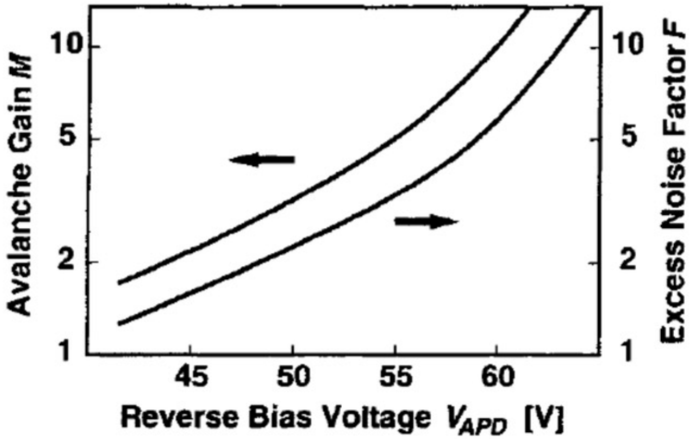
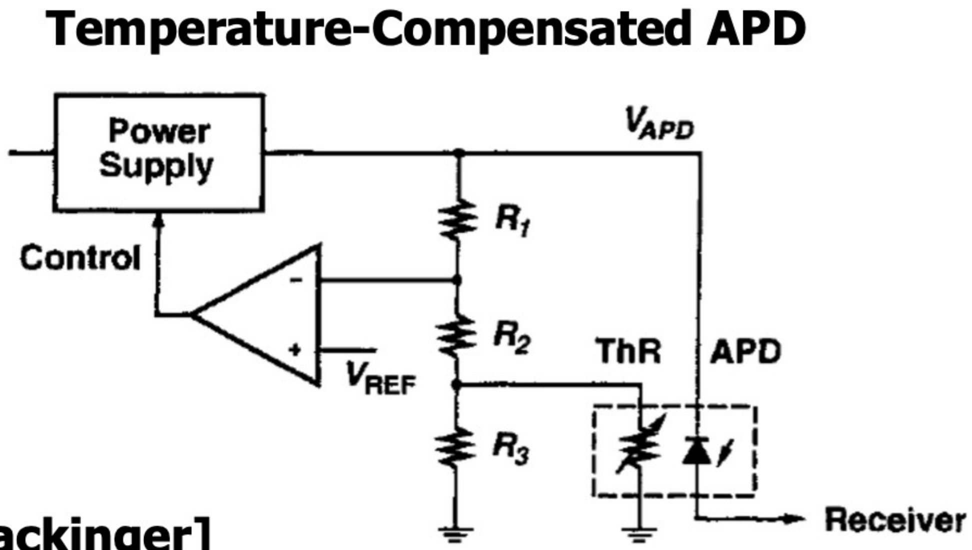
APD Gain Sensitivity





[Sackinger]

- APD gain is sensitive to both reverse bias and temperature
- Feedback control with temperature sensors can adjust the reverse bias to implement temperature compensate and/or automatic gain control

21 [Sam Palermo]

APD Avalanche Noise

- APDs also display additional noise, on top of scaled shot noise, as the multiplication is a random process, with *M* only representing the average current gain
- If the gain factor *M* was constant (it's not), then for every photogenerated electron *M* carriers would be produced and the shot noise would be

$$\overline{i_{n,APD}^2} = 2(Mq)(MI_{PIN})BW_n = M^2 2qI_{PIN}BW_n$$

$$\text{where } I_{PIN} = \frac{I_{APD}}{M}$$

- But, as *M* is a random process, an excess noise factor *F* is added to the APD noise

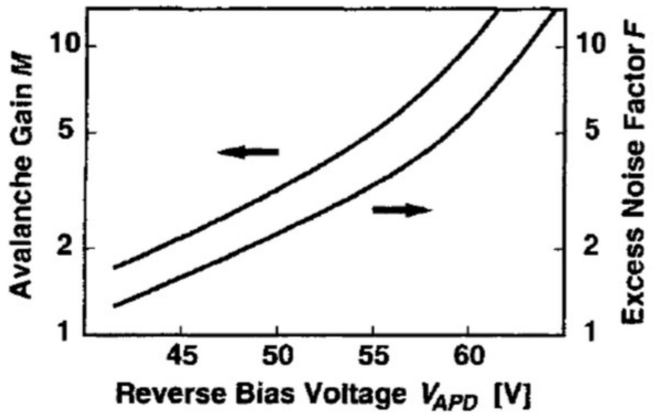
$$\boxed{\overline{i_{n,APD}^2} = F \cdot M^2 2qI_{PIN}BW_n}$$

[Sam Palermo]

APD Avalanche Noise

- The excess noise factor increases with reverse bias, roughly tracking the avalanche gain
- *F* and *M* are related, as a function of the ionization-coefficient ratio k_A

$$F = k_A M + (1 - k_A)\left(2 - \frac{1}{M}\right)$$



[Sackinger]

- Thus, there is an optimum M setting for receiver sensitivity
- As with the p-i-n photodetector, APD noise is also signal dependent

$$\overline{i_{n,APD,0}^2} \approx 0$$

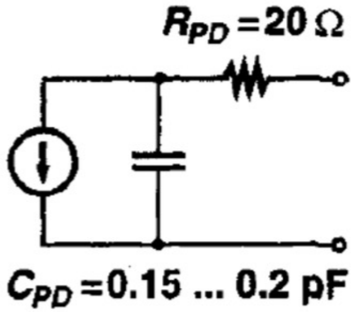
$$\overline{i_{n,APD,1}^2} = F \cdot M^2 \cdot 2qR(2\overline{P})BW_n$$

[Sam Palermo]

APD Bandwidth

- If we increase the reverse bias the APD gain (and excess noise) will increase, but the bandwidth will unfortunately reduce
- APD gain-bandwidth product remains approximately constant with different bias levels, and can be used to quantify the device's speed
- High-performance APDs have GBWs of 100-150GHz
- We can model the APD with a similar RC circuit

$$i_{APD}(t) = M \cdot RP(t)$$



25

[Sam Palermo]

Noise Figure

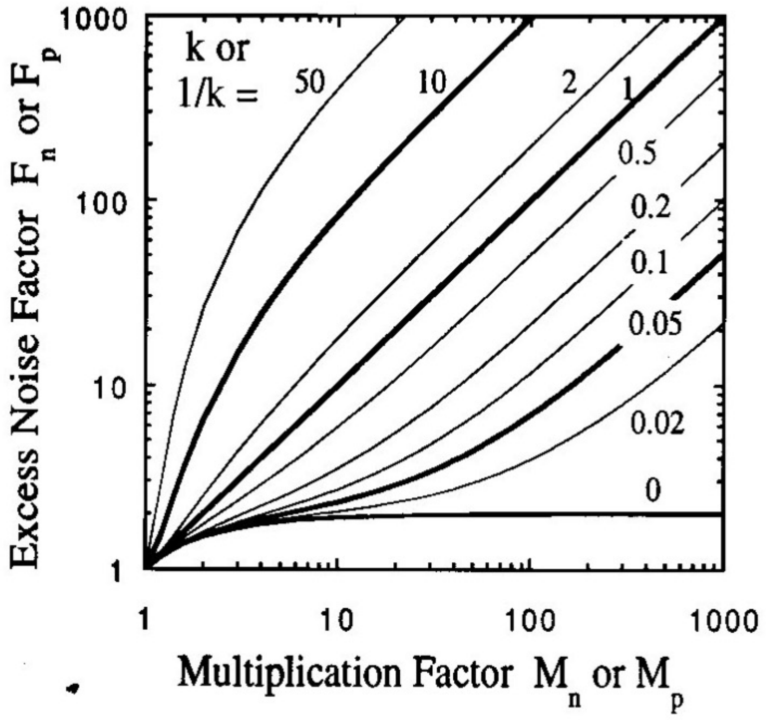
Excess noise factor F

(due to fluctuation in gain):

