HAMAMATSU

PHOTON IS OUR BUSINESS

Introduction to Photodetectors (Part I)

Slawomir Piatek

New Jersey Institute of Technology &
Hamamatsu Photonics, Bridgewater, NJ (USA)

05.26. 2020

Index (Part I)

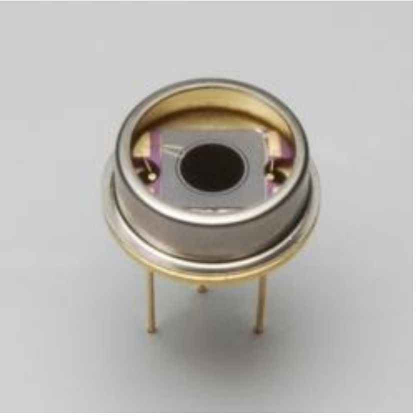
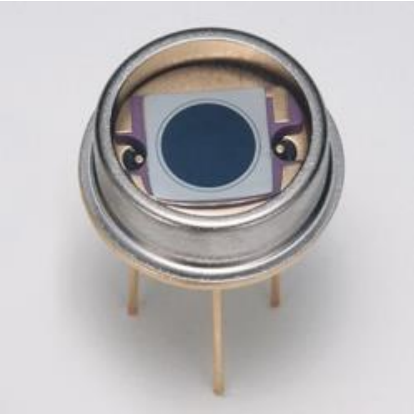
- Photodetector characteristics
- Front-end electronics
- Noise

Index (Part II)

- Structure and operation of point photodetectors
- Applications of photodetectors
- Selection of a photodetector

Photodetector Characteristics

Point photodetectors


PMT PD APD SiPM

PMT – photomultiplier tube

PD – photodiode

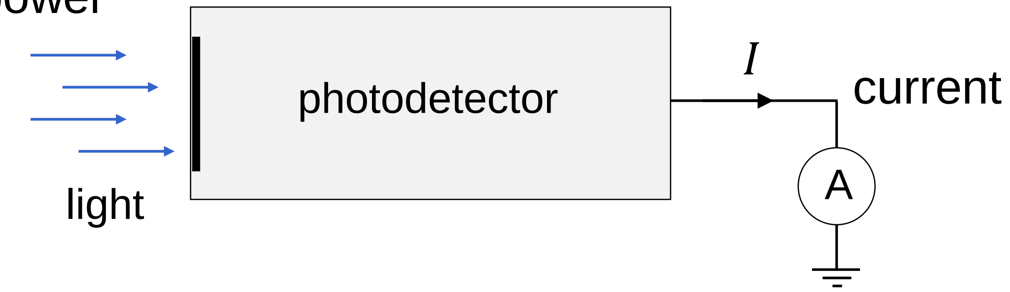
APD – avalanche photodiode

SiPM – silicon photomultiplier

Spectral sensitivity and quantum efficiency

σ – Spectral sensitivity; η – Quantum efficiency

P_0 – incident light power



$$I = \sigma P_0 \qquad \text{(monochromatic)}$$

$$\eta = \frac{hc\sigma}{\lambda e} = \frac{1240\sigma}{\lambda[nm]} \qquad \text{(monochromatic)}$$

Spectral sensitivity and quantum efficiency

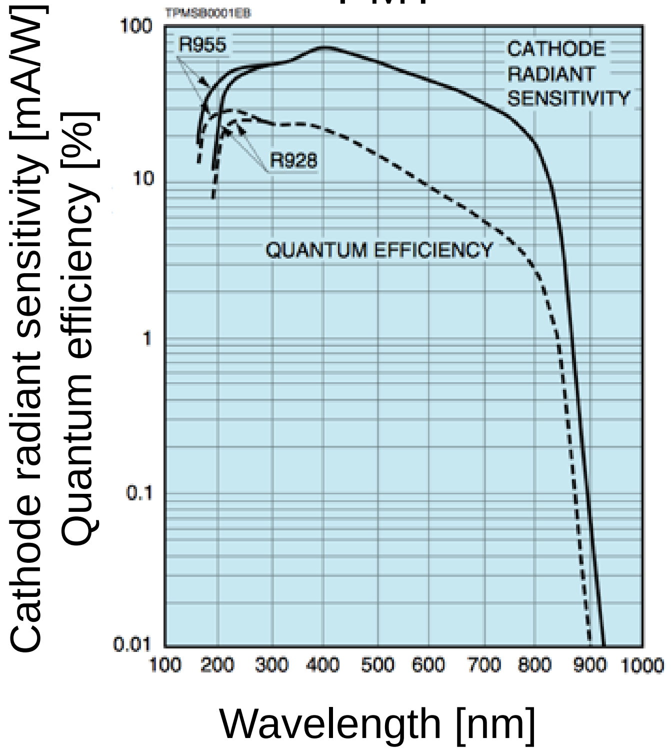
HAMAMATSU
PHOTON IS OUR BUSINESS

1. Spectral sensitivity is the most fundamental opto-electronic characteristic of a photodetector
2. Spectral sensitivity is, most importantly, a function of the input light wavelength
3. Spectral sensitivity can also be a function of temperature and bias voltage
4. Quantum efficiency is a probability that an incident photon is detected (that is, an output signal is produced)
5. Quantum efficiency and spectral sensitivity are related
6. Manufacturers of photodetectors provide spectral sensitivity and/or quantum efficiency curves

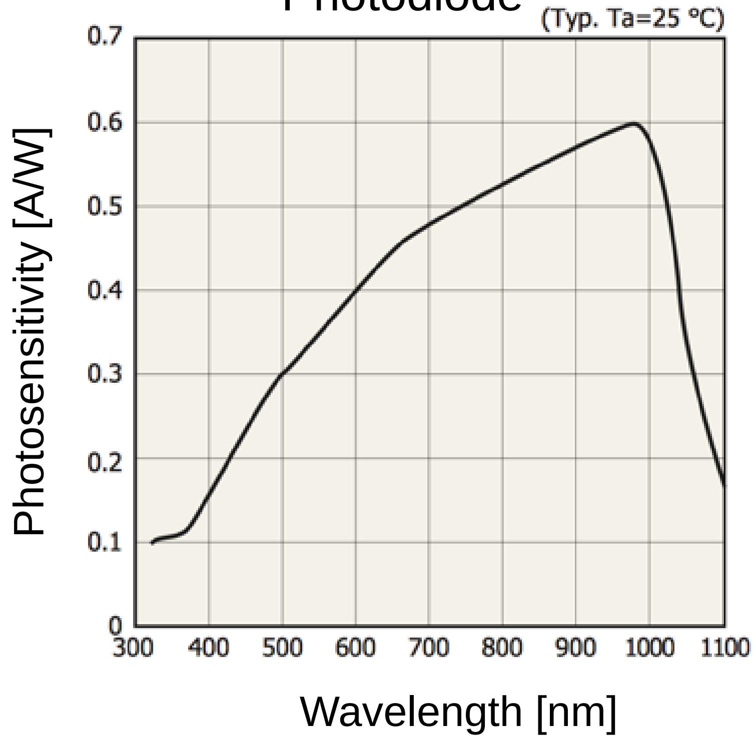
Spectral sensitivity and quantum efficiency

