Dipartimento INFOCOM
Università degli Studi di
Roma “La Sapienza”

Departamento de Señales y
comunicaciones
ULPGC

Optical Communications

Telecommunication Engineering
School of Engineering
University of Rome La Sapienza
Rome, Italy
2005-2006

Lecture #4, May 9 2006

Receivers

OVERVIEW

Photodetector types:

• Photodiodes

• Phototransistors

Desirable characteristics of a photodiode:

• High sensitivity at the operating wavelength range (700-900 nm and 1200-1600 nm)

• Short response time

• Linearity

• Stability (in time and with temperature changes)

• Low cost and high reliability

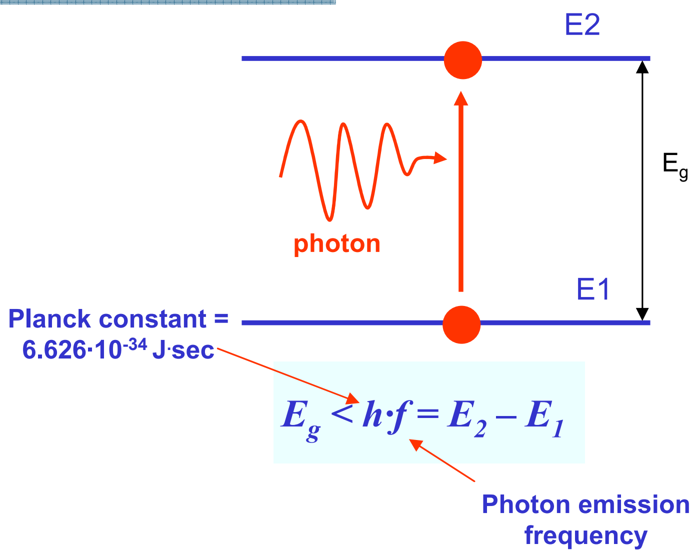
PHOTODIODE BASICS

- Absorption of photons in a photodiode with a suitable bandgap energy causes an electron to move from the valence band to the conduction band

- Absorption most likely occurs in or near the depletion region.

- Generated carriers are swept out of the device to form a current

- Two modes of operation are possible:
    - photovoltaic
    - photoconductive



$$E_g < h \cdot f = E_2 - E_1$$

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PHOTOVOLTAIC VS. PHOTOCONDUCTIVE

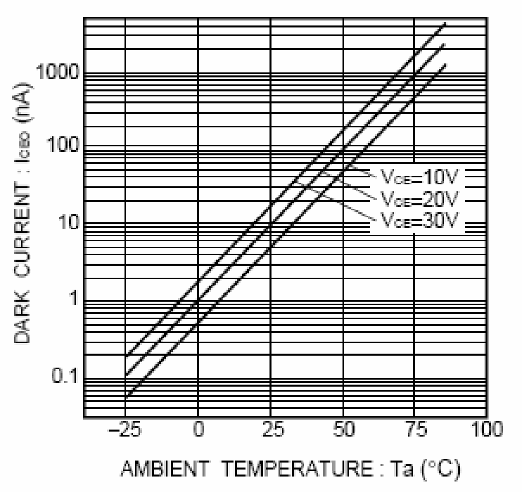
Photodiodes can be used in either **zero** bias or **reverse** bias.

In **zero** bias, light falling on the diode causes a voltage to develop across the device, leading to a current in the forward bias direction. This is called the **photovoltaic** effect, and is the basis for solar cells - in fact a solar cell is just a large number of big, cheap photodiodes.

Diodes usually have extremely high resistance when **reverse** biased. This resistance is reduced when light of an appropriate frequency shines on the junction, leading to a high sensitivity to light exposure. Hence, a reverse biased diode can be used as a detector. Circuits based on this effect called photoconductive are more sensitive to light than those based on the photovoltaic effect.

DARK CURRENT

- When a photodiode is reverse biased (photoconductive mode) a small current flows even in absence of incident light: the so-called **dark current**.
- The dark current increases noise at the output of the receiver, reducing the Signal-to-Noise Ratio
- Typical values of dark current span from tens to hundreds of nAmpères
- Dark current is temperature dependent; the higher the temperature, the higher the dark current



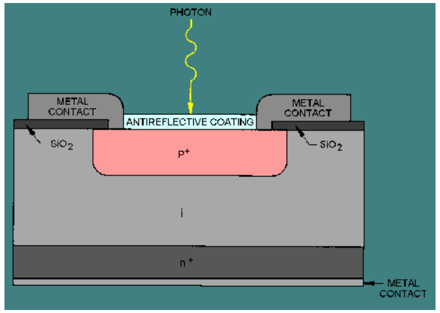
Variation of dark current as a function of ambient temperature for different reverse biases

(Rohm RPT-38PB3F)

PHOTODIODES AND PHOTOTRANSISTORS

A **photodiode** is a p-n junction designed to be responsive to optical input. Photodiodes are provided with either a window or optical fiber connection, in order to let in the light to the sensitive part of the device.

A **phototransistor** is in essence nothing more than a normal bipolar transistor that is encased in a transparent case so that light can reach the Base-Collector diode. The phototransistor works like a photodiode, but with a much higher sensitivity to light, because the electrons that tunnel through the Base-Collector diode are amplified by the transistor function.