$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} = k\langle M_n \rangle + (1-k)\left(2 - \frac{1}{\langle M_n \rangle}\right)$$

Noise Figure:

$$NF = 10\log F$$



Small k has small F under high gain $\langle M_n \rangle$

Minimum noise figure = 3 dB occurs when $k = 0$

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Prof. Ming Wu

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RX Noise Analysis

APD Noises

Signal is amplified by the average gain $\langle M \rangle$:

$$i_p^2 = \frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2 \langle M \rangle^2$$

Shot noise is amplified by $\langle M^2 \rangle$:

$$\langle i_S^2 \rangle = 2e\left(I_p + I_B + I_D\right)\langle M^2 \rangle dv$$

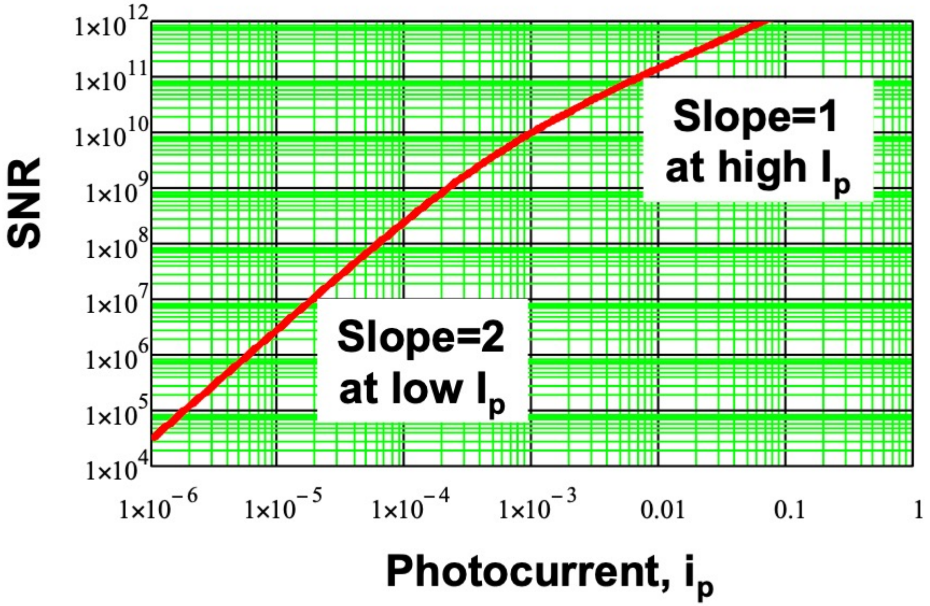
$$= 2e\left(I_p + I_B + I_D\right)F\langle M \rangle^2 dv$$

I_p : photocurrent;

I_B: background photocurrent

I_D: dark current

$$\langle i_T^2 \rangle = \frac{4k_B T\Delta v}{R}$$



$$SNR = \frac{\frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2 \langle M \rangle^2}{2e\left(I_p + I_B + I_D\right)F\langle M \rangle^2 dv + \frac{4k_B T\Delta v}{R}}$$

EE232 Lecture 21-9

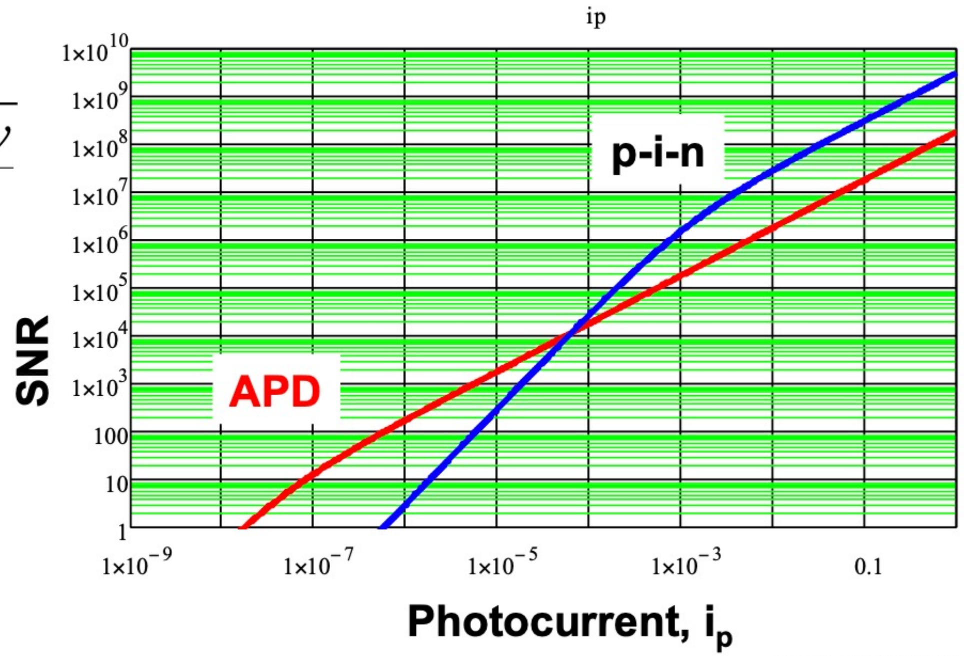
Prof. Ming Wu

SNR Comparison of p-i-n and APD

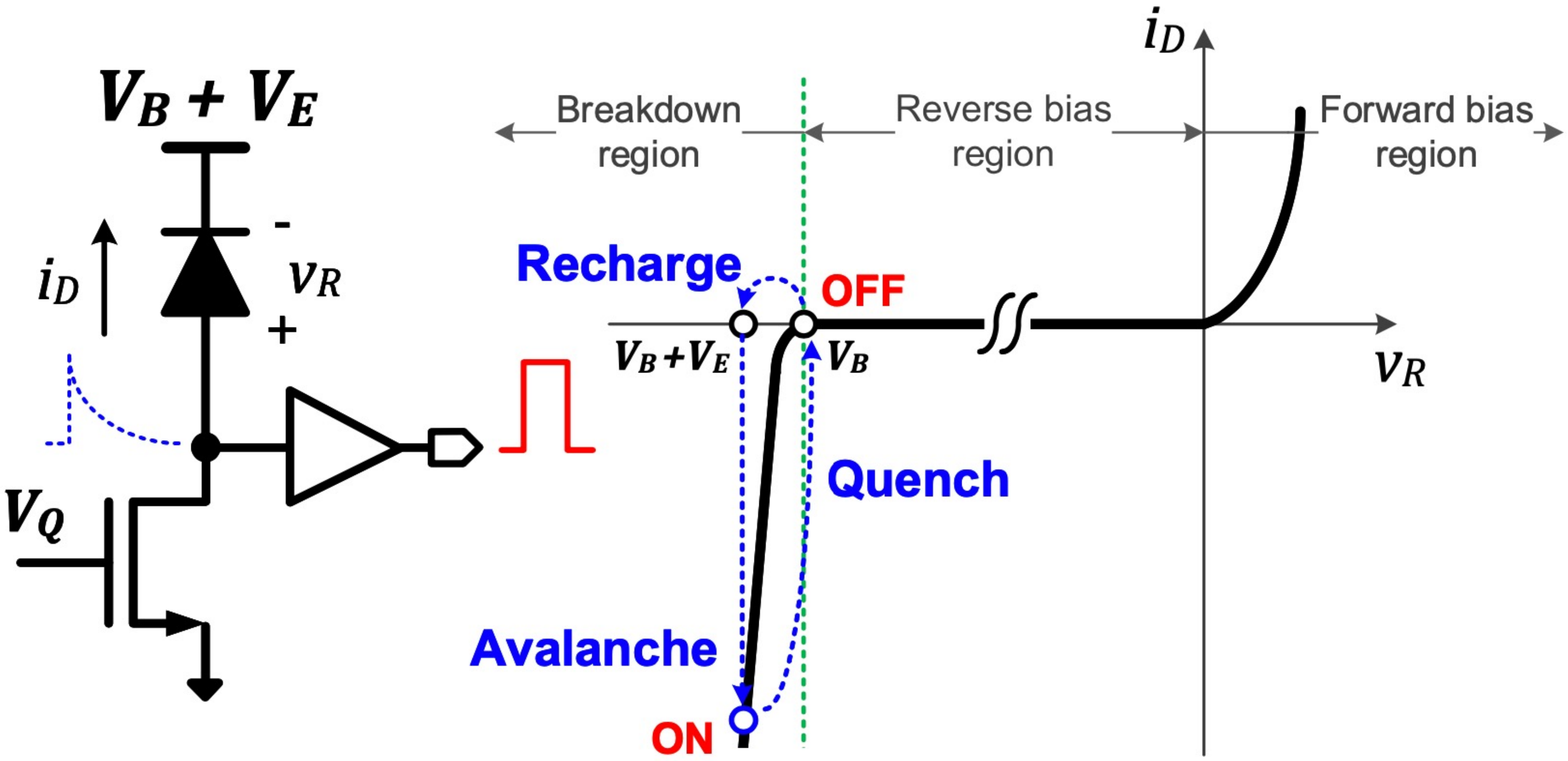
$$\text{APD:}\ \ SNR = \frac{\frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2\langle M\rangle^2}{2e\left(I_p + I_B + I_D\right)F\langle M\rangle^2 d\nu + \frac{4k_B T\Delta\nu}{R}}$$