HAMAMATSU
PHOTON IS OUR BUSINESS

PMT

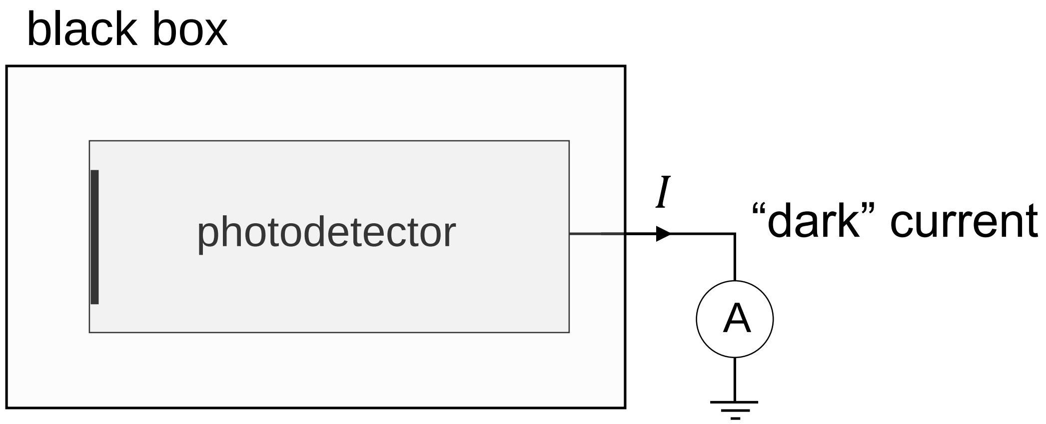


Photodiode



Examples of spectral sensitivity/quantum efficiency curves for a PMT and photodiode

Dark current

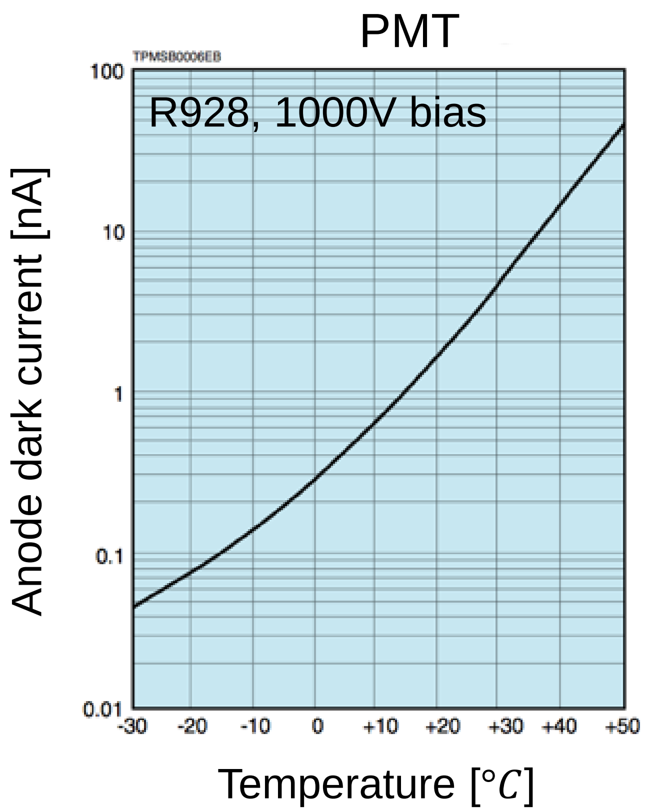


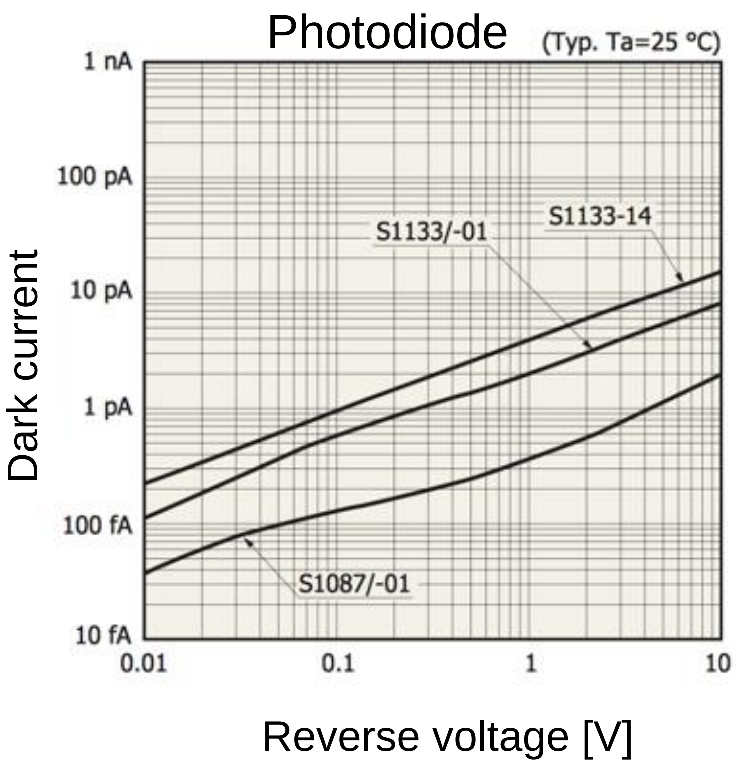
Even in absence of incident light, a photodetector outputs current known as "dark current"

Dark current

1. A photodetector outputs dark current regardless of the incident light
2. The magnitude of dark current depends on factors such as temperature, type of the photosensitive material, bias voltage, active area, gain, and more
3. In some cases, it is possible to operate a photodetector without dark current; however, there are tradeoffs.
4. Dark current causes an offset in the output signal; the offset can be subtracted off.
5. Dark current contributes shot noise to the output signal; the shot noise cannot be subtracted off.
6. Manufacturers of photodetectors provide information on dark current, often as a plot versus temperature or bias voltage (or some other relevant parameter).

