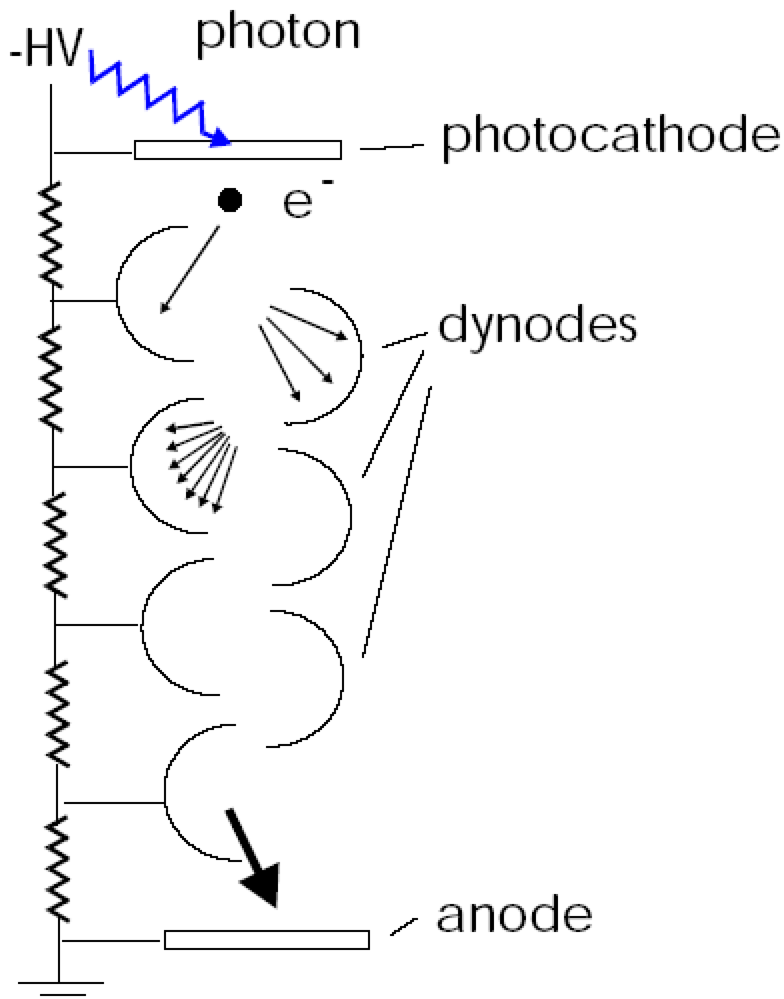
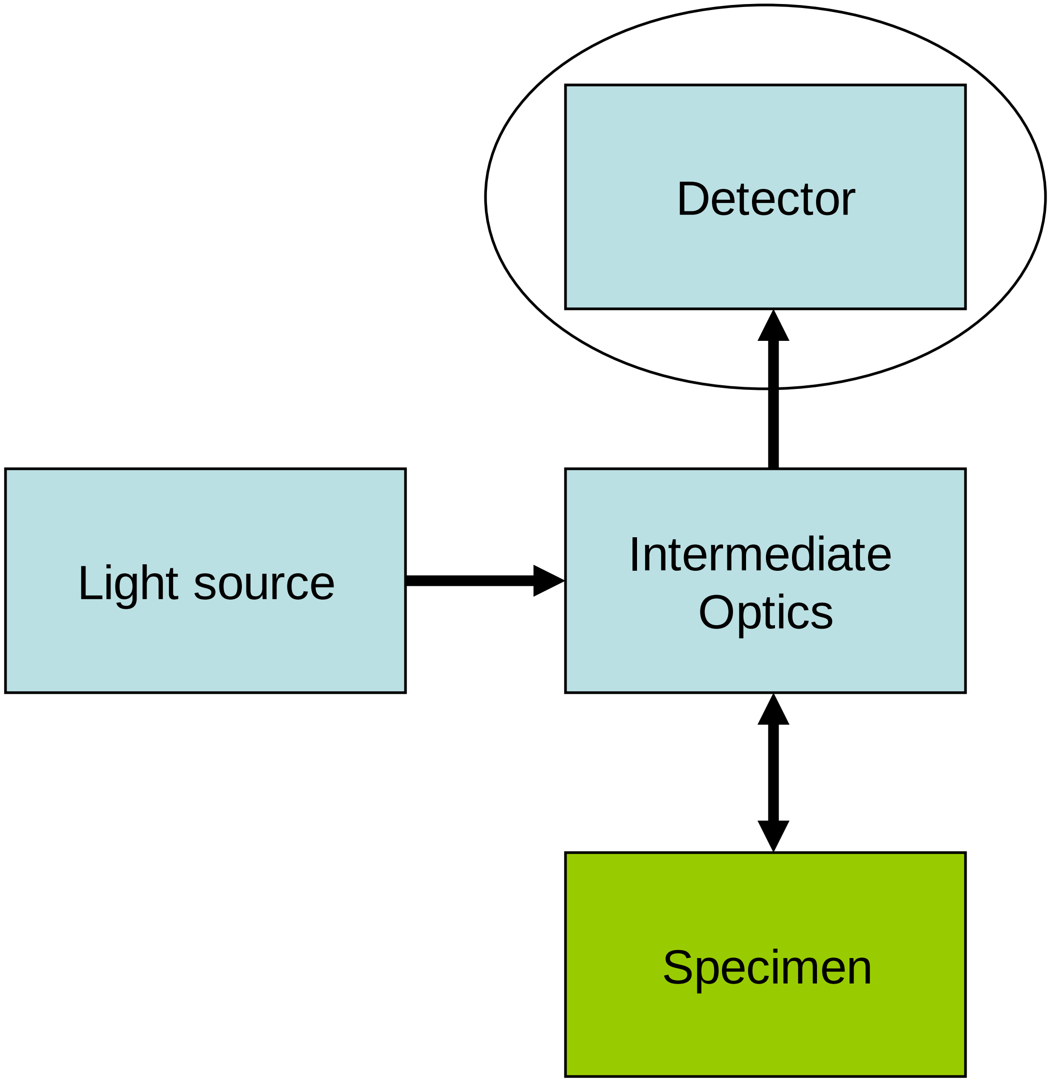
Optoelectronics II