Top illuminated diode

PHOTODIODE MATERIALS

Parameter	Si	Ge	InGaAs
Wavelength (nm)	300-1100	500-1800	1000-1700
Peak response (nm)	800	1550	1700
Peak responsivity (A/W)	0.5	0.7	0.9
Dark current (nA)	1	200	10
Typical risetime (ps)	500	100	300

Germanium is only used in some special applications
that require covering all three windows, due
to its high dark current

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PHOTODIODES: PIN and APD

Two types of medium- and large-area silicon photodiodes are widely available:

positive-intrinsic-negative (*p-i-n*) → ordinary silicon *p-i-n* photodiodes are employed in nearly all commercial infrared links at present

avalanche photodiode (APD) → *p-i-n* devices that are operated at very high reverse bias, so that photogenerated carriers create secondary carriers by impact ionization, resulting in internal electrical gain

APD advantages

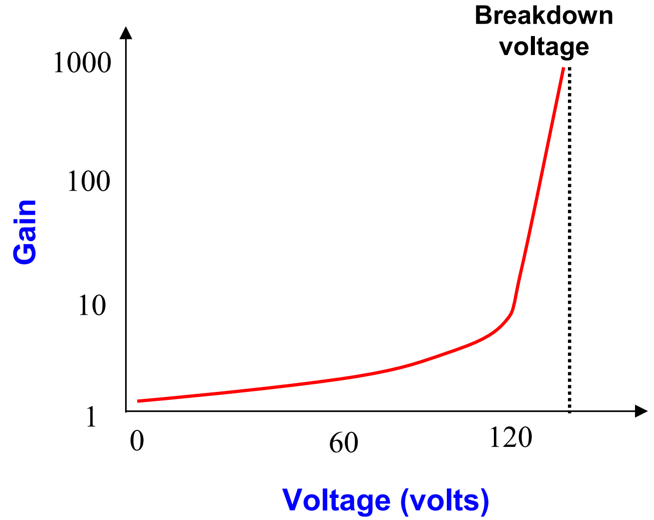
- Their internal gain helps overcome preamplifier thermal noise, by increasing the receiver SNR

APD drawbacks

- The random nature of the APD internal gain increases the variance of the generated current
- High cost requirement for high bias
- Temperature-dependent gain.

GAIN AND REVERSE VOLTAGE IN APD

• Gain is measured with respect to the number of hole-electron pairs created at low voltage, were no gain takes place.
• Achieving a high gain means operating close to the breakdown voltage
• Damage to the device may result if the breakdown voltage is exceeded.



Gain versus reverse bias voltage for an avalanche photodiode

Gain (*M*) is defined as the ratio of the output current (at an operating reverse bias voltage) to the current at a low voltage

N.B. M=1 for PIN

PHOTODIODES: PHOTOCURRENT

When hit by an instantaneous optical power $p_{opt}(t)$, a *p-i-n* produces an instantaneous current i(t) proportional to the optical power and to ρ that *is* the *responsivity* (A/W)

$$\rho = \eta \frac{q}{hf}$$

$$i(t) = \rho \cdot p_{opt}(t)$$

The generated current is proportional to the received optical power and therefore the available electrical power is proportional to the square of the optical power

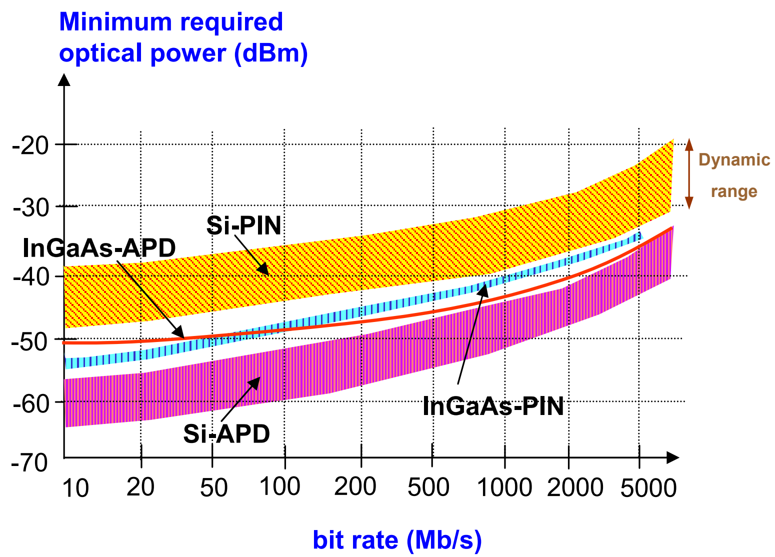
$$p_{ele}(t) = i^2(t) \cdot R = \rho^2 \cdot p_{opt}^2(t) \cdot R$$

PARAMETERS: SENSITIVITY AND DYNAMIC RANGE

- Receiver sensitivity is defined as the average optical input power required to ensure that the bit error probability is lower than a threshold, typically 10^{-9} in transmissions over the optical fiber

- Input power level is normally expressed in dBm

- Dynamic range is the range of optical input powers over which a receiver works properly. The overload level indicates saturation at the receiver



Typical receiver sensitivity for various designs for an error probability of 10^{-9}

Dynamic range (dB) = Overload level (dBm) - Sensitivity (dBm)

PARAMETERS: QUANTUM EFFICIENCY

Quantum Efficiency η

It expresses the photodiode capability to convert light energy to electrical energy.