p-i-n: set $\langle M\rangle = 1,\ F = 1$

$$SNR = \frac{\frac{1}{2}\left(\eta P_{opt}\frac{q}{\hbar\omega}\right)^2}{2e\left(I_p + I_B + I_D\right)d\nu + \frac{4k_B T\Delta\nu}{R}}$$



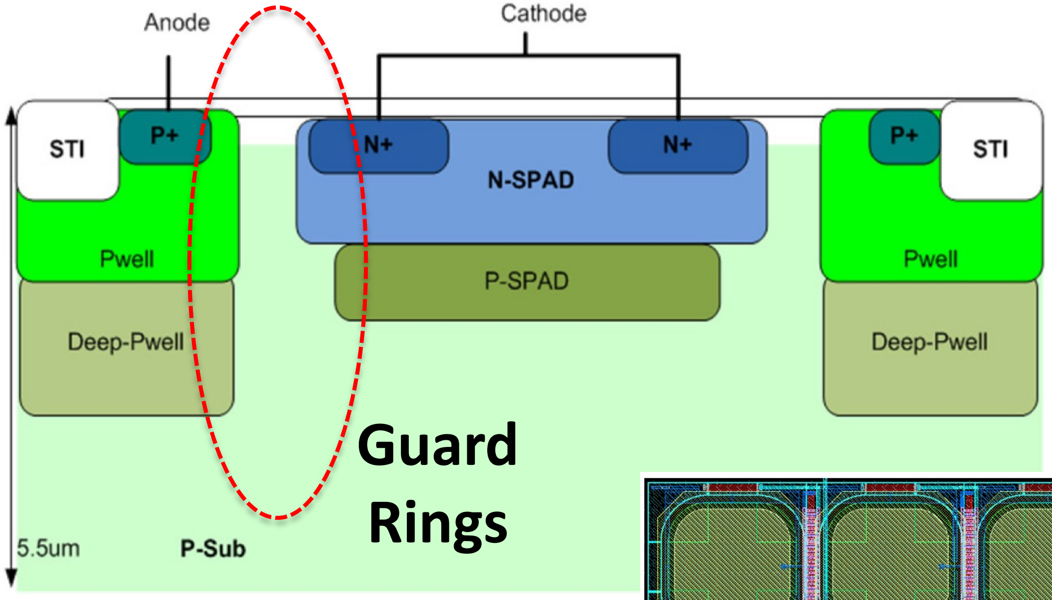
SiPM (or SPAD)



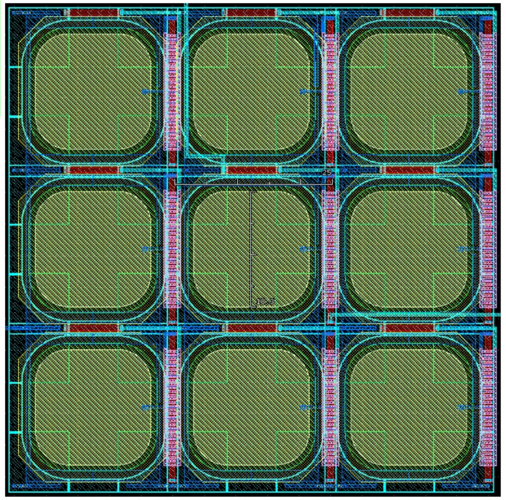
- Silicon photon multiplier (SiPM)/Single photon avalanche diode (SPAD)
- Geiger mode operation

[Ximenes, ISSCC2018]

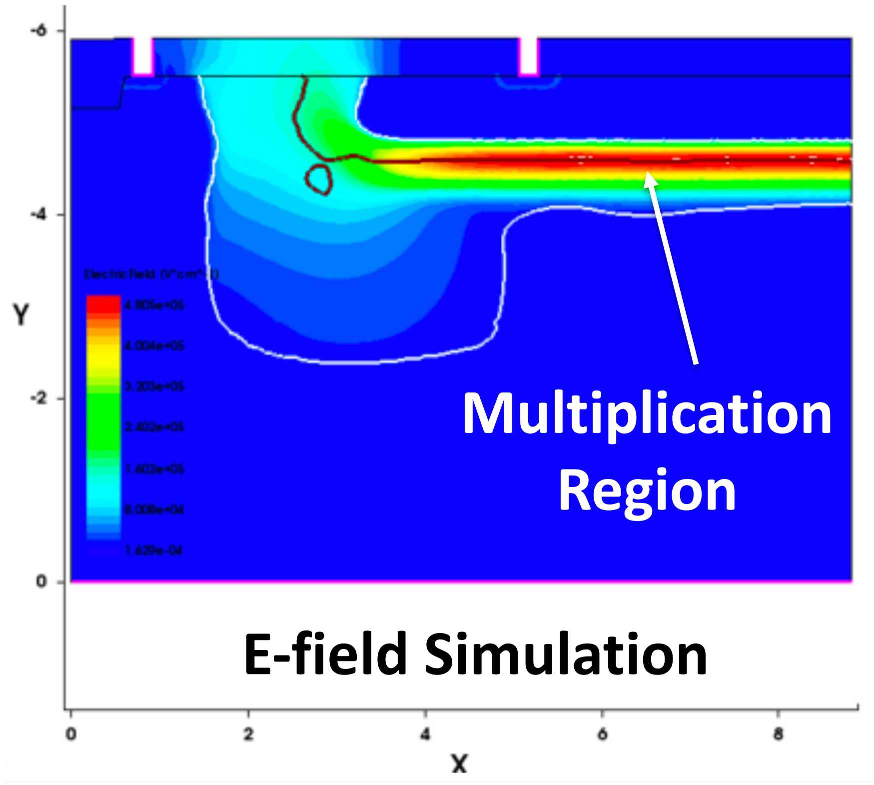
SiPM (or SPAD)