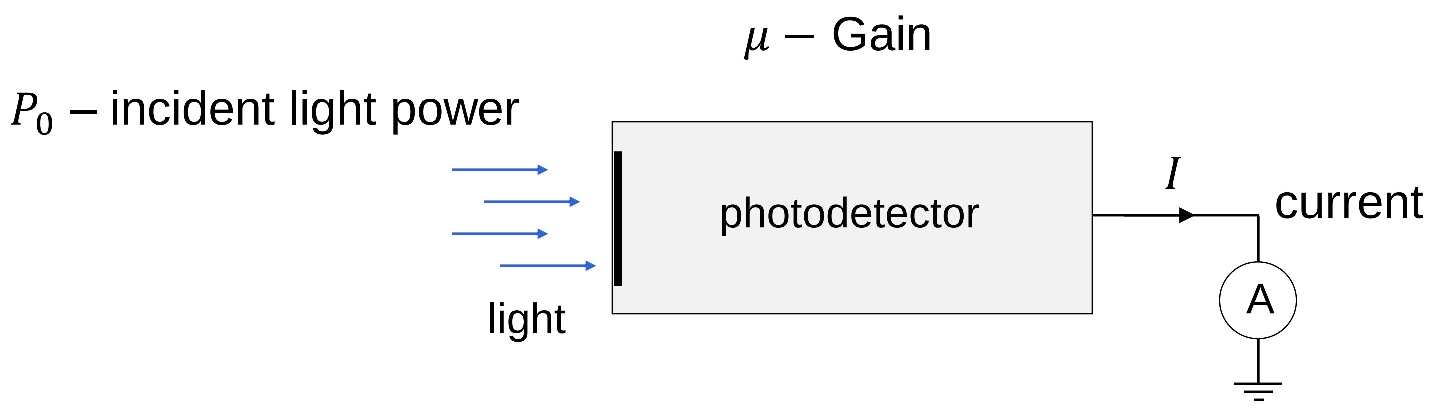
Dark current





Examples of plots showing dark current as a function of temperature (left) and as a function of reverse voltage (right)

Gain



$$I = \mu\sigma P_0$$

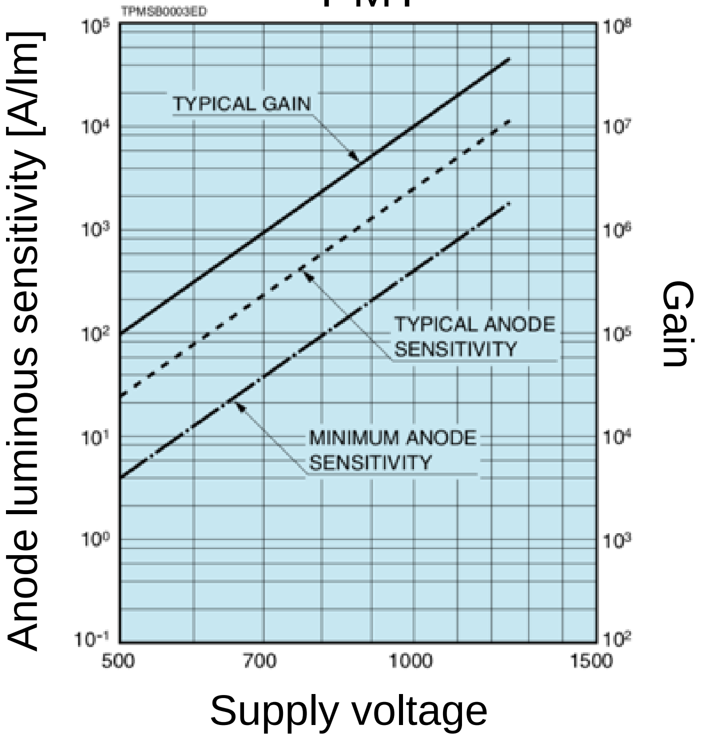
Intrinsic gain of a photodetector increases the output photo-current by a factor μ.

Gain

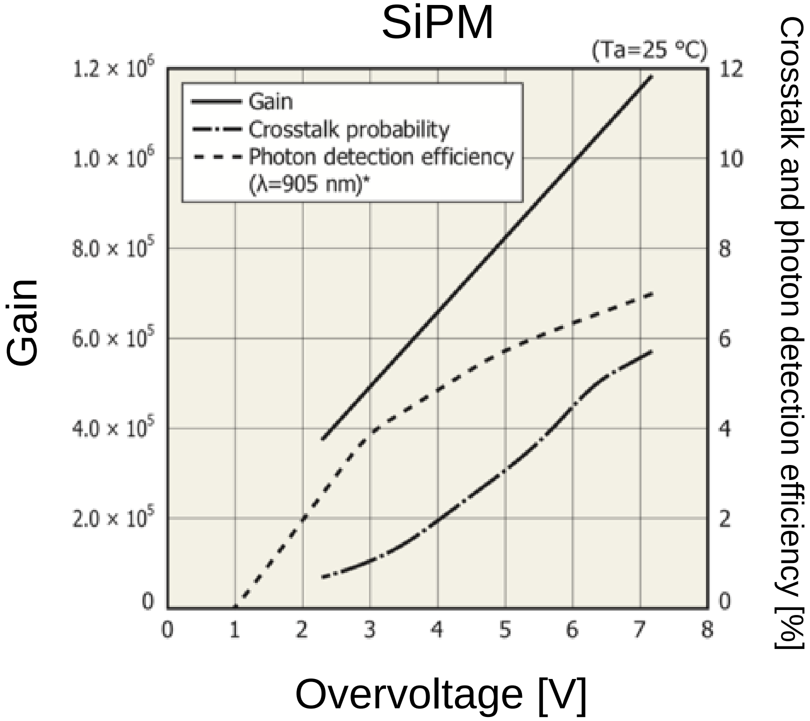
1. Photomultiplier tube (PMT), silicon photomultiplier (SiPM), and avalanche photodiode (APD) are photodetectors with intrinsic gain
2. Intrinsic gain increases the output photocurrent (and some forms of dark current) by a factor μ
3. *Secondary electron emission* is the gain mechanism in a PMT
4. *Impact ionization* is the gain mechanism in SiPM and APD
5. Intrinsic gain can improve the detection signal-to-noise ratio (S/N)
6. Bias voltage is the most important parameter affecting gain.
7. Manufacturers provide information about the gain in the form of a plot of gain versus some other relevant parameter, such as bias voltage

Gain

PMT

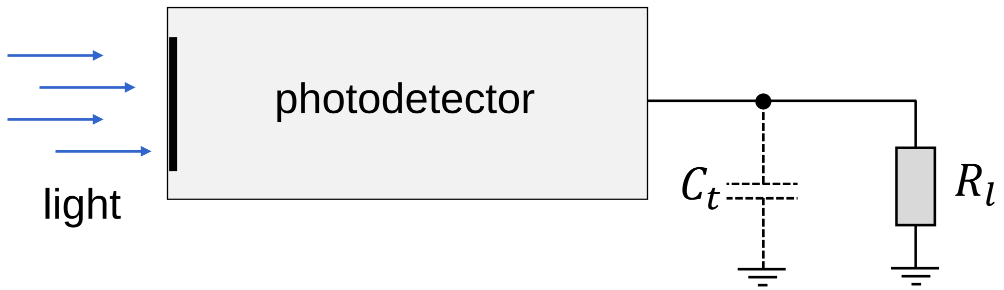


SiPM



Examples of gain curves for a PMT (left) and SiPM (right)