What have we learned last lecture:

1. Photoelectric & photovoltic effects
2. Addition rule for noises
3. SNR & NEP
4. Poisson statistics ($\overline{n} = \sigma_n^2$)
5. Wiener-Khintchine Theorm
6. Shot noise ($\tilde{N}_s(f, \Delta f) = 2R\alpha q < I > \Delta f$)
7. Ideal detector

A typical biomedical optics experiment

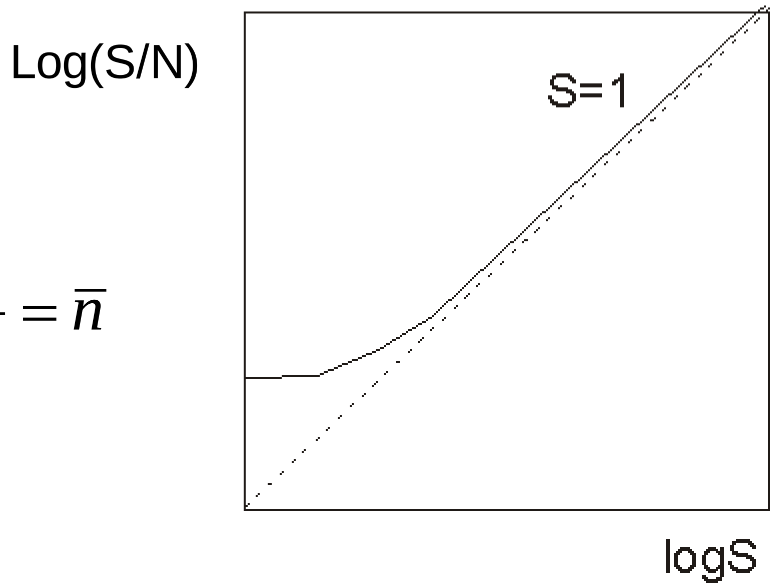


Photon Shot Noise

Originates from the Poisson distribution of signal photons as a function of time

$$\tilde{N}_s(f, \Delta f) = 2R\alpha q < I > \Delta f$$

$$SNR = \frac{< I >}{2\alpha q \Delta f} = \frac{\alpha q \bar{n} / \Delta t}{2\alpha q \Delta f} = \frac{2\alpha q \bar{n} \Delta f}{2\alpha q \Delta f} = \bar{n}$$



Dark Current Noise

The ideal photoelectric or photovoltic device does not produces current (electrons) in the absence of light. However, thermal effect results in some probability of spontaneous production of free electrons. This effect is measured by the dark current amplitude of the device: $< I_d >$

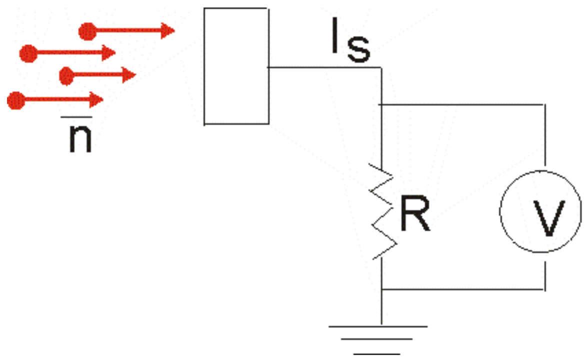
The average dark current is constant at constant temperature, but the electron generated fluctuate in time according to Poisson statistic similar to the fluctuation of the signal photons.

From our discussion of photon shot noise, we have immediately

$$\tilde{N}_d(f, \Delta f) = 2R\alpha q < I_d > \Delta f$$

Johnson Noise

Johnson noise originates from the temperature dependent fluctuation in the load resistance R of the transimpedance detection circuit.