Guard Rings



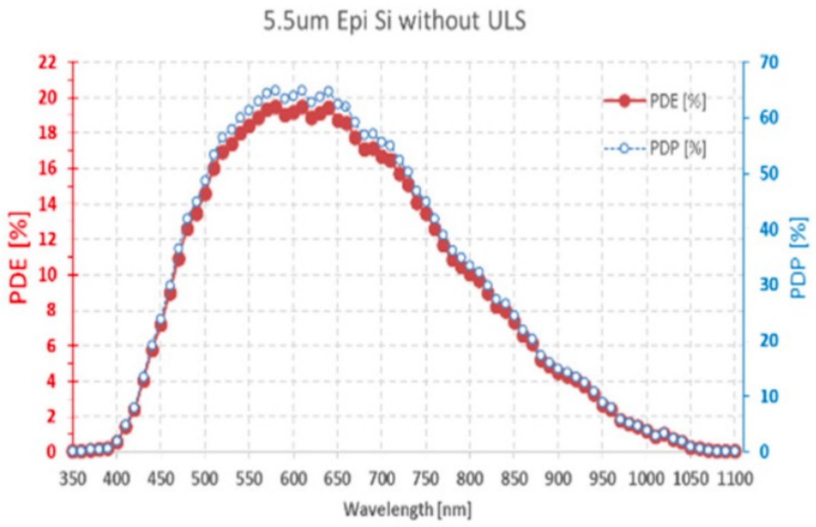
SPAD Array Layout
***Fill-factor (FF)**

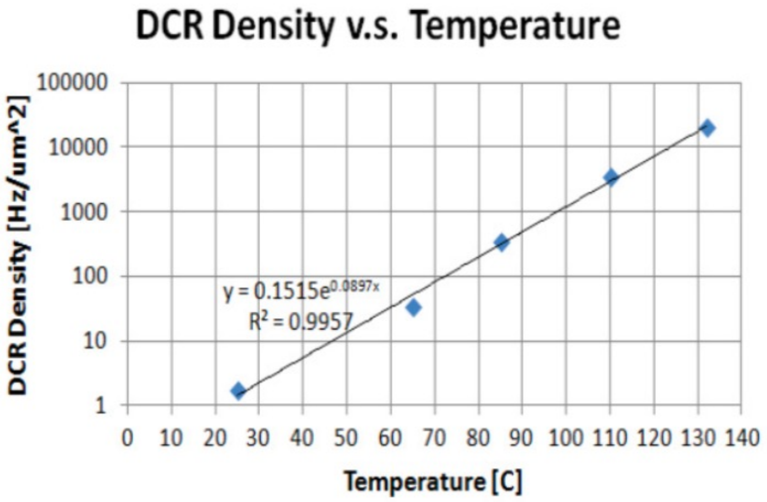


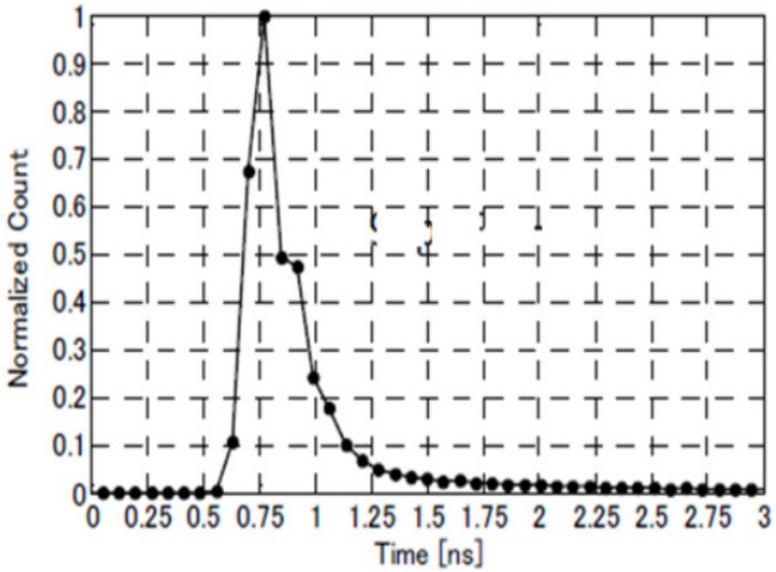
E-field Simulation

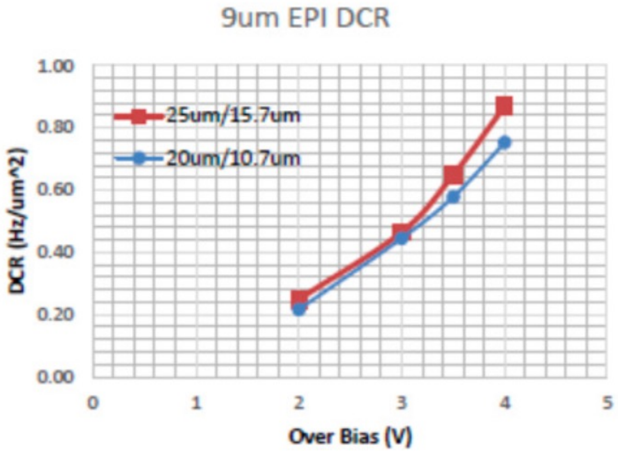
Ref: Fully Depleted SiPMs Optimized for Automotive NIR ToF in 180nm Technology, TowerJazz

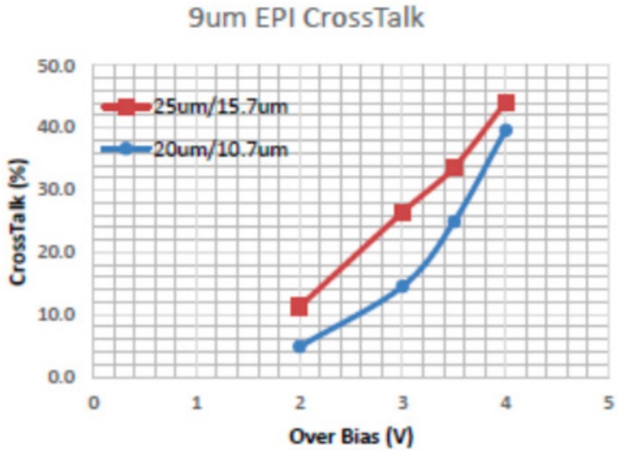
SiPM (or SPAD)'s important metrics

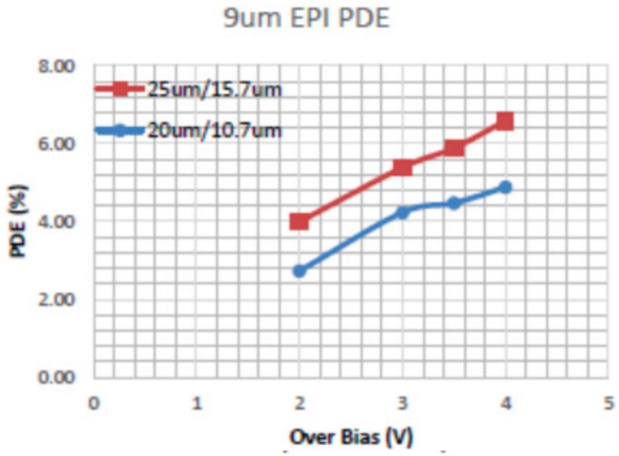












Ref: Fully Depleted SiPMs Optimized for Automotive NIR ToF in 180nm Technology, TowerJazz

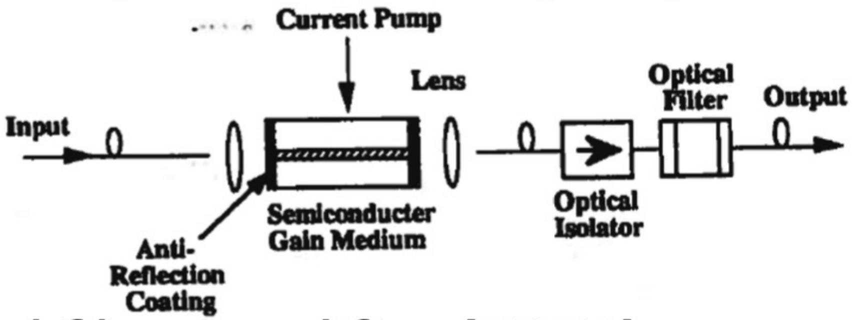
p-i-n Detector w/ Optical Preamplifier

- Fabricating APDs with high GBW can be difficult
- Utilizing an optical amplifier before a p-i-n detector can support higher data rates
- These optical amplifiers can provide gain over a wide optical bandwidth, such as 10nm or ~1.25THz
- Generally, utilizing an optical preamp and p-i-n detector will yield better noise performance relative to and APD
- Major trade-off is the cost of the optical amplifier

[Sam Palermo]