It influences the responsivity of the photodiode

Quantum Efficiency may approach values around 0.8

The following reference table identifies, at η =1, the responsivity of an ideal photodiode over the 200-1100 nm wavelength range.
Note that η =1 is not attainable.

$$\rho = \frac{\eta q}{hc/\lambda}$$

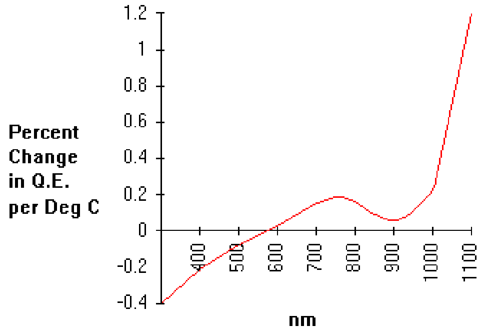
for λ in nm and ρ in A/W one has:

$$\rho = \eta \frac{\lambda}{1.24 \cdot 10^3}$$

Wavelength, (nm)	Responsivity @ η =1 in A/W
200	0.161
300	0.242
400	0.323
500	0.403
600	0.484
700	0.565
800	0.645
900	0.726
1000	0.806
1100	0.887

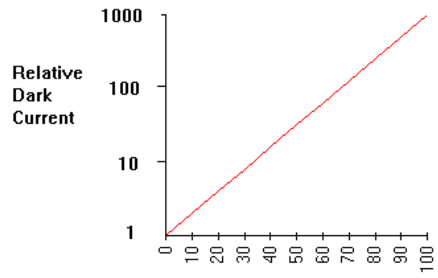
PARAMETERS: TEMPERATURE EFFECTS

Increasing the operating temperature of a photodiode modifies Quantum Efficiency η due to changes in the radiation absorption of the device. Values shift lower in the UV region and higher in the IR region.



Temperature Dependence of Q.E.

Increasing the operating temperature increases the dark current. This leakage doubles for each 8 to 10 ºC temperature increase

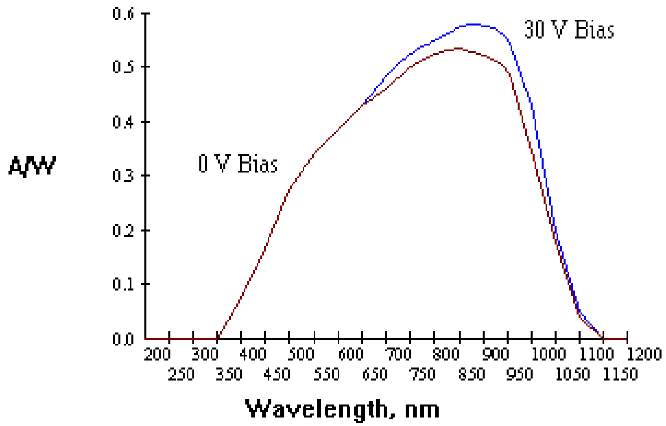


Dark Current vs Temperature

PARAMETERS: RESPONSIVITY

Photodiode Responsivity:

As already defined, responsivity is the ratio between the photocurrent output in ampères and radiant power (in watts) incident on the photodiode. It is expressed in A/W



A typical responsivity curve as a function of wavelength

Risetime (t_r)

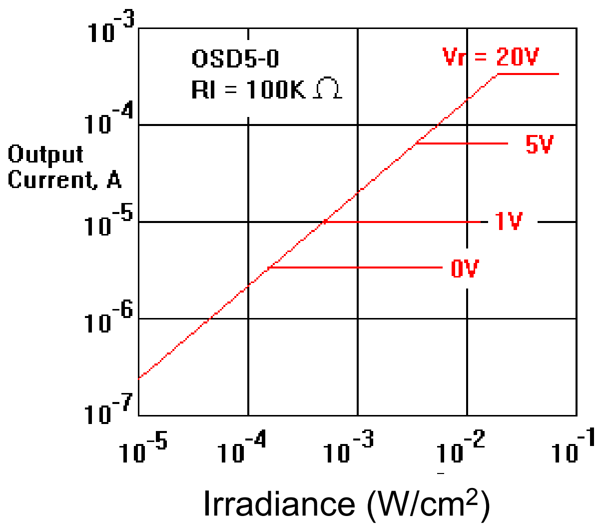
This is the measure of the photodiode response speed to a stepped light input signal. It is the time required for the photodiode to increase its output from 10% to 90% of final output level

Maximum Reverse Voltage (V_r)

Applying excessive reverse voltage to photodiodes may cause breakdown and severe degradation of device performance. Any reverse voltage applied must be kept lower than the maximum rated vale, (V_{rmax}).

PARAMETERS: LINEARITY

Linearity: The output of photodiode when reverse-biased is highly linear with respect to the irradiance applied to the photodiode junction.