Consider a simple dimensional analysis argument:

Thermal energy: kT

Thermal power: $kT\Delta f$

Power of Johnson noise current I_J : $I_J^2 R$

$$I_J = \sqrt{\frac{kT\Delta f}{R}}$$

$$\tilde{N}_J(f, \Delta f) = kT\Delta f$$

Characterizing Photodetectors

1. Quantum Efficiency: The probability of generating of a photoelectron from an incident photon

2. Internal Amplification: The amplification ratio for converting a photoelectron into an output current

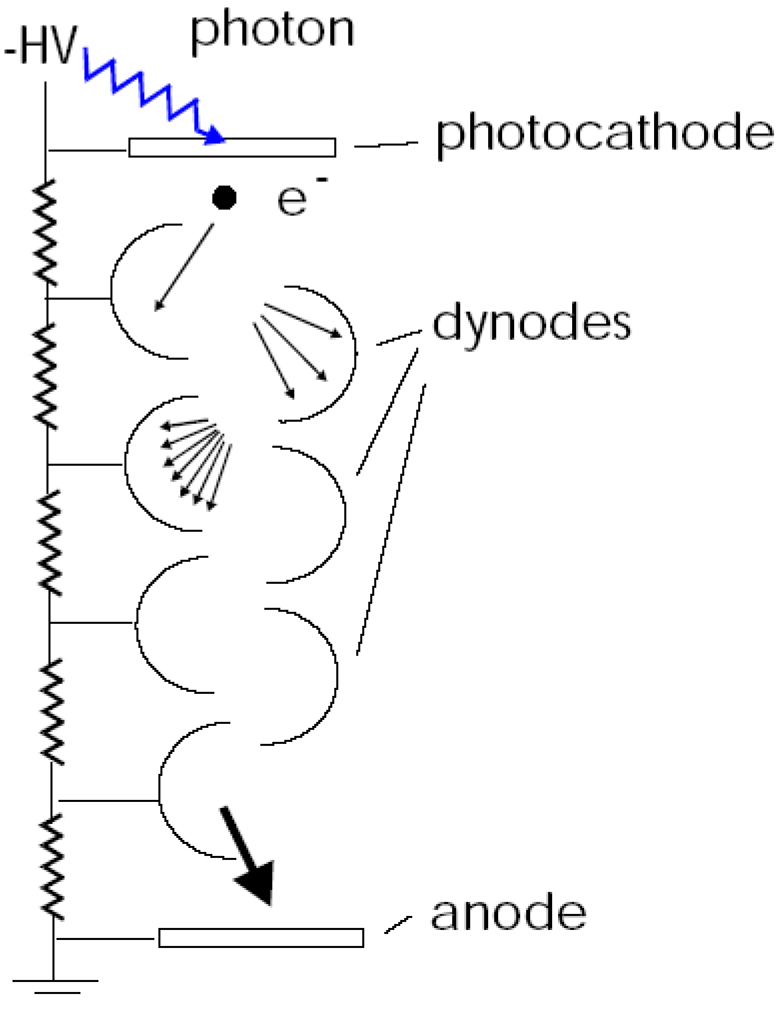
3. Dynamic Range: What is the largest and the lowest signal that can be measured linearly

4. Response Speed: The time difference and spread between an incoming photon and the output current burst

5. Geometric form factor: Size and shape of the active area and the detector

6. Noise: Discussed extensively already

Photomultiplier tube (PMT)



The PMT are characterized by two important parameters

Cathode sensitivity, *S* (A/W): 0.06 A/W

Gain, α: 10^7 to 10^8

We can relate current measured at the anode to the number of incident photons, *n*, arriving within a time interval Δt

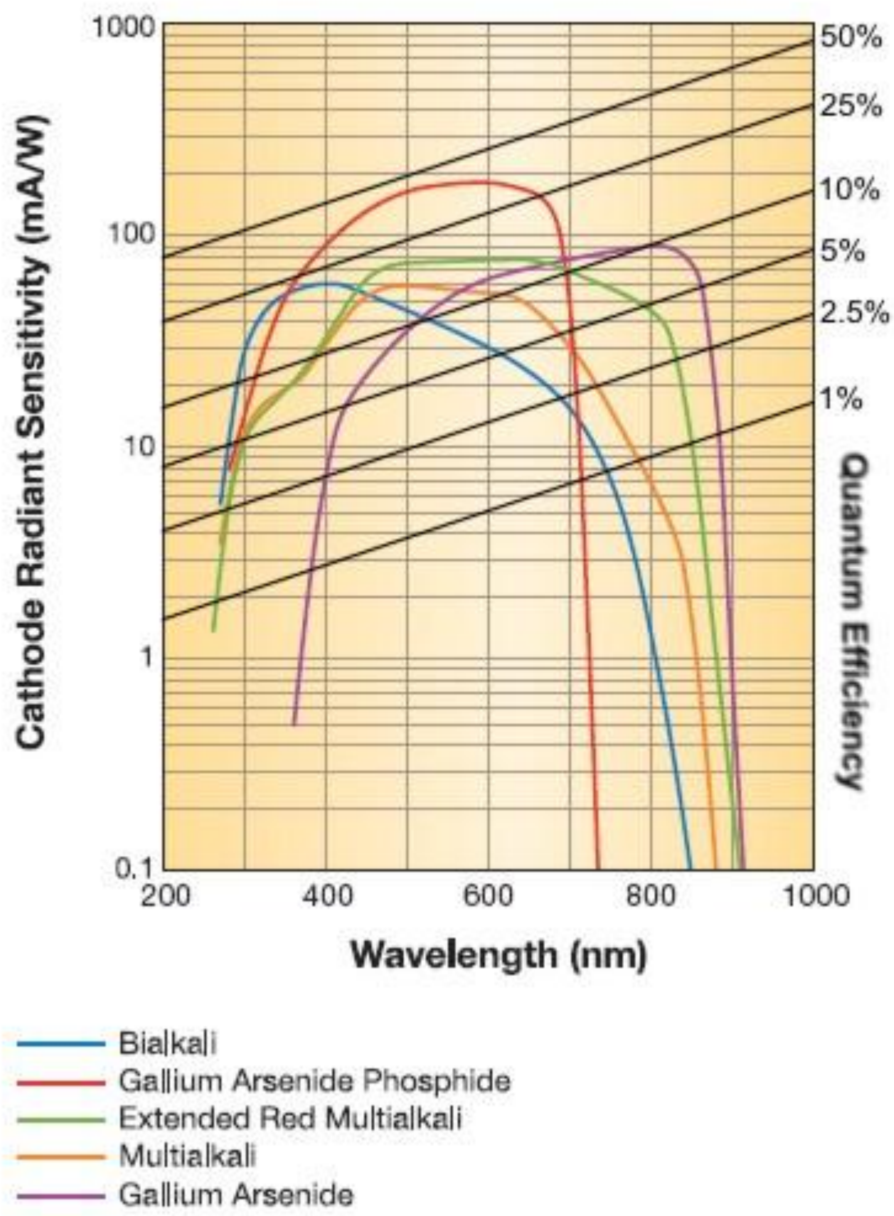
$$I = S \cdot \alpha \cdot E_\gamma \cdot n / \Delta t$$