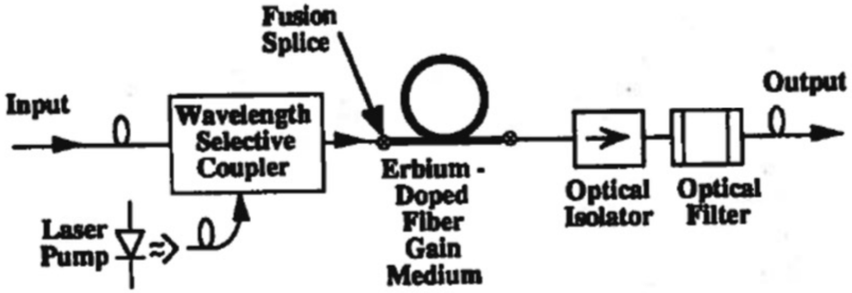
Optical Amplifiers

- Semiconductor optical amplifier (SOA)



[Kazovsky]

- Erbium-doped fiber amplifier (EDFA)

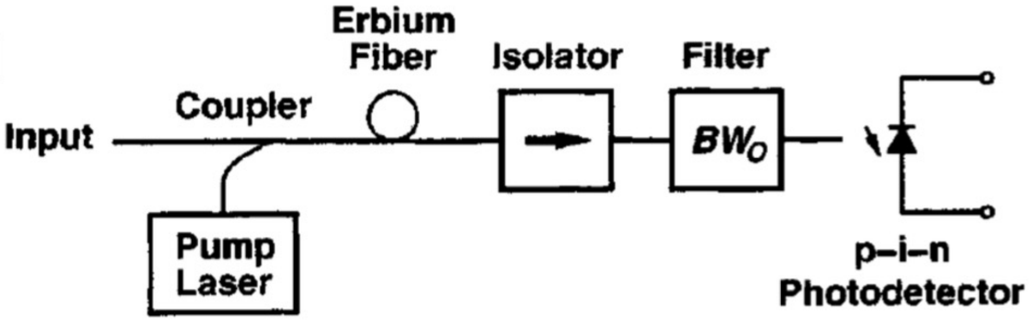


- SOAs can be small and perhaps integrated on the same PIC as the p-i-n detector (not SiP)
- EDFAs generally offer better performance and are more popular, despite their size overhead

[Sam Palermo]

Erbium-Doped Fiber Amplifier (EDFA)

[Sackinger]



- An optical coupler combines the received optical input signal with light from a continuous-wave (CW) pump laser source
- These two light sources are sent through an erbium-doped fiber, typically ~10m, where amplification occurs via stimulated emission
- An isolator follows to prevent feedback and instability
- A filter is also used to suppress amplified spontaneous emission (ASE) noise, which has a white spectrum with a PSD of S_{ASE} $$P_{ASE} = S_{ASE} \cdot BW_O$$

28

[Sam Palermo]

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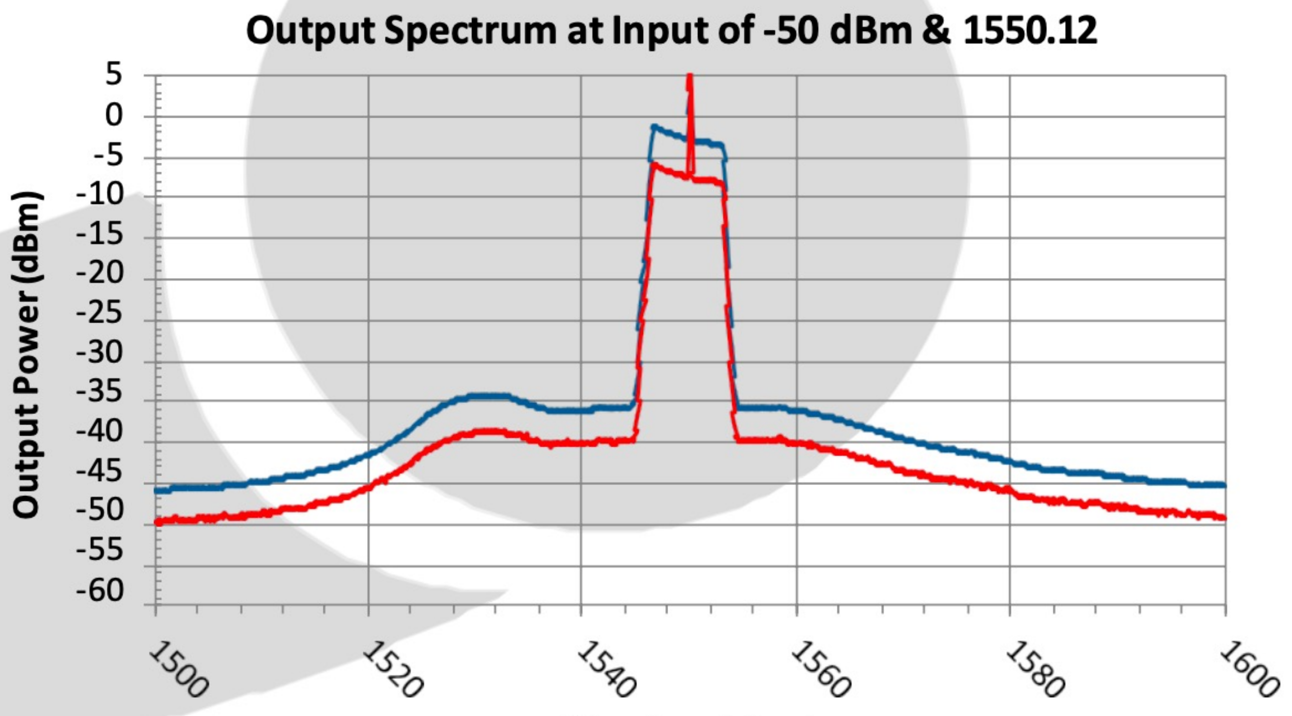
Example EDFA

Center Wavelength	1530nm to 1560nm
Amplification Window	± 1.0 nm typ.
Output Power Levels	10 dBm max.
Optical Gain	50 dB typ.
Noise Figure	4.0 dB typ.
Optical Return Loss	50 dB min
Input/Output Optical Isolation	30 dB min.
Polar. Mode Dispersion	0.1 ps max.
Polar. Dependent Gain	0.1 dB max.
Input Power Range	-60 dBm to -25 dBm
Output Power Stability	0.1 dB over 8 hours



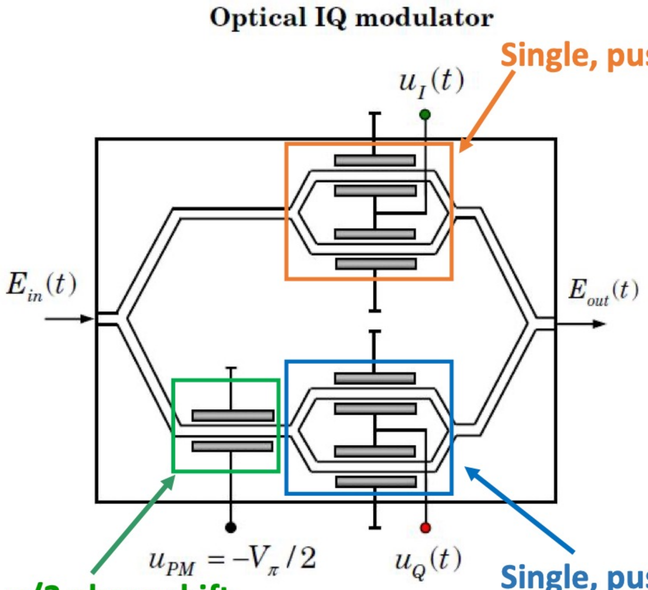
[Optilab, EDFA-PA-LN-N-M]