Terminal Capacitance



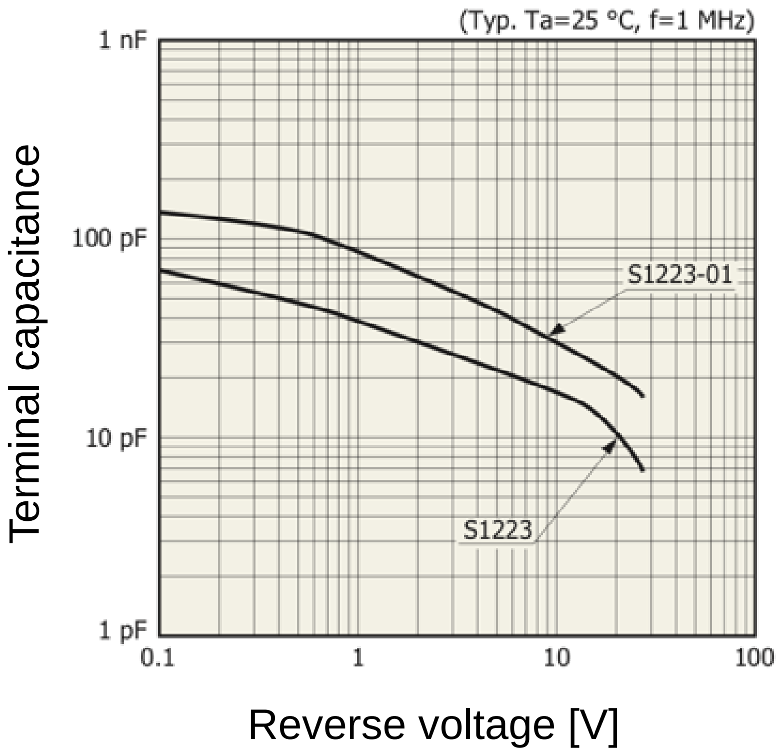
Terminal capacitance C_t is a capacitance between the output lead of the photodetector (commonly an anode) and the ground.

Terminal capacitance

HAMAMATSU
PHOTON IS OUR BUSINESS

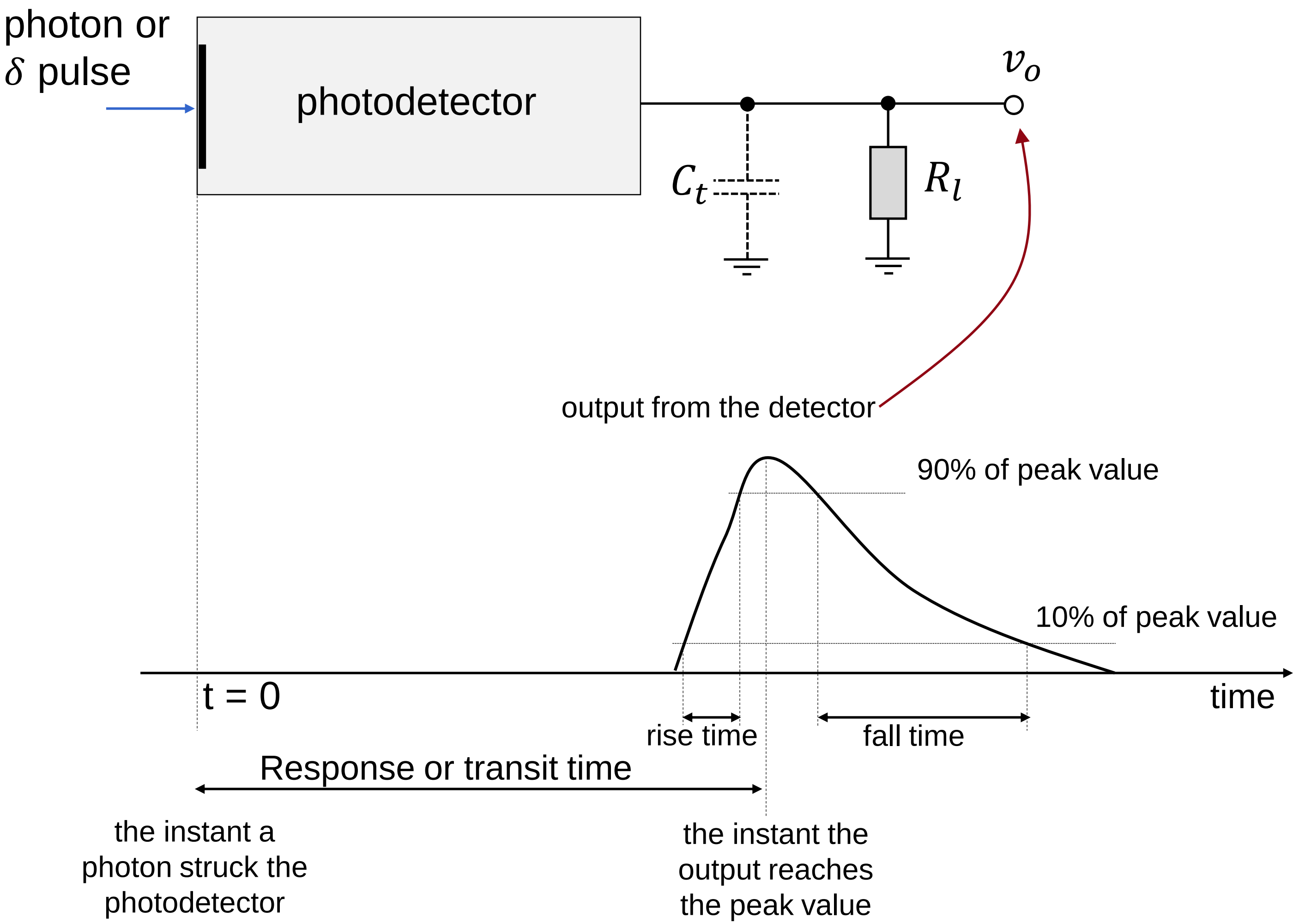
1. Terminal capacitance will affect the output current/voltage in an AC and pulse operation
2. Terminal capacitance will affect detection bandwidth
3. Terminal capacitance will affect time characteristics of a photodetector, such as rise and response times
4. Terminal capacitance will affect detection S/N by increasing amplifier noise
5. Terminal capacitance can depend on factors such as bias voltage, active area, and construction of the photodetector
6. If relevant, manufacturers provide information about terminal capacitance in the form of a plot of terminal capacitance versus the relevant parameter, such as bias voltage