Output current as a function of irradiance and for different values of Reverse Bias

PARAMETERS: Noise Equivalent Power

The noise current generated by a silicon photodiode operating under reverse bias is a combination of a “shot noise” that depends on the dark leakage current and of the current generated by thermal noise introduced by the shunt resistance of the device at a given temperature, typically ambient (290 °K).

The **Noise Equivalent Power (NEP)** is the minimum incident power required on a photodiode to generate a photocurrent equal to the photodiode noise current

Since the photodiode light power-to-current conversion depends on the radiation wavelength, the NEP power is quoted at a particular wavelength. The NEP is non-linear over the wavelength range, as is responsivity.

$$NEP(\lambda) = \frac{noise\ current}{\rho(\lambda)}$$

PARAMETERS: SHOT or QUANTUM NOISE

The Shot Noise current is related to the intrinsic uncertainty in the process of generation of electrons from quanta of light. It is also called Quantum Noise and can be expressed as a current I_S by the following shot noise equation:

$$I_S = \sqrt{\left(I_d + I_p\right) \cdot q \cdot 2B}$$

where

$$q = 1.6 \cdot 10^{-19}\ C$$

$$I_p = \text{photogenerated current } (A)$$

$$I_d = \text{dark current } (A)$$

$$B = \text{system bandwidth } (Hz)$$

PARAMETERS: JOHNSON or THERMAL NOISE

The Johnson noise contribution is introduced by the output resistance of the device *R*, that is after optical/electrical conversion. The Johnson noise can be expressed as a current I_J in the following way:

$$I_J = \sqrt{\frac{2RkFT_0 \cdot 2B}{R^2}} = \sqrt{\frac{4kFT_0B}{R}}$$

where

$$k = 1.38 \cdot 10^{-23} \ Joules / K$$

PARAMETERS: EXCESS NOISE

• Only present in APD, and is due to the Gain M introduced by the photo-multiplication effect

• One can define an excess noise factor F_e

$$F_e = \frac{M^2 \cdot M^a}{M^2} = M^a$$

where 0.2<*a*<1, depending upon the diode material (Germanium vs. Silicon)

•Shot noise current would increase with gain *M* in the ideal case of M≠1, but since M≠1 implies excess noise is present, one has:

$$I_S = \sqrt{\left(I_d + I_p\right) \cdot q \cdot 2B \cdot M^2 F_e}$$

NOISE AND SNR

$$I_N^2 = I_S^2 + I_J^2$$

THERMAL NOISE $$I_J^2 = \frac{4kFT_0B}{R}$$

SHOT NOISE, PIN $$I_S^2 = \left(I_d + I_p\right) \cdot q \cdot 2B$$

SHOT NOISE, APD $$I_S^2 = \left(I_d + I_p\right) \cdot q \cdot 2B \cdot M^2 \cdot F_e$$

$$SNR = \frac{\text{available power dissipated at } R}{\text{available noise power developed at } R} = \frac{I_p^2 M^2 \cdot R}{I_S^2 \cdot R + I_J^2 \cdot R} = \frac{1}{\frac{1}{SNR_S} + \frac{1}{SNR_J}}$$

- when shot noise is dominant

$$SNR \approx SNR_S = \frac{I_p^2 M^2 \cdot R}{I_S^2 \cdot R} \approx \frac{I_p^2 M^2}{I_p \cdot q \cdot 2B \cdot M^2 F_e} = \frac{1}{2B \cdot F_e} \frac{\eta \cdot P_{opt}}{hf}$$

- when thermal noise is dominant

$$SNR \approx SNR_J = \frac{I_p^2 M^2 \cdot R}{I_J^2 \cdot R} = \frac{I_p^2 M^2}{4kFT_0B / R} = \frac{R \cdot M^2 \cdot q^2}{4kFT_0B} \left(\frac{\eta \cdot P_{opt}}{hf}\right)^2$$

COMMERCIAL DEVICES

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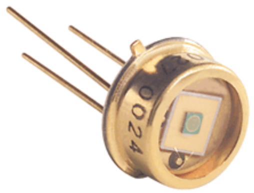
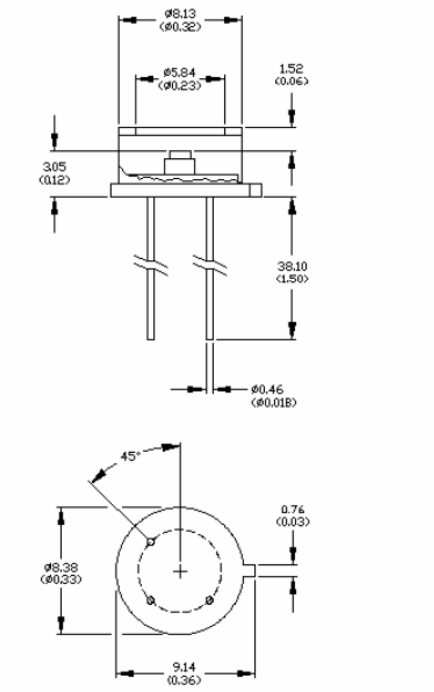
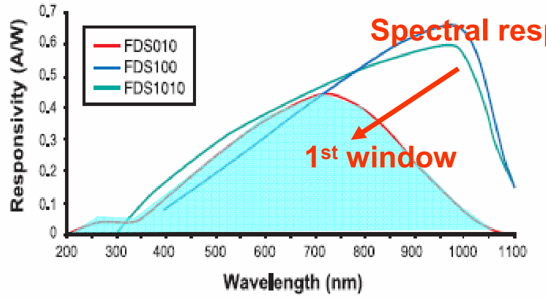
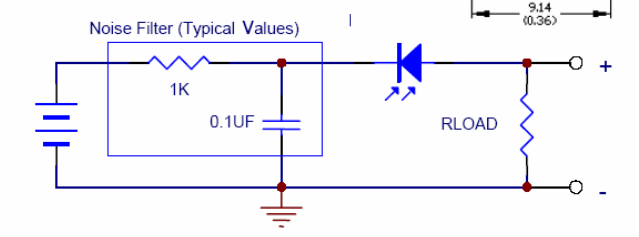
FDS010 Si Photodiode
High Speed