Summary

- p-i-n detectors have typical responsivities between 0.6-0.9A/W and are mostly used in short-haul applications
- APDs have typical effective responsivities between 5-20A/W and are used in long-haul applications, but their GBW can limit operation above 10Gb/s
- Using an optical amplifier – p-i-n detector combination allows for typical effective responsivities between 6-900A/W and can achieve higher data rates for long-haul applications
- All of these detectors generate current $\propto$ to optical power
- All also have signal-dependent noise currents
  - p-i-n have shot noise
  - APDs have avalanche noise quantified by the excess noise factor F
  - Optical pre-amplifier systems are often dominated by ASE noise, which determines their noise figure F

34 [Sam Palermo]

Coherent Optical Link



Single, push-pull MZM modulating the In-Phase component

$\pi/2$ phase shift

Single, push-pull MZM modulating the Quadrature component

$$\frac{E_{out}(t)}{E_{in}(t)} = \boxed{\frac{1}{2}\cos\left(\frac{\Delta\varphi_I(t)}{2}\right)} + \boxed{j}\boxed{\frac{1}{2}\cos\left(\frac{\Delta\varphi_Q(t)}{2}\right)}$$

$$\Delta\varphi_I(t) = \frac{u_I(t)}{V_\pi}\pi,\ \Delta\varphi_Q(t) = \frac{u_Q(t)}{V_\pi}\pi.$$

BPSK Optical TRx

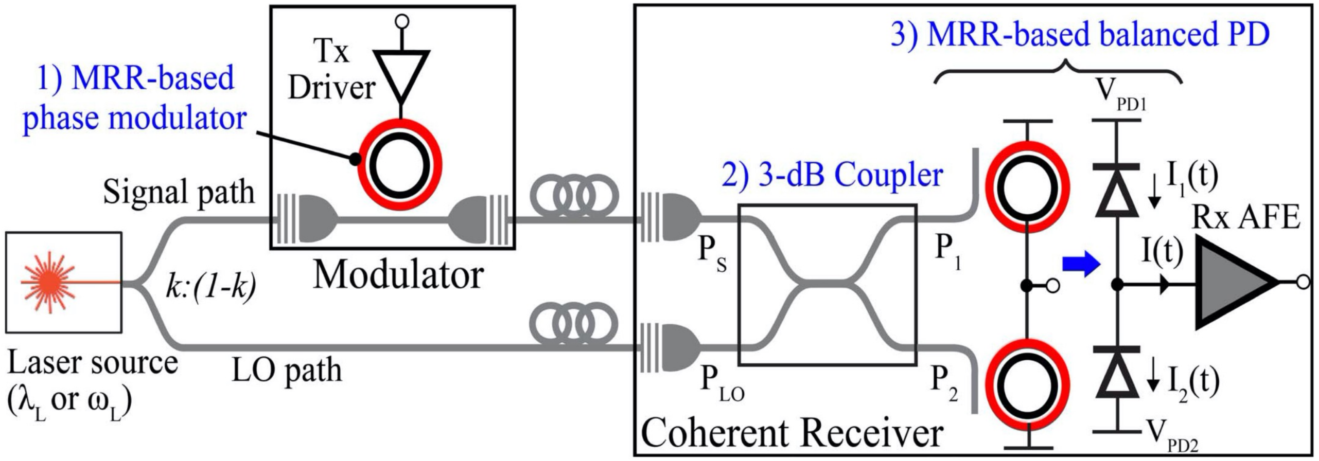
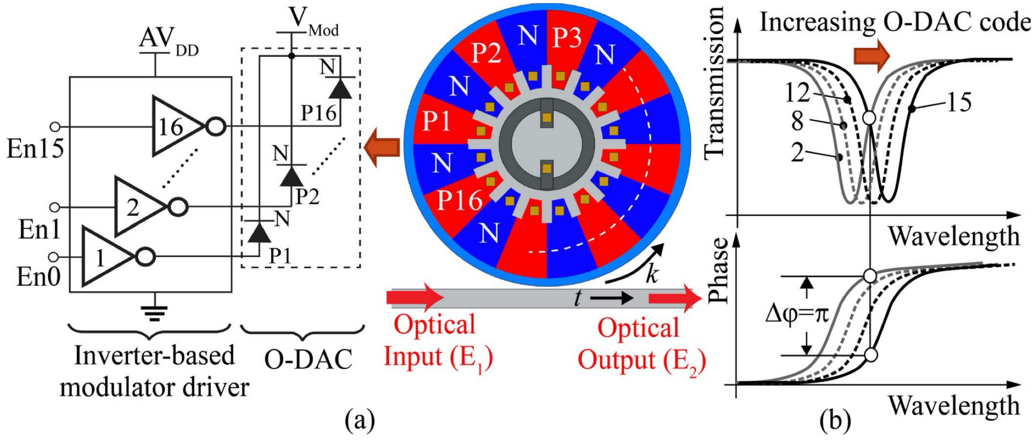


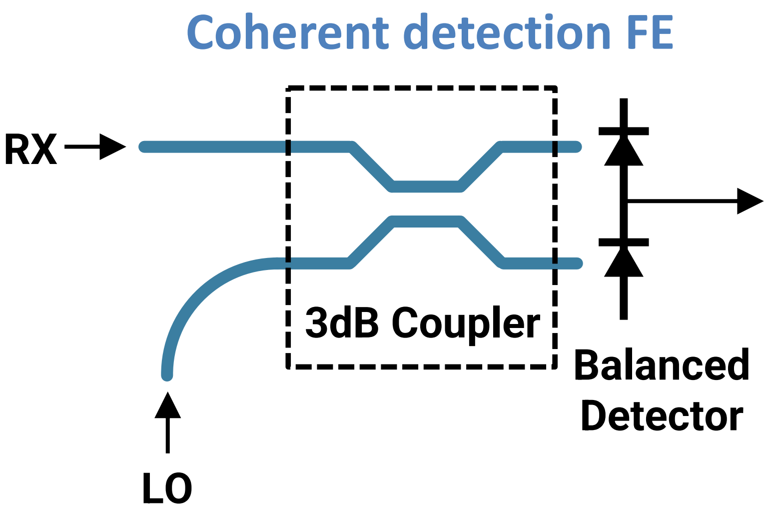
Fig. 4. MRR-based LF coherent link concept [15].

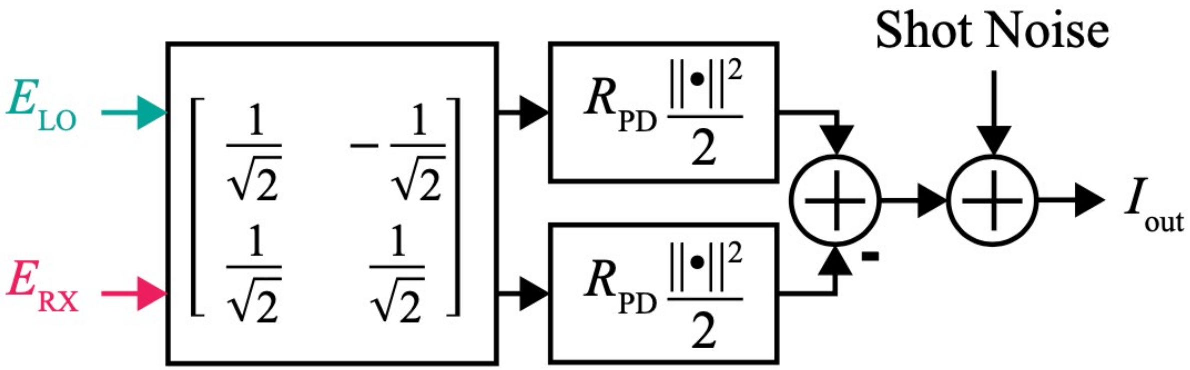


[Nandish Mehta, JSSC 2020]

Coherent Detection Principle

- Optical coherent detection frontend → diode-based mixer





[Taehwan Kim, UC Berkeley]