Terminal Capacitance



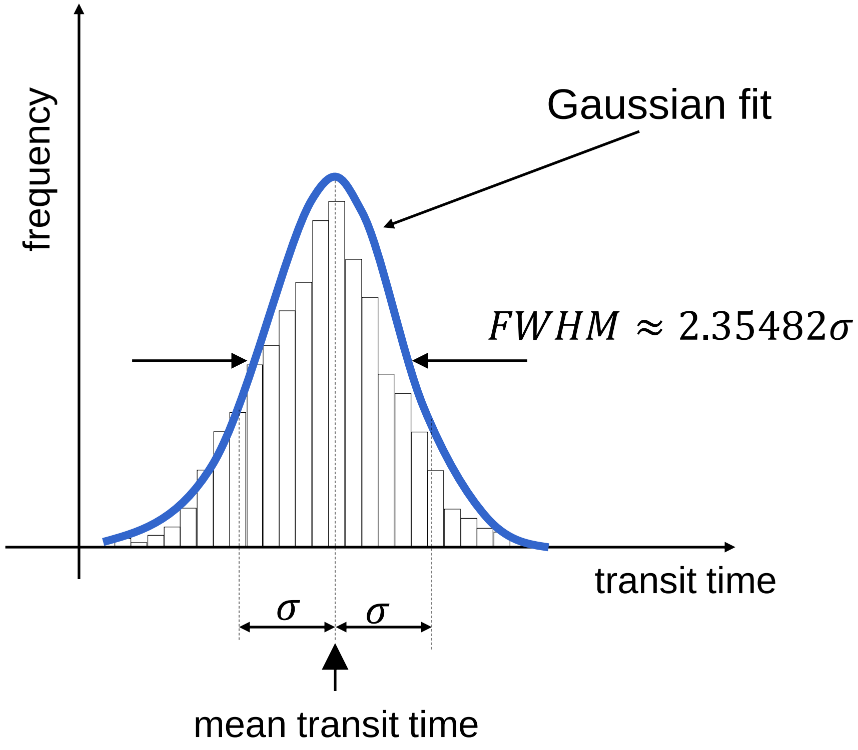
Example of a plot of terminal capacitance as a function of reverse voltage for the S1223 photodiode

Time characteristics



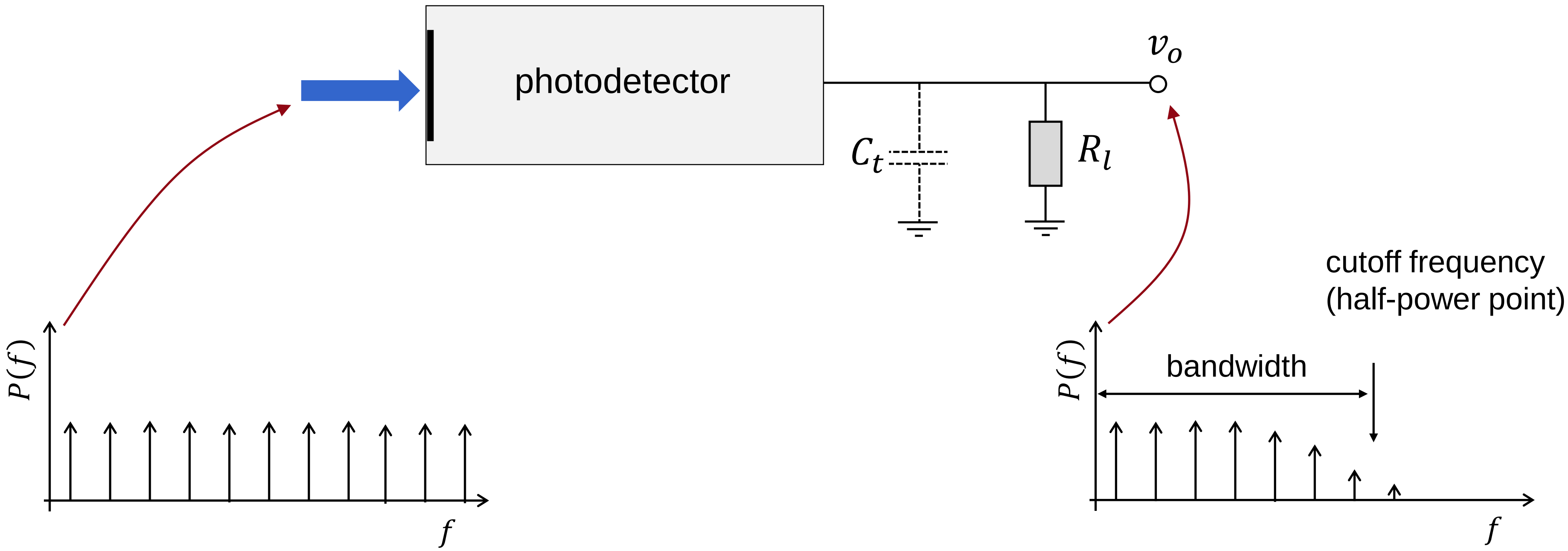
Time jitter

histogram of single-photon transit times



Time jitter is a crucial consideration in applications where short time intervals are measure (LiDAR, PET).