Circuit connection



Electrical Characteristics
Spectral Response: 200-1100nm
Active Area: 0.8mm²
Rise Time (RL=50Ω): <1ns (20V bias)
Fall Time (RL=50Ω): <1ns (20V bias)
NEP@900nm: 5.0 x 10^{-14} W·$Hz^{-1/2}$ (@20V bias)
Dark Current: 2.5nA max (20V)
Package: T05, 0.36" can

Maximum Ratings
Damage Threshold CW: 100 mW/cm^2
Damage 10ns Pulse: 500mJ/cm²
Max Bias Voltage: 25V

Other
Price: €46,00 Weight: 10 g.

COMMERCIAL DEVICES

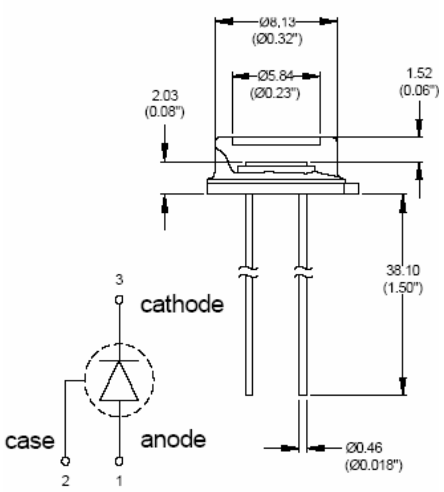
THORLABS

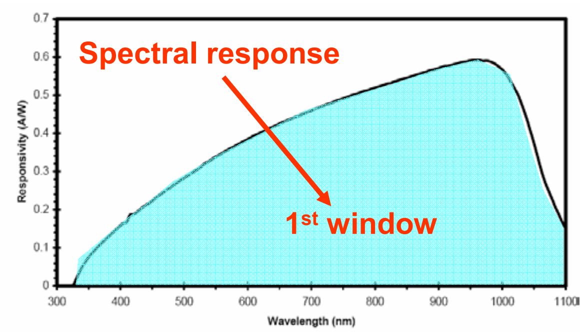
FDS100 Si Photodiode
Medium Speed
Large Active Area

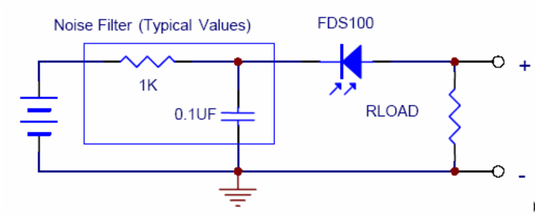
Electrical Characteristics
Spectral Response: 350-1100nm
Active Area: 13.0mm²
Rise Time (RL=50Ω): 10ns (20V bias)
Fall Time (RL=50Ω): 10ns (20V bias)
NEP@900nm: 1.2 x 10^{-14} W/√Hz (@20V bias)
Dark Current: 20nA max (20V)
Package: T05, 0.36” can

Maximum Ratings
Damage Threshold CW: 100 mW/cm2
Damage 10ns Pulse: 500mJ/cm²
Max Bias Voltage: 25V