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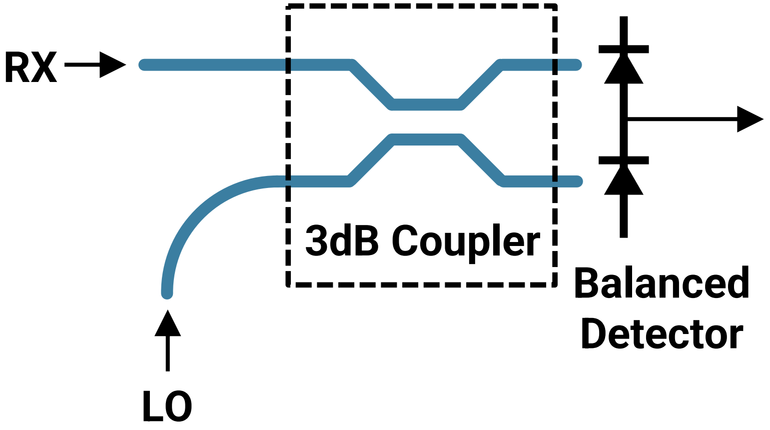

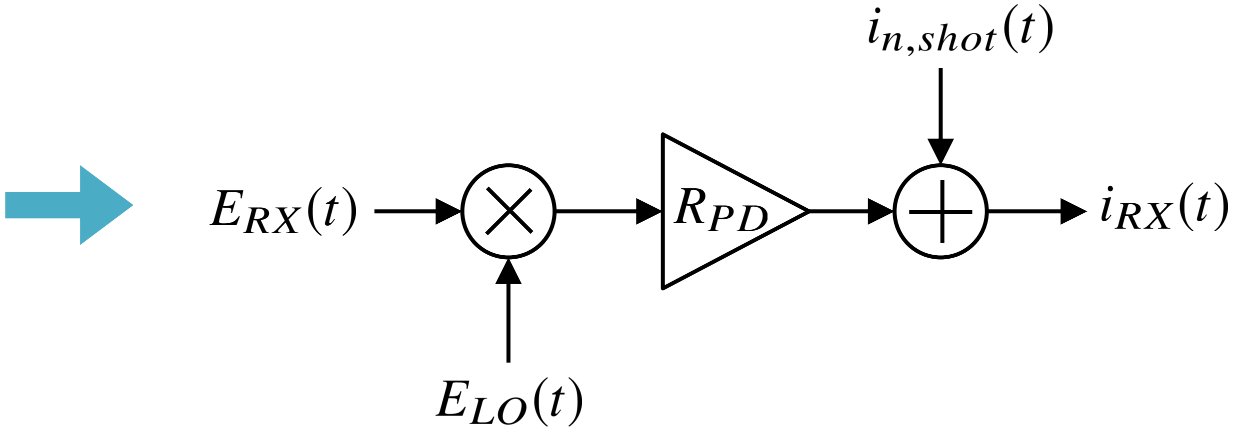

Signal: $i_{RX}(t) = 2R_{PD}\sqrt{P_{LO}P_{RX}}\cos\left(\phi_{LO}(t) - \phi_{RX}(t)\right) + i_{n,shot}(t)$

Noise: $S_{i_n,shot}(\omega) = 2qR_{PD}(P_{LO} + P_{RX}) \sim 2qR_{PD}P_{LO} \quad (P_{LO} \gg P_{RX})$

FMCW: $\phi_{LO}(t) - \phi_{RX}(t) = 2\pi f_{beat}t = 2\pi\gamma\tau t + \phi_0, \quad \gamma = \text{chirp slope}, \ \tau = \text{time of flight}$

[Taehwan Kim, UC Berkeley]

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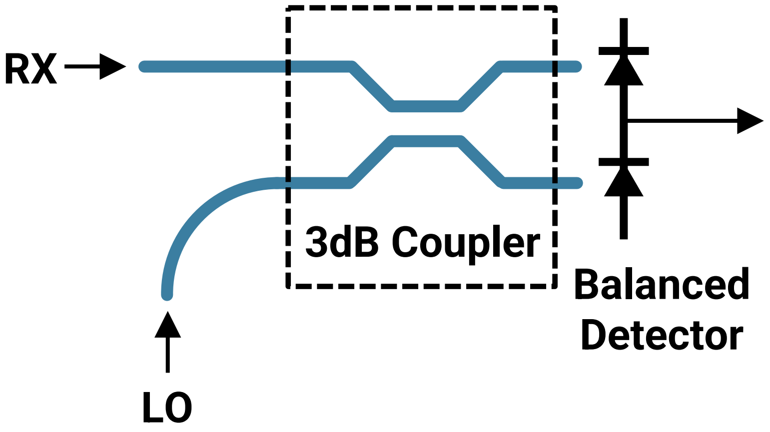

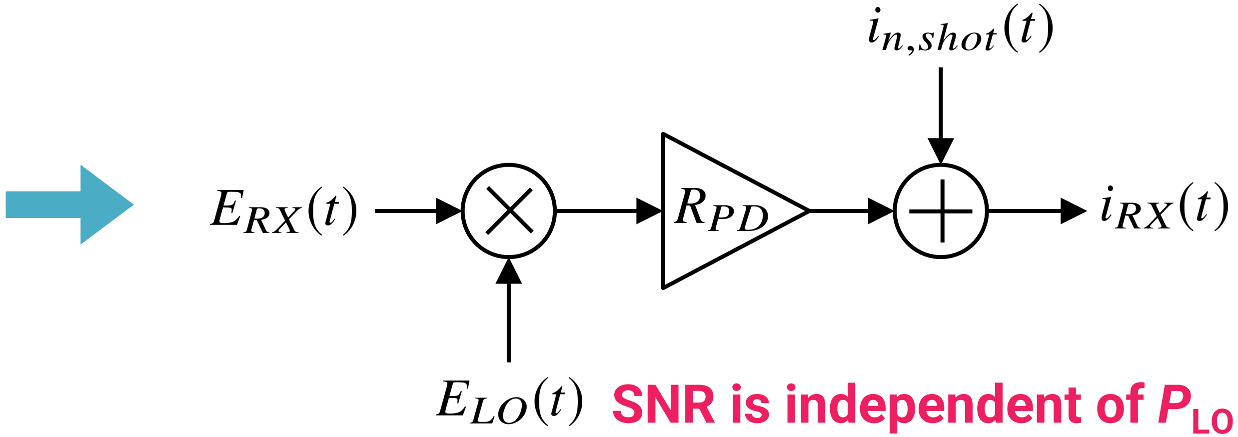

SNR is independent of P_{LO} (fundamental limit of optical detection, *quantum-limit*)

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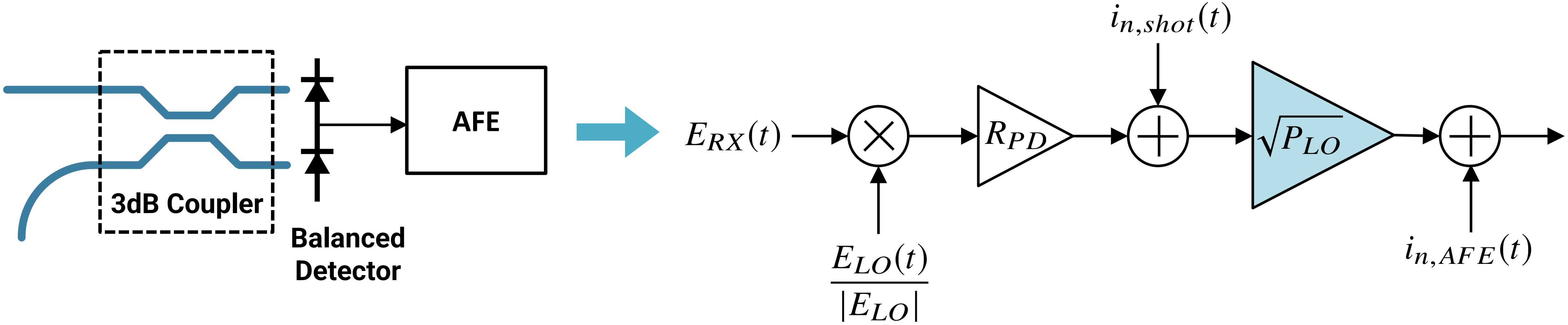
[Taehwan Kim, UC Berkeley]