Bandwidth

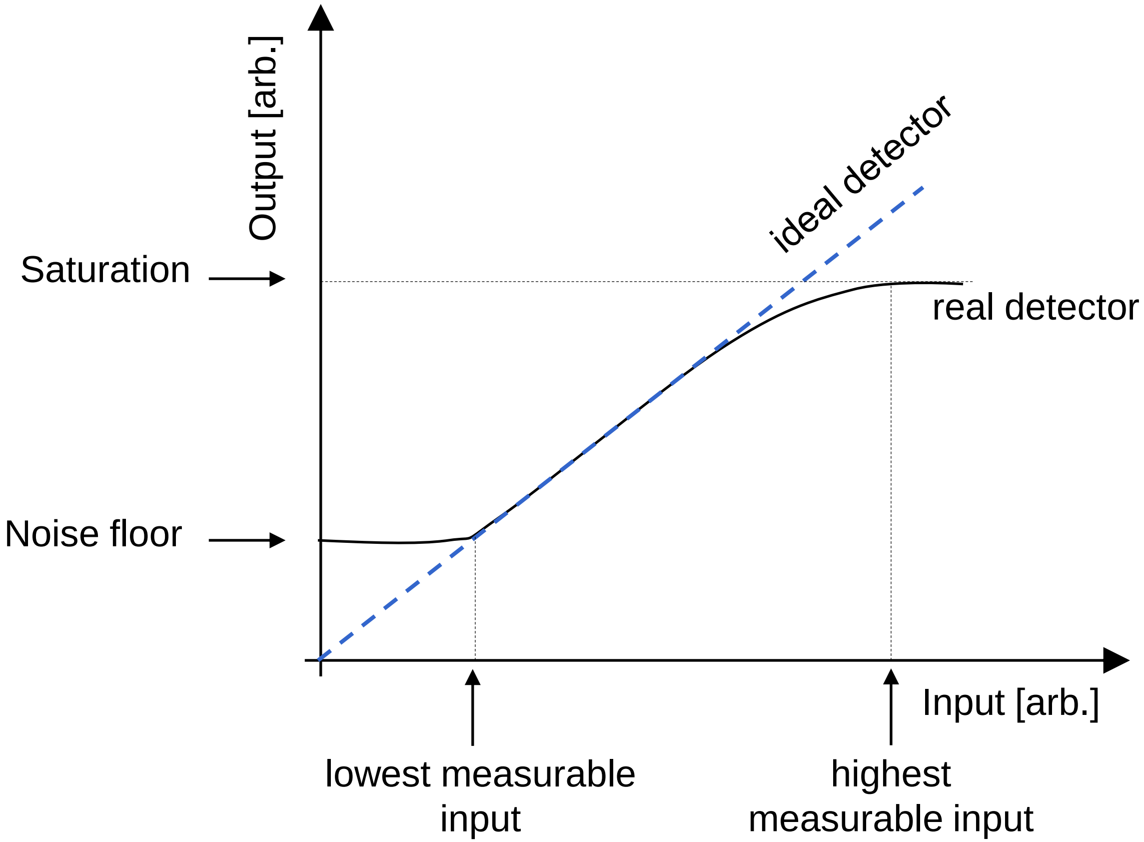


Frequency spectrum of the **input**.

Frequency spectrum of the **output.**

Both the photodetector and front-end electronics affect the detection bandwidth.

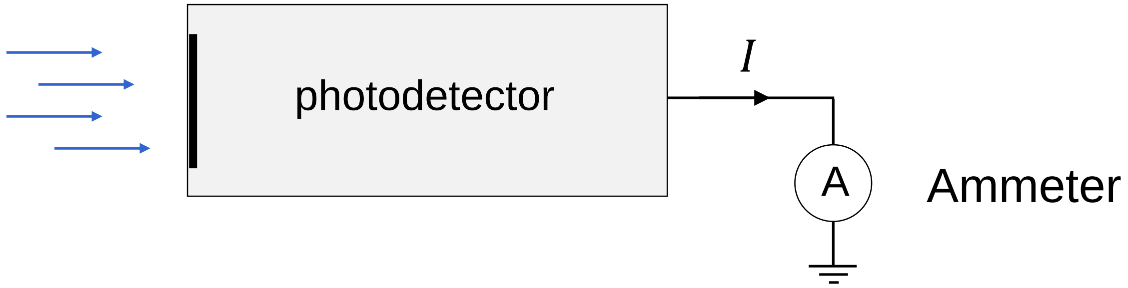
Dynamic Range



Dynamic range is a ratio of the highest and lowest measurable light levels.

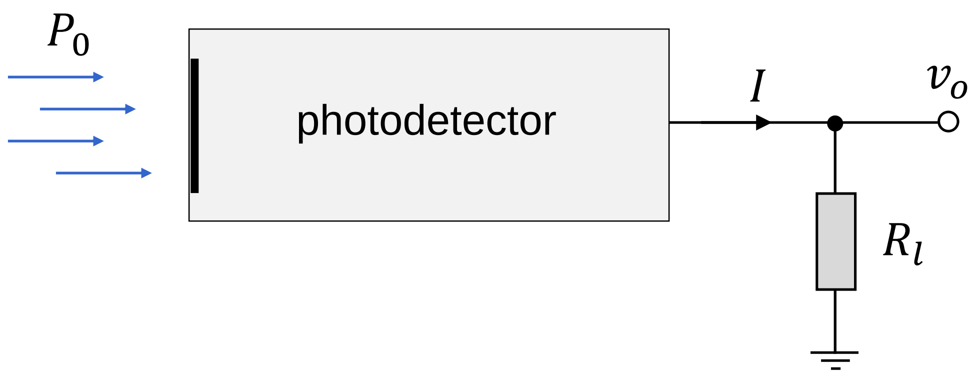
Front-end electronics

Ammeter



Most photodetectors are light-driven current sources. Ammeter is nearly ideal because it does not load the photodetector.

Resistive termination



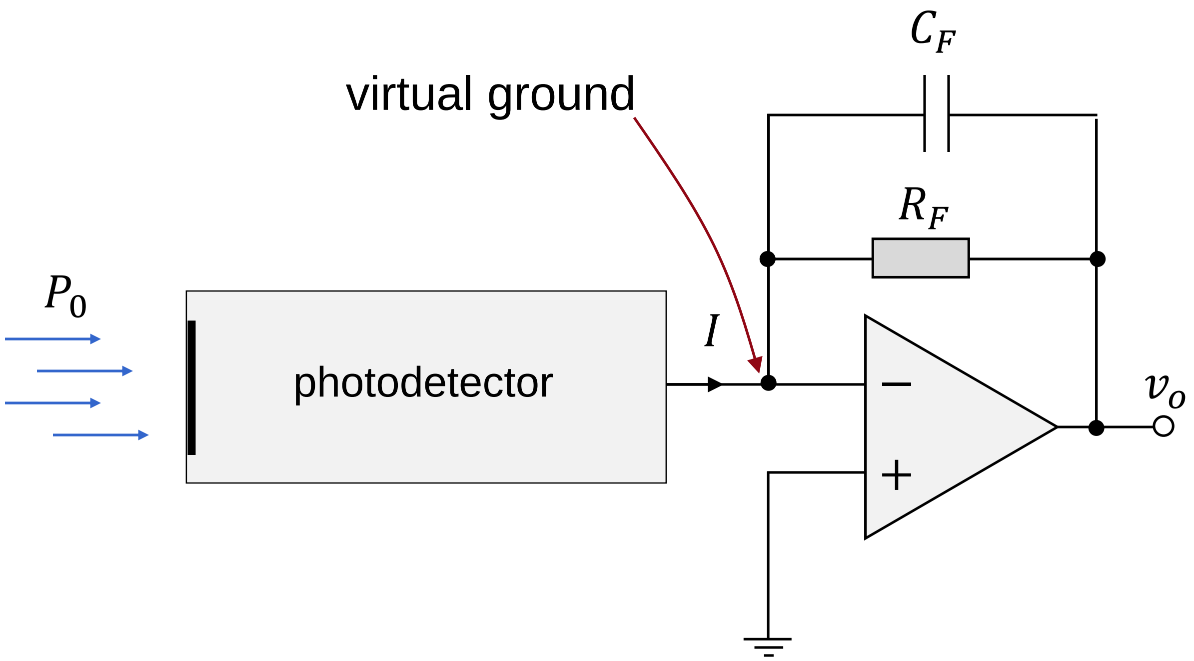
$$v_o = IR_l = \sigma\mu P_0 R_l \qquad \text{(DC)}$$

$$v_o = IZ \qquad \text{(AC)}$$

Z – impedence

1. Output polarity of v_o depends on the direction of the current, I.
2. Increasing R_l increases v_o, but also progressively loads the photodetector, leading to nonlinearity and saturation.
3. The value of R_l affects detection bandwidth: larger the R_l, smaller the bandwidth.