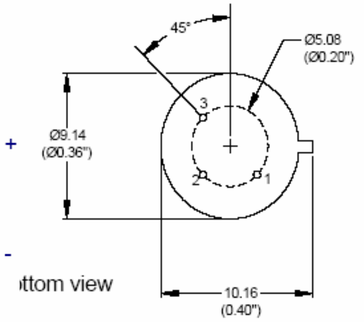
Other
Price: 14,5 €







Circuit conection



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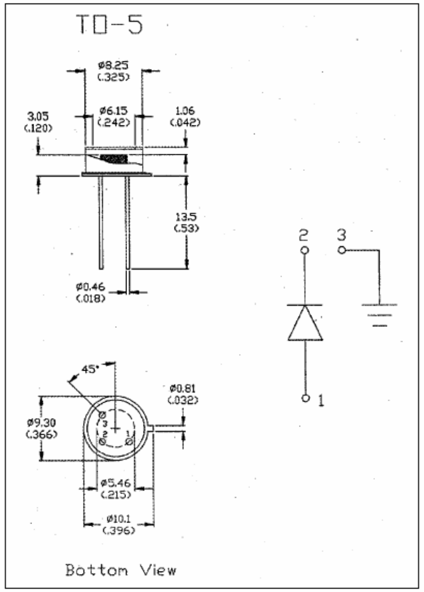
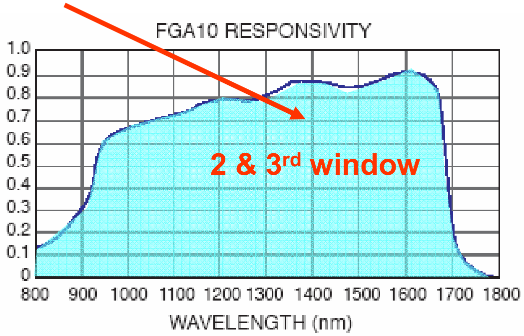


Spectral response



MODEL FGA10 (InGaAs PIN Photodiode)

Electrical Characteristics

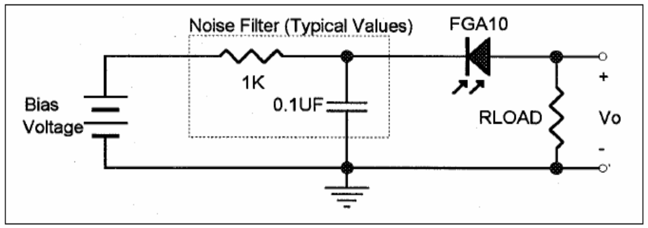
Spectral Response: 800-1800nm
Active Diameter: 1.0mm
Rise/Fall Time (RL=50Ω): 5.0ns (5V)
Bandwidth (RL=50Ω, -3dB,5V): 40 MHz min
NEP@1550nm: $1 \cdot 10^{-14}$ W/√Hz min
Dark Current: 100nA max, (25nA typical) @ 5V
Package: TO-5

Maximum Ratings

Damage Threshold CW: 100mW
Max Bias Voltage: 20V
Storage Temperature: -40 to 125° C
Operating Temperature: -40 to 85° C
Reverse Current: 10mA
Forward Current: 10mA

Other

Price: €146,00 **Weight:** 10 g.



Circuit connection

LENSES AT THE RECEIVER

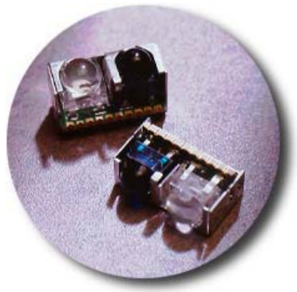
Using lenses at the receiver has four main effects:

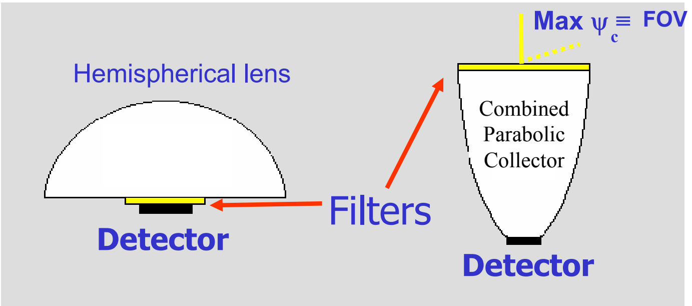
· **Increasing FOV (Field-of-view):** that is more received optical power but also more multipath dispersion (different delays inside the lens)

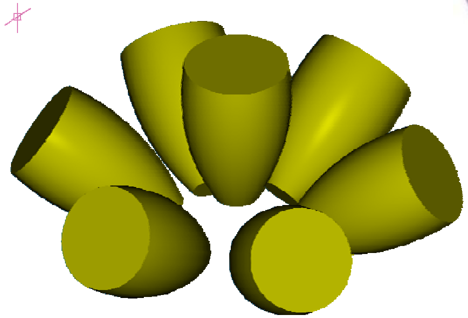
· **Optical Filtering:** tinted lenses may act as filters, blocking for example sun light in the visible part of the spectrum

· Producing an **optical-power gain** proportional to the ratio between the area of the lens and the active area of the receiver