Coherent Detection Principle

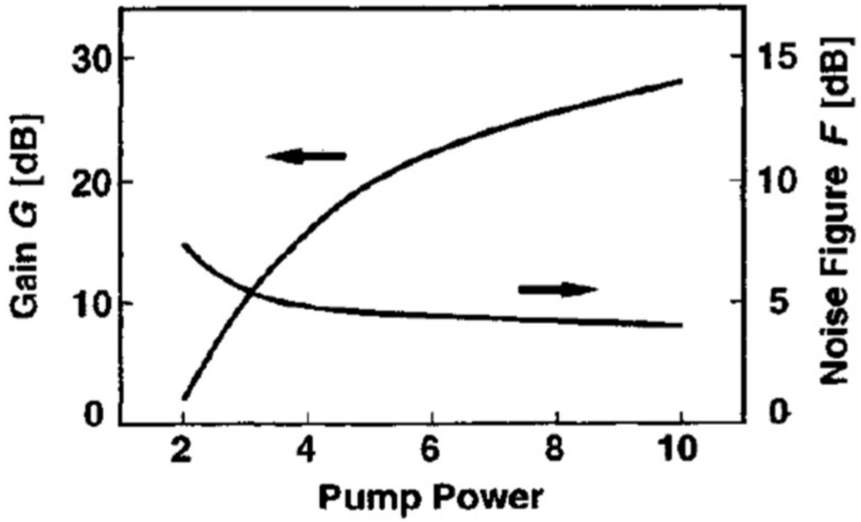


- The signal is effectively ***pre-amplified*** by LO beam power (P_{LO})
  - Sufficient P_{LO} guarantees shot-noise limited detection independent of electrical frontend noise (TIA, ADC, etc.)
  - No need for avalanche mode PDs

[Taehwan Kim, UC Berkeley]

Extra Slides

EDFA Gain



[Sackinger]

- The EDFA introduces a power gain *G* which is a function of the erbium-doped fiber length and the pump power
  - Typical value is 100 or 20dB
  - This is 10X a typical APD *M* factor
- An input power *P* into the EDFA results in the following p-i-n detector current

$$I_{OA} = G \cdot RP$$

Amplified Spontaneous Emission (ASE) Noise

- As the photodetector responds to the incoming light intensity and performs a squaring operation, a signal-dependent ASE term results

$$(signal + noise)^2 = (signal)^2 + 2(signal \cdot noise) + (noise)^2$$

The ASE noise terms are

$$\overline{i_{n,ASE}^2} = R^2\left(\underline{2P_S S_{ASE}} + S_{ASE}^2 BW_O\right)BW_n$$

where P_S is the signal power at the output os the EDFA, $P_S = GP_{in}$

- The signal-spontaneous beat noise is generally the dominant term and is not affected by the optical filter bandwidth, but the electrical receiver bandwidth
- The spontaneous-spontaneous beat noise can be reduced with the optical filter

SNR w/ an EDFA RX

The received signal current average power in the electrical domain is

$$\overline{i_S^2} = R^2 P_S^2$$

and the ASE noise power is

$$\overline{i_{n,ASE}^2} = R^2\left(2P_S S_{ASE} + S_{ASE}^2 BW_O\right)BW_n$$

Using $P_{ASE} = S_{ASE} BW_O$, the SNR is

$$SNR = \frac{\overline{i_S^2}}{\overline{i_{n,ASE}^2}} = \frac{R^2 P_S^2}{R^2\left(2P_S S_{ASE} + S_{ASE}^2 BW_O\right)BW_n} = \frac{\left(P_S/P_{ASE}\right)^2}{P_S/P_{ASE} + 1/2} \cdot \frac{BW_O}{2BW_n}$$

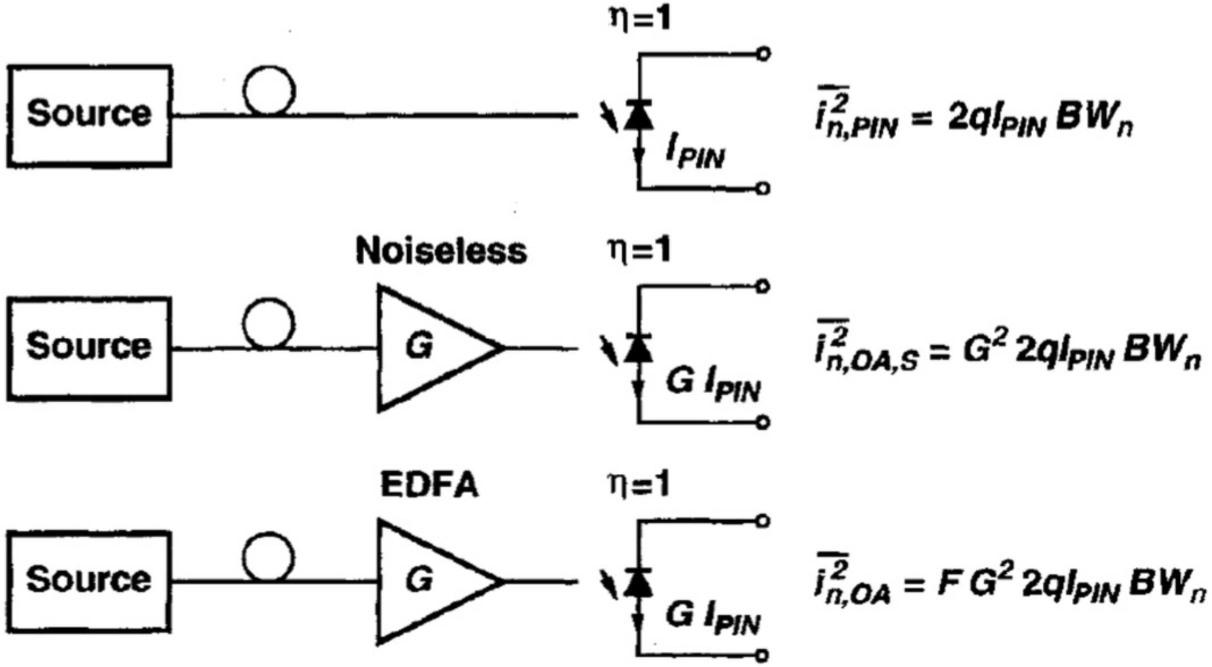
The ratio P_S/P_{ASE} is known as the optical SNR (OSNR)

$$\boxed{SNR = \frac{OSNR^2}{OSNR + 1/2} \cdot \frac{BW_O}{2BW_n} \approx OSNR \cdot \frac{BW_O}{2BW_n}}$$

- The electrical SNR is well approximated by scaling the OSNR by the ratio of the optical filter bandwidth over twice the electrical receiver bandwidth

EDFA Noise Figure

- Optical amplifier noise figure is defined as the ratio of the total output noise power to the fraction of the noise power due to the shot noise of the optical source



EDFA Noise Figure

- If we assume that the EDFA ASE noise dominates, i.e. neglect the shot noise to calculate F

$$\overline{i^2_n}_{,OA} = \overline{i^2_n}_{,ASE}$$

$$FG^2 2qI_{PIN}BW_n = R^2\left(2P_S S_{ASE} + S_{ASE}^2 BW_O\right)BW_n$$

$$\boxed{F = \frac{\lambda}{hc}\left(\frac{S_{ASE}}{G} + \frac{S_{ASE}^2}{2G^2P}BW_O\right)}$$

Signal-Spontaneous Beat Noise   Spontaneous-Spontaneous Beat Noise

- Note that the noise figure depends on the input power P
- However, for reasonable input power levels and/or small optical bandwidths the first term typically dominates and we can define a signal-spontaneous beat noise limited noise figure

$$\boxed{\tilde{F} = \frac{\lambda}{hc}\cdot\frac{S_{ASE}}{G}}$$