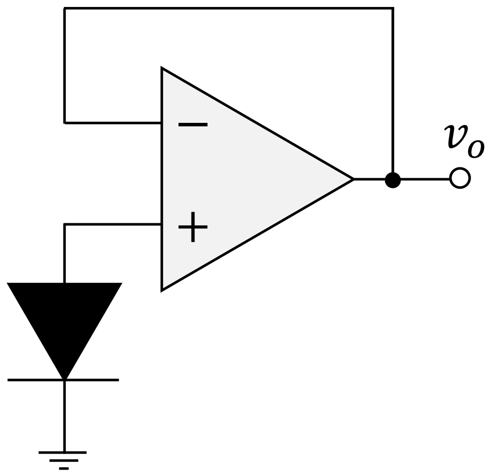
Transimpedance amplifier



$$v_o = -IR_F$$

1. Output polarity of v_o can be controlled by inverting and noninverting inputs.
2. Increasing R_F increases v_o but also affects noise and bandwidth of the amplifier.
3. Superior linearity compared to resistive termination.
4. The maximum v_o is constrained by the bias voltage of the amplifier, leading to amplifier saturation.
5. The feedback capacitor C_F improves stability and noise of the amplifier.

High input impedance amplifier

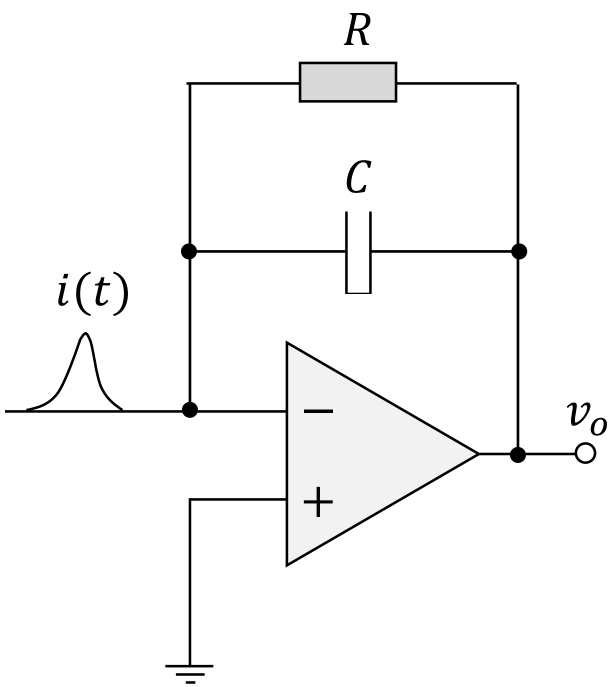


Photodiode operating in the *open-circuit mode*

$$v_o = v_{oc} = \frac{kT}{q}\ln\left(\frac{I_{ph}}{I_0}+1\right)$$

1. One mode of operating a photodiode is called *open circuit operation*.
2. It requires a high input impedance amplifier.
3. Other photodetectors, such as PMTs or SiPMs are not operated in the open circuit mode.

Charge integrator

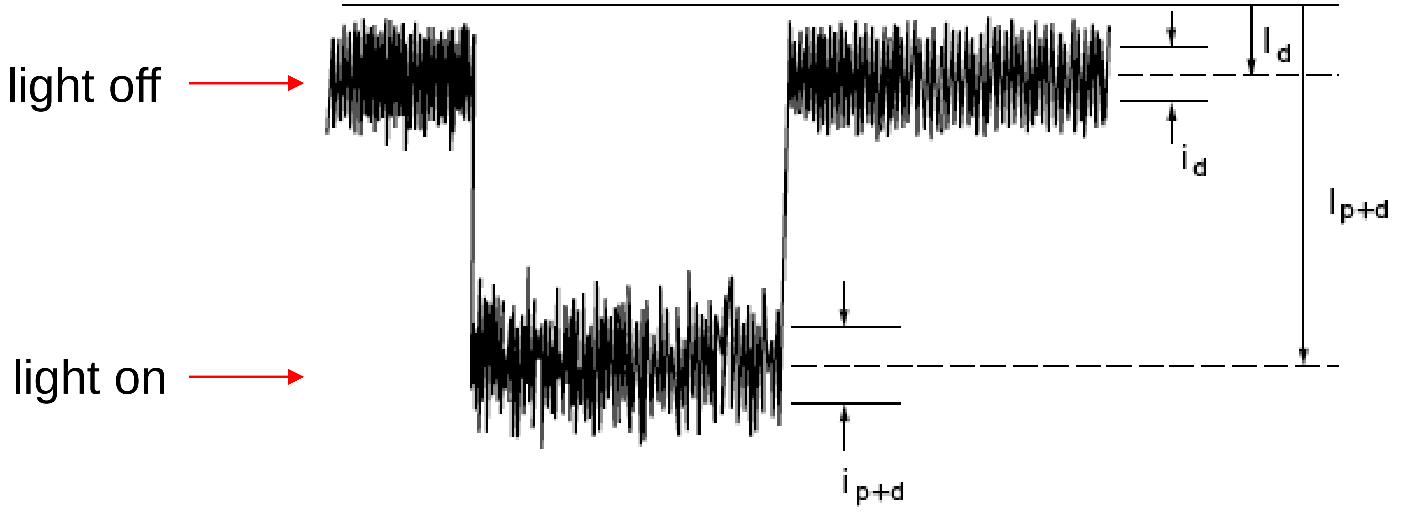


$$v_o = -\frac{1}{C}\int i(t)\,dt + Const.$$

1. Commonly used in scintillation-based spectroscopy
2. The resistor R allows the capacitor to discharge
3. The choice of C and R is critical for the operation

Noise

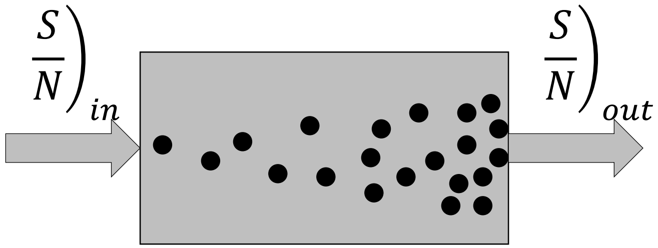
Signal and Noise



$$I_P = I_{P+d} - I_d$$ (dark current subtraction)

$$I_P = P_0 \sigma \mu$$ (signal)