· **Sectorizing the receiver**, by using several lenses







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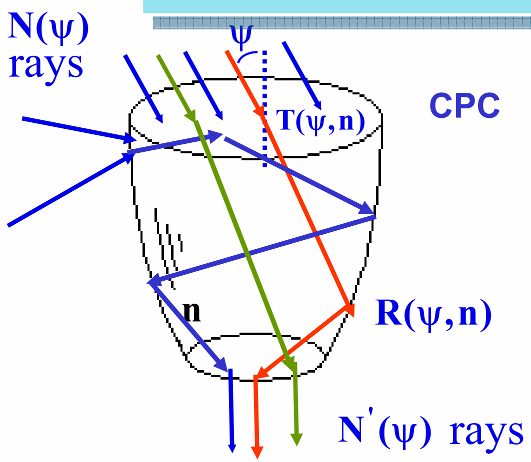
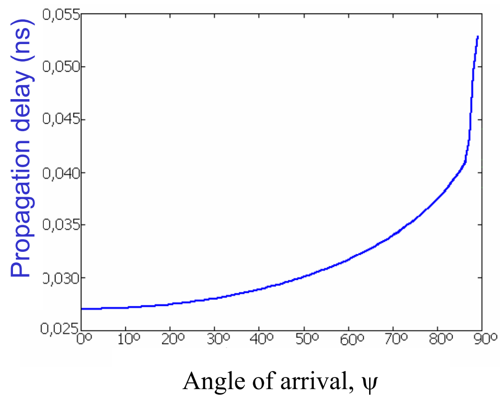
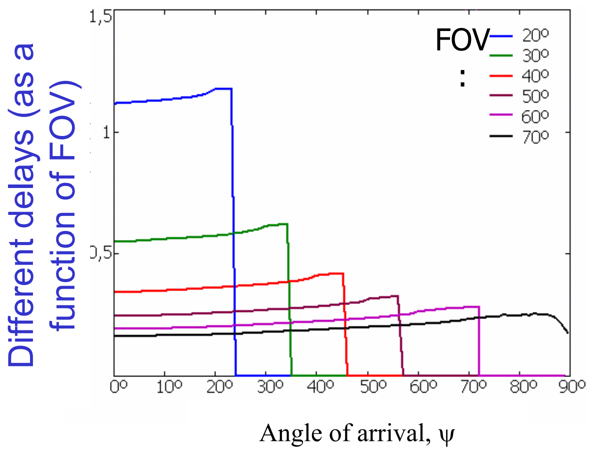
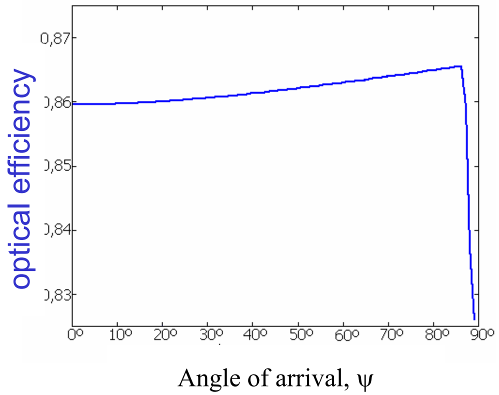
LENSES AT THE RECEIVER



Hemispherical lens







FRONT-END CIRCUITRY

• Front-end provides amplification and current to voltage conversion for the signal current from the photodiode

• To achieve a high sensitivity the front-end must add as little noise as possible to the detected signal.

• In the front-end, a "pre-amplifier" is used, providing amplification

Front-end amplification circuit typology

• Low impedance front-end (also called a voltage amplifier)
  Feature: large bandwidth but low sensitivity that is weak signals cannot be detected

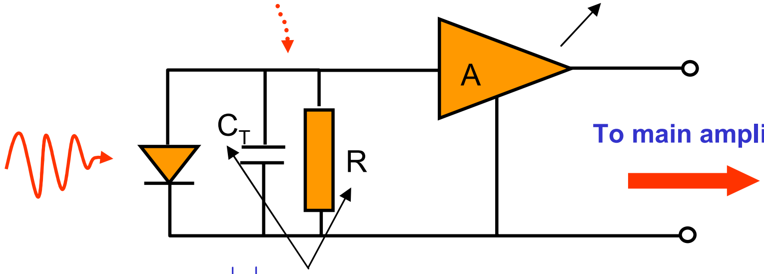
• High impedance front-end
  Feature: high sensitivity but low bandwidth

• Trans-impedance front-end
  Feature: trade-off between the previous two

LOW IMPEDANCE AMPLIFIERS

↓ **Impedance** → ↓ **Signal to Thermal Noise Ratio** → ↑ **Cut-off frequency f_{3dB}**

We can use off–the-shelf 50 Ω amplifiers (e.g. minicircuits)



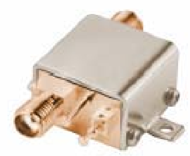
To main amplifier

↓↓ **Impedance about 50Ω**

$$f_{3dB} = \frac{1}{2\pi R C_T}$$

$$SNR_J = \frac{R\, M^2 \cdot q^2}{4kFT_0B}\left(\frac{\eta \cdot P_{opt}}{hf}\right)^2$$

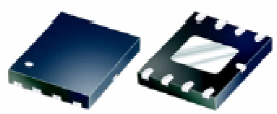
Examples:



ZX60-M

ZX60-M Amplifiers
50Ω, 0,9 to 5,9 GHz

Dual Matched MMIC Amplifiers
MERA-7456, 50Ω,
High dynamic range (DC to 1GHz)



CASE STYLE: DL1020
PRICE: $ 4.70 ea. QTY (25)

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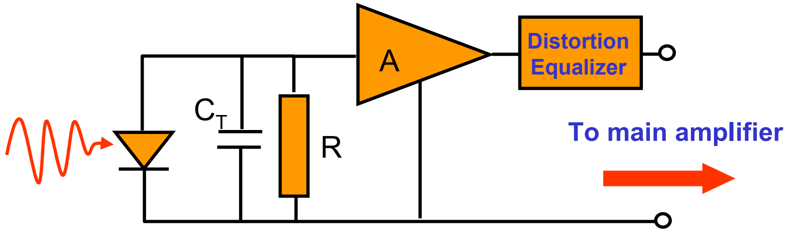
HIGH IMPEDANCE AMPLIFIERS