E_γ is photon energy

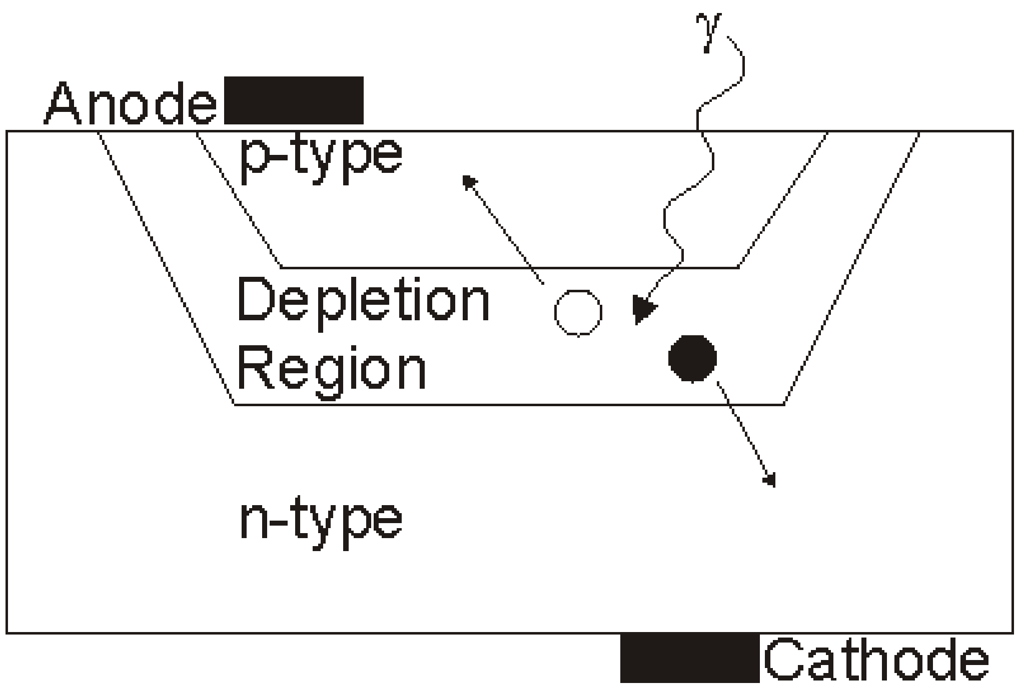
For green (500 nm wavelength) photons:

$$E_\gamma = \frac{hc}{\lambda} = \frac{6.6\times10^{-34}\,Js \cdot 3\times10^{8}\,m/s}{5\times10^{-7}\,m} = 4\times10^{-19}\,J$$