Multiplication noise

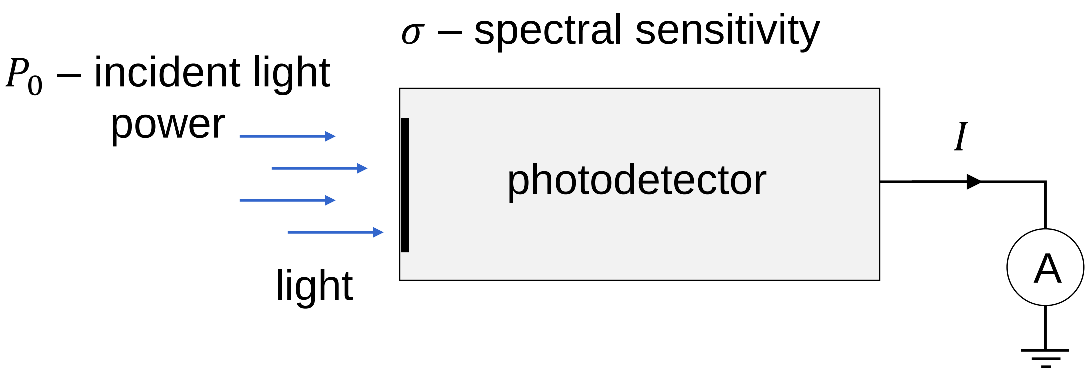


Gain section of a photodetector

$$F = \frac{\left(S/N\right)_{in}}{\left(S/N\right)_{out}}$$ (Excess noise factor)

$F = 1$ for a photodetector without gain and $F > 1$ for a photodetector with gain.

Photon shot noise

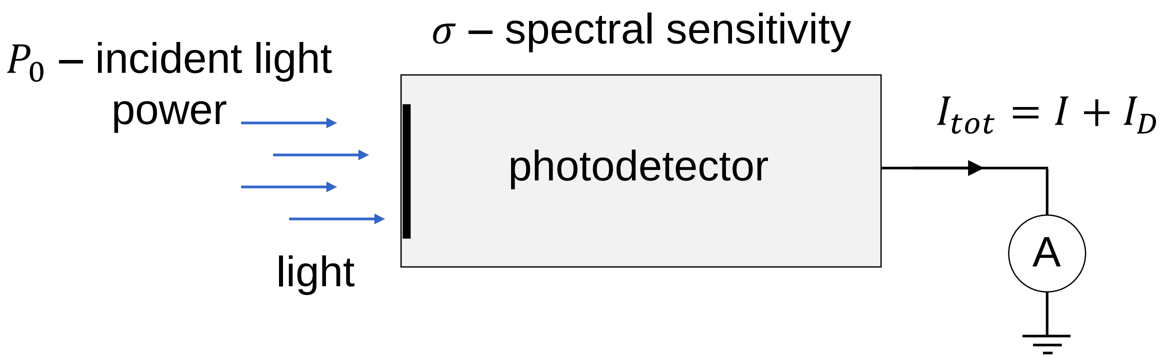


$$I = P_0 \sigma \mu$$ (Signal current, μ is the gain)

$$i_{rms}^2 = 2eIF\mu B = 2eP_0\sigma F\mu^2 B$$ (variance, a measure of noise)

$$i_{rms} = \sqrt{i_{rms}^2} = \sqrt{2eP_0\sigma F\mu^2 B}$$ (Noise)

Dark current shot noise



Both I_{tot} and I_D are measured

$I_{tot} = I + I_D$ $\qquad$ $I = I_{tot} - I_D$ (dark current subtraction)

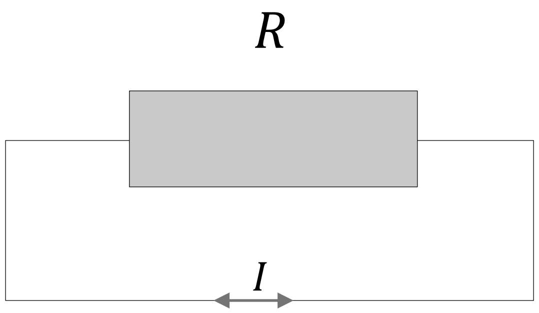
$$i_{rms,s}^2 = 2eIF\mu B = 2eP_0\sigma F\mu^2 B$$

(photon shot noise)

$$i_{rms,dc}^2 = 2eI_D F\mu B$$

(dark current shot noise)

Johnson thermal noise



$$i^2 = \frac{4kTB}{R}$$ (Johnson noise variance)

Signal-to-noise ratio

$$\frac{S}{N} = \frac{P \cdot \sigma \cdot \mu}{\sqrt{2eB[(P + P_B)\sigma + I_D]F\mu^2 + \frac{4kTB}{R}}}$$

Front-end electronics noise

P – Instantaneous optical power

σ – Detector’s sensitivity

μ – Detector’s intrinsic gain

I_D – Detector’s dark current (without gain)

F – Detector’s excess noise factor

B – Detection bandwidth

P_B – Background light optical power

e – elementary charge; k – Boltzmann constant; T – temperature

Signal-to-noise ratio

- Signal-to-noise ratio must be greater than 1 for a detection to contain useful information.
- Optimizing signal-to-noise ratio is the main objective of developing a detection system
- The choice of the photodetector is the major part of the above optimization.

Thank you

Thank you for listening

Contact information:

piatek@njit.edu

Join Us for 10 Weeks of FREE Photonics Webinars (17 Topics)

HAMAMATSU
PHOTON IS OUR BUSINESS

Week #	Weekly Topics	# of Talks	Talk #1 Date	Talk #2 Date
1	Introduction to Photodetectors	2	26-May-20	28-May-20
2	Emerging Applications - LiDAR & Flow Cytometry	2	2-Jun-20	4-Jun-20
3	Understanding Spectrometer	2	9-Jun-20	11-Jun-20
	1 Weeks Break			
4	Specialty Products – Introduction to Light Sources & X-Ray	2	23-Jun-20	25-Jun-20
5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
	1 Weeks Break			
6	Specialty Products – Laser Driven Light Sources	2	14-Jul-20	16-Jul-20
7	Image Sensor Circuits and Scientific Camera	2	21-Jul-20	23-Jul-20
8	Mid-Infrared (MIR) Technologies & Applications	2	28-Jul-20	30-Jul-20
	1 Weeks Break			
9	Photon Counting Detectors – SiPM and SPAD	1	11-Aug-20	
10	Using SNR Simulation to Select a Photodetector	1	18-Aug-20	

To register and attend other webinar series, please visit link below:
https://www.hamamatsu.com/us/en/news/event/2020/20200526220000.html

www.hamamatsu.com