↑ Impedance → ↑ Signal to Thermal Noise Ratio → ↓ Cut-off frequency f_{3dB}

- High impedance reduces the effect of thermal noise, improving sensitivity

- In order to limit distortion, f_{3dB} must be set to a fraction δ of the signal bandwidth B; the maximum value of R is thus given by:



$$f_{3dB} \geq \delta B \Leftrightarrow \frac{1}{2\pi \cdot R \cdot C_T} \geq \delta B \Rightarrow R \leq \frac{1}{2\pi \cdot \delta \cdot B \cdot C_T}$$

- And the corresponding SNR_J is:

$$SNR_J = \frac{M^2 \cdot q^2}{4kFT_0 B \cdot 2\pi \cdot \delta \cdot B \cdot C_T}\left(\frac{\eta \cdot P_{opt}}{hf}\right)^2 = \frac{M^2 \cdot q^2}{4kT_0 B \cdot 2\pi \cdot B \cdot Q}\left(\frac{\eta \cdot P_{opt}}{hf}\right)^2$$

where $Q = \delta \cdot C_T \cdot F$ takes into account the effect of both PIN and amplifier on SNR_J

- When $\delta < 1$ distortion is introduced; it can be removed with a post-front-end equalizer

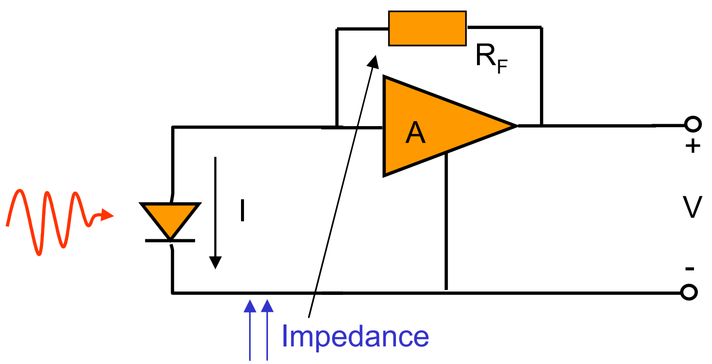
TRANS-IMPEDANCE AMPLIFIERS

- In a trans-impedance front-end a feedback resistor R_F is used. The value of this resistor is kept relatively large and thus any current noise contribution is minimized.

- The output voltage is:

$$V \approx -R_F \cdot I \cdot M$$

where:
I is the photodiode current
M is the APD gain (when used)



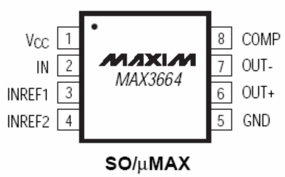
The trade-off between noise reduction and bandwidth is achieved thanks to the dependence of the cut-off frequency on amplifier gain A

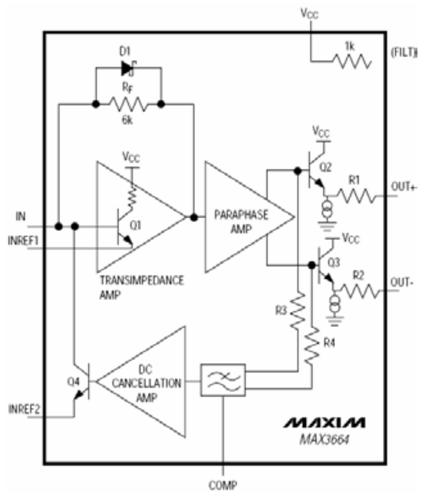
$$f_{3dB} = \frac{1+A}{2\pi \cdot R_F \cdot C_T}$$

TRANS-IMPEDANCE AMPLIFIERS

MAXIM MAX3664
622Mbps, Ultra-Low-Power, 3.3V Transimpedance Preamplifier

- **Single +3.3V Supply Operation**
- **55nARMS Input-Referred Noise**
- **6k½ Gain**
- **85mW Power**
- **300µA Peak Input Current**
- **200ps Max Pulse-Width Distortion**
- **Differential Output Drives 100½ Load**
- **590MHz Bandwidth**





PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Small-Signal Bandwidth	BW_{-3dB}	Relative to gain at 10MHz		590		MHz
Low-Frequency Cutoff					150	kHz
Pulse-Width Distortion (Note 5)	PWD	2µA to 100µA peak input current, 50% duty cycle, 1–0 pattern		6	100	ps
		100µA to 300µA peak input current, 50% duty cycle, 1–0 pattern		80	200	
RMS Noise Referred to Input	i_n	C_{IN} = 0.3pF (Note 6), I_{IN} = 0		55		nA
		C_{IN} = 1.1pF (Note 6), I_{IN} = 0		73	86	

FURTHER READING

comprehensive tutorials on optical receivers can be found in several url directions, e.g.

http://www.commspecial.com/fiberguide-pt3.htm#opticalreceivers

Other sources about optical receivers can be found at some manufacturers pages:

http://www.chipsat.com/products/
http://www.thorlabs.com