Sensitivity of PMT Cathode as a Function of Material

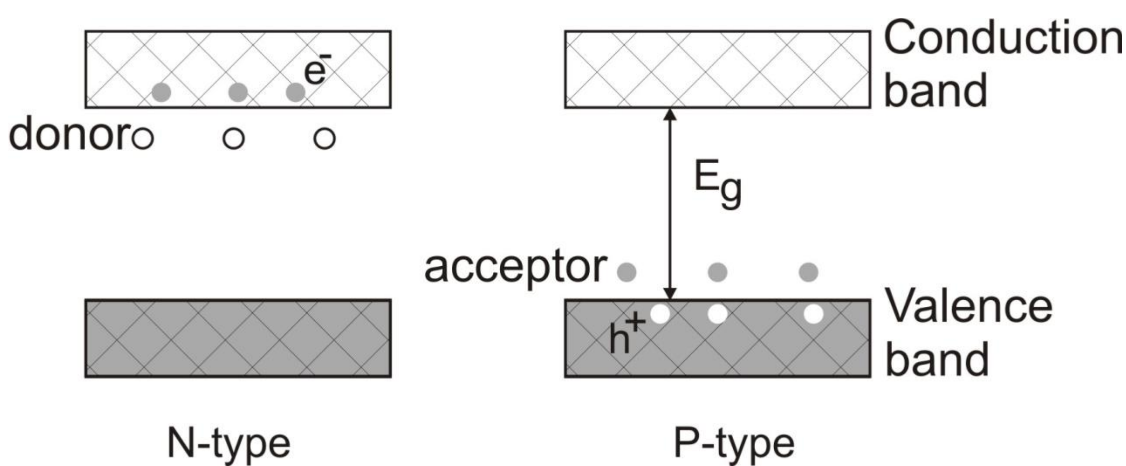


Photodiodes

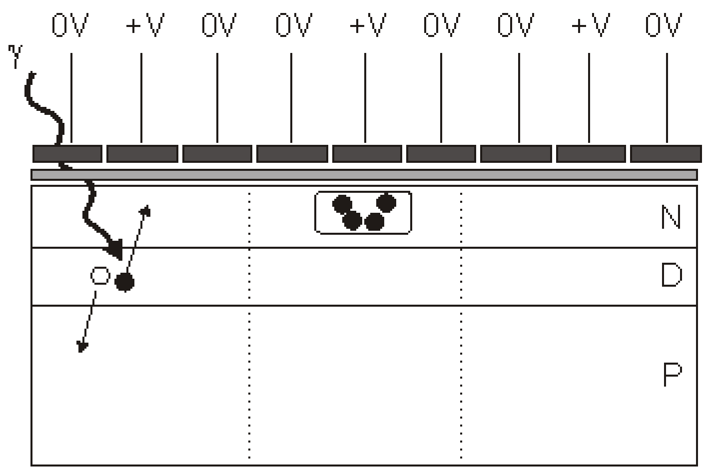


Biasing can increase device temporal Response speed

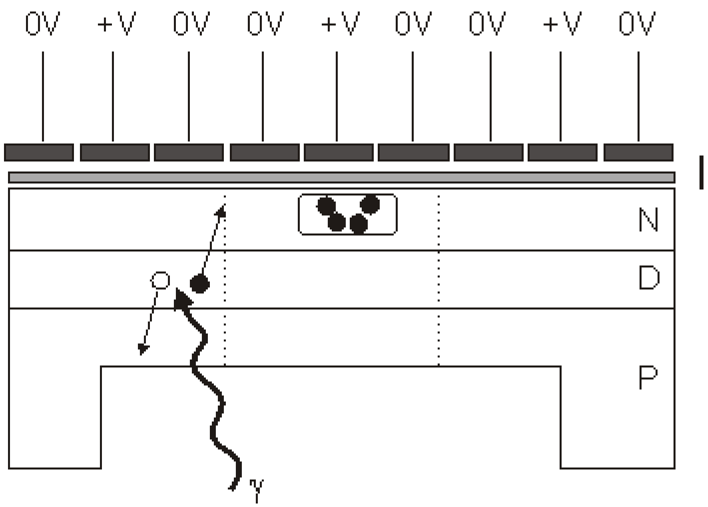
Recall:



Charge Coupled Device (CCD) Cameras

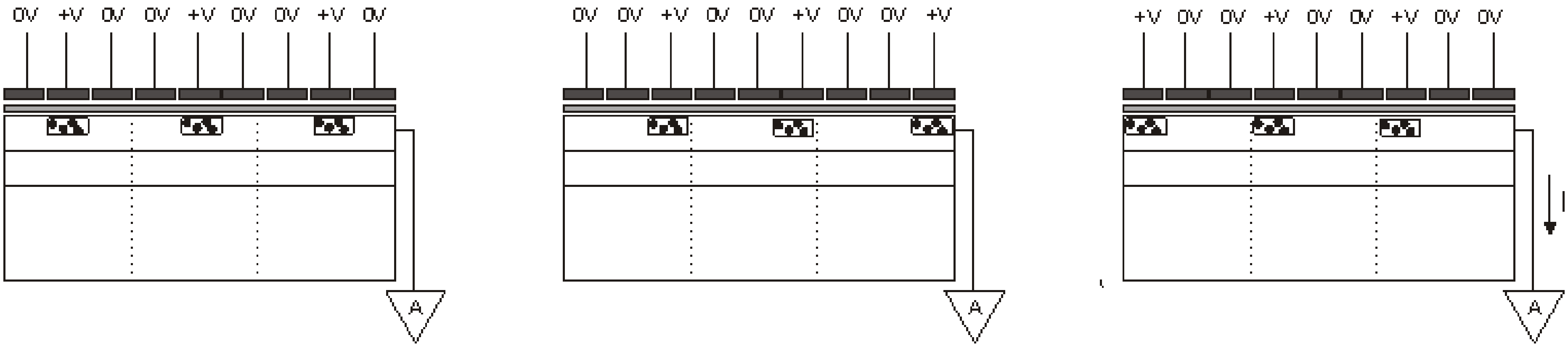


Front Illuminated



Back (thinned) Illuminated

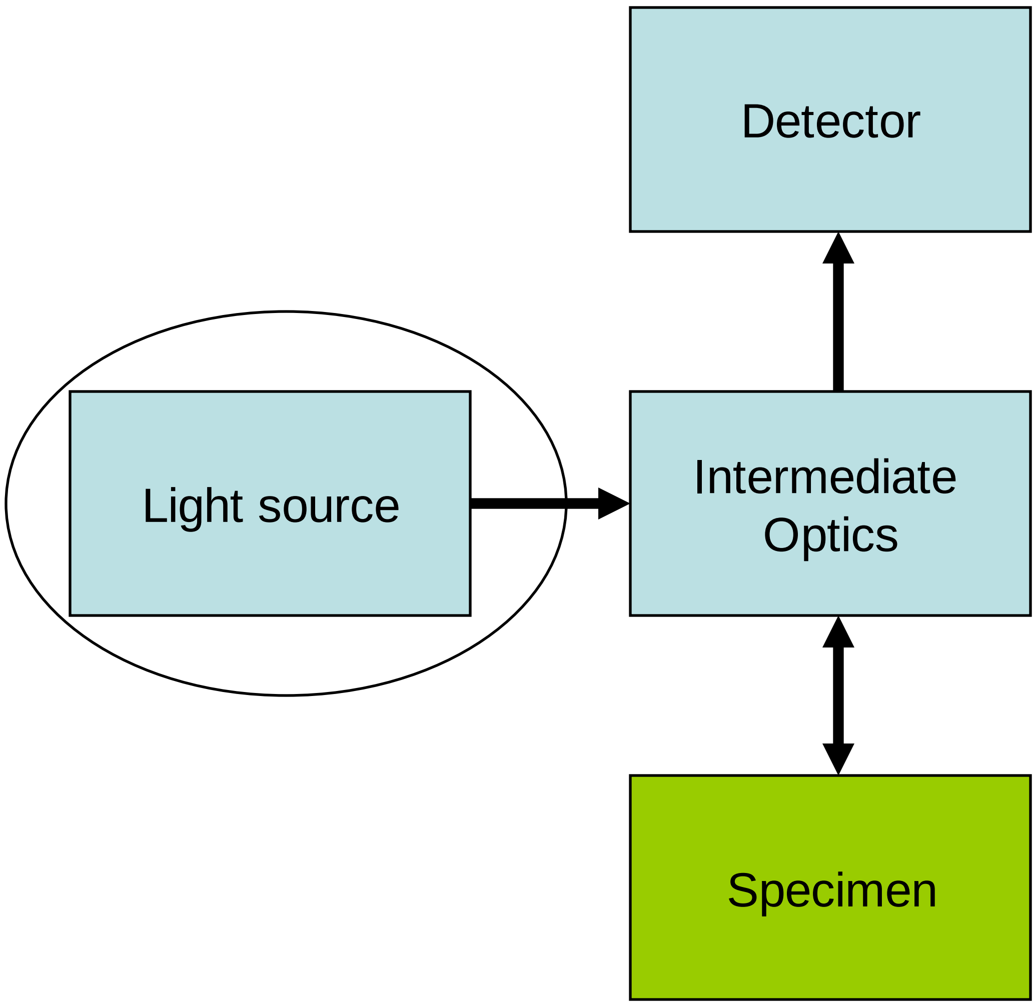
Readout Sequence Principle of CCD



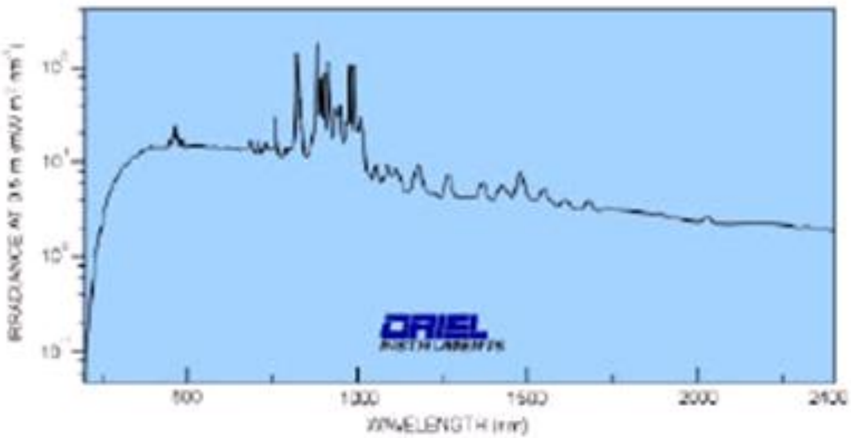
A Comparison of Detector Characteristics

	PMT	Photodiode	APD	CCD
QE	40%	80%	80%	80%
Spectral Range	UV-Green	Blue-NIR	Blue-NIR	Blue-NIR
Internal Gain	10^6-10^8	1	100-1000	1
Dark Noise	e^-/sec	1000 e^-/sec	e^-/sec	e^-/sec
Electronic (Read) Noise	NA	1000 e^-	NA	3-1000 e^-
Response Speed	+++	+++	+	-
Pixel Size	cm	mm	mm	μm

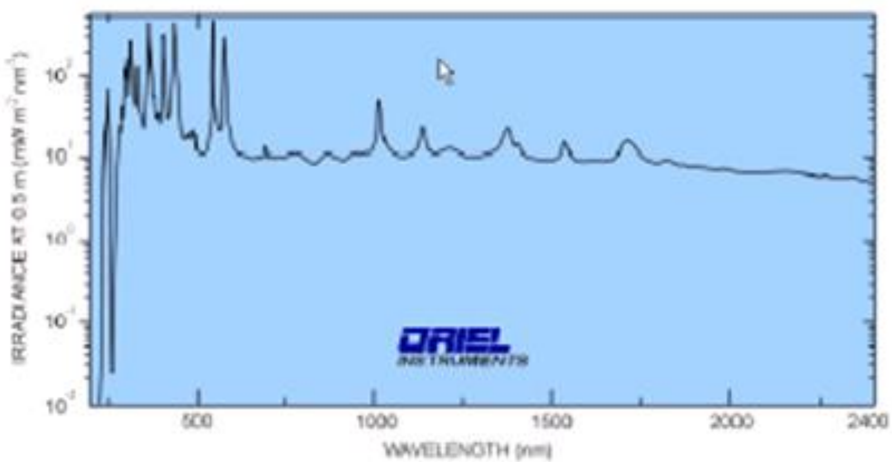
A typical biomedical optics experiment



Lamps – An Incoherent Light Source



Xenon arc lamp



Mercury arc lamp

Features of lamp source:

Broad spectral background – black body radiation

Sharp emission peaks – electronic transitions in gases

Uses of Lamp Source in Microscopy

Advantages: Low cost
Broadband or allow easy selection of spectral band
Ease of use

Disadvantages: Low spectral radiance (power within a given wavelength range)
High divergence (non-point source)
Lack of coherence

Xeon arc lamp: Smooth emission spectrum in the visible. The most common white light source in microscopy

Mercury arc lamp: Sharp emission lines in the near UV and blue green. Broadband light source for fluorescence microscopy

Semiconductor Light Sources

Light emitting photodiodes: LEDs

The works by exciting electrons across a semiconductor bandgap (more of that later in the detector section) and their subsequent decay

Advantage of LED light source

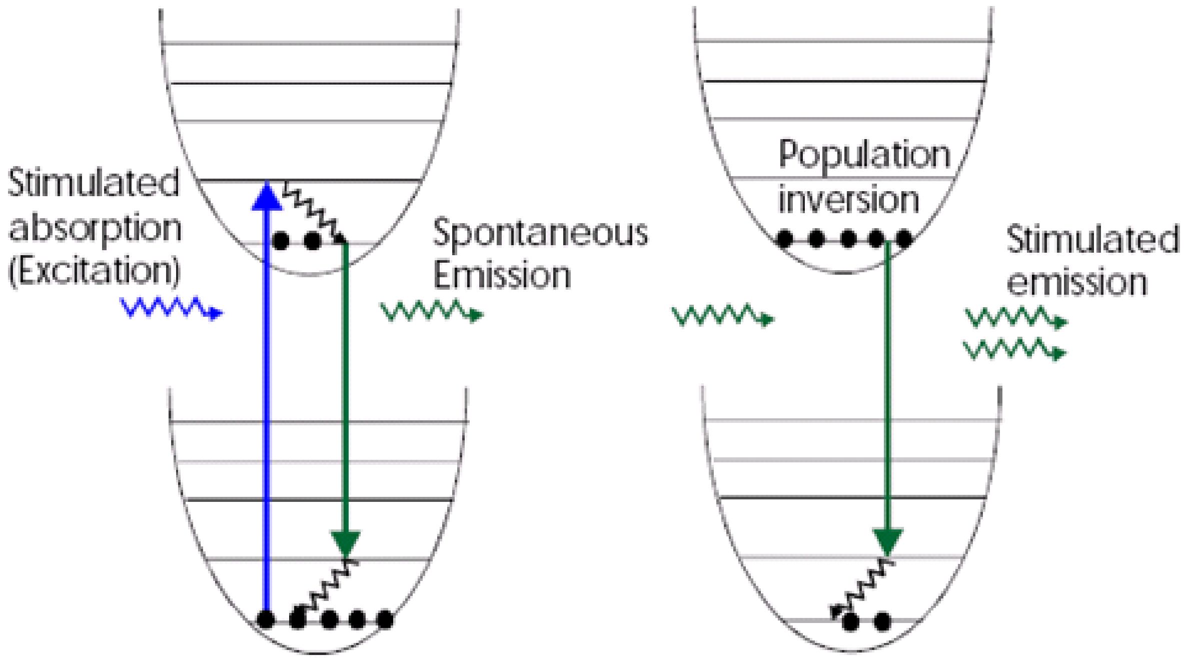
* Relative narrow emission band
* Low power consumption
* High brightness
* Long life
* Can be modulated rapidly

Disadvantages of LED light source is similar to other lamps

Lasers – A Coherent Light Source

Laser = Light amplification of stimulated emission of radiation

Invented in 1950s by Charles Townes, Alexandr Prokhorov, & Nikolai Basov



Stimulation emission is the opposite of (stimulated) absorption
Stimulated emission is a “photon copier.”
The emitted photon has identical properties as the “stimulating” photon:
same color, direction, polarization: Indistinguishable

What does all these have to do with laser?

What is good about laser? What we want from a light source that a lamp is not?

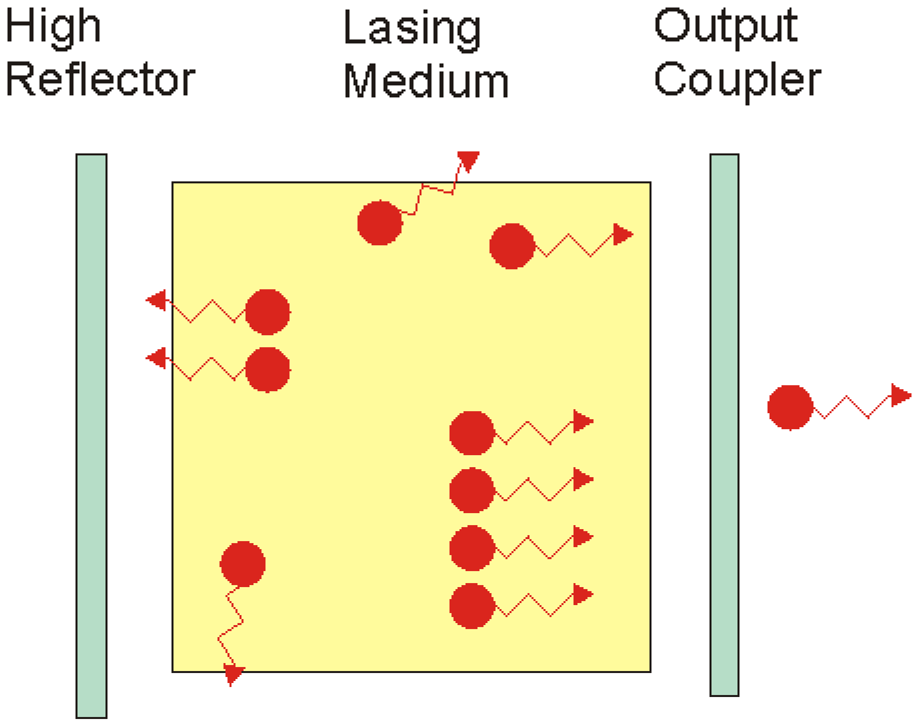
(1) Monochromatic
(2) High spectral radiance
(3) Low divergence
(4) Unique polarization
(5) Long coherence length

How do we achieve this? If we can "copy" a photon many times. Then we have IT … laser, Nobel prize, ….

We need two things: (1) amplification, (2) population inversion

Basic Idea of A Laser

Put a lasing medium in “population inversion” between two mirrors. An avalanche, amplification, process occurs as a spontaneous emitted photon bounce back and forth between the two mirrors to “copy” more of itself.



Uni-directionality comes from the fact that only photons going between the two mirrors are amplified.

Population inversion is needed so that the probability of stimulated emission is much greater than absorption to sustained the avalanche process

A Better Understanding of How Light Interaction with Molecules Is Needed to Know How to Create Population Inversion

Einstein studied these three processes: stimulated absorption, Stimulated emission, and spontaneous emission

Let N_i, N_j be the population of molecules in the ground and excited states

Let I be the energy density of light

$$\frac{dN_j}{dt} = -B_{ji}N_jI - A_{ji}N_j + B_{ij}N_iI$$

At steady state, the ground and excited states population is constant:

$$B_{ij}N_iI = B_{ji}N_jI + A_{ji}N_j \qquad \frac{N_j}{N_i} = \frac{B_{ij}I}{B_{ji}I + A_{ji}}$$

The relative populations of the states not only can be determined by kinetic consideration but also by thermodynamics

We also know from statistical mechanics that the populations of two states in thermal equilibrium is described by Boltzmann statistics

$$N_{i,j} = N_0 e^{-\frac{E_{i,j}}{kT}}$$

where E is the energy of states i and j, k is the Boltzmann's constant and T is the absolute temperature

$$\frac{N_j}{N_i} = e^{-\frac{(E_j - E_i)}{kT}} = e^{-\frac{\Delta E}{kT}}$$

Einstein B Coefficients

Combining kinetics and thermodynamics:
$$I = \frac{\frac{A_{ji}}{B_{ji}}}{\frac{B_{ij}}{B_{ji}} e^{\frac{\Delta E}{kT}} - 1}$$

What happens when temperature approach infinity?

We expect light density also grows to infinity
(driving all the molecules instantly to the excited state).

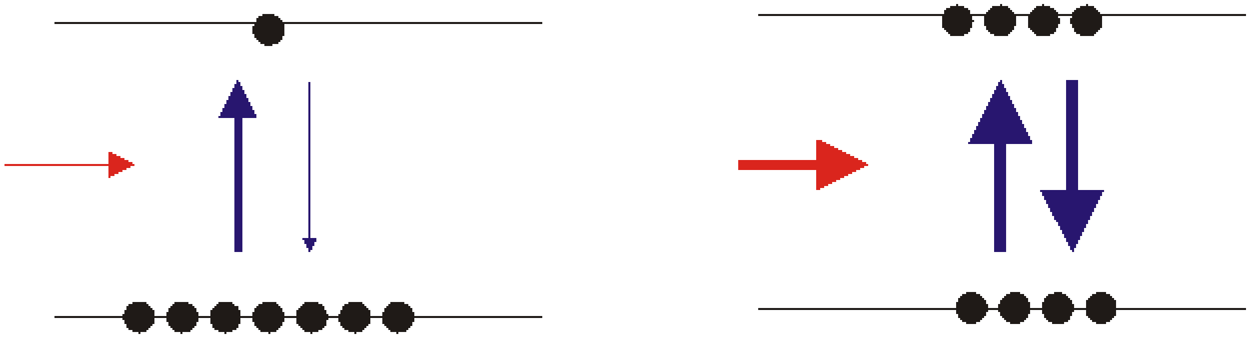
$$I \to \infty \quad as \quad T \to \infty \quad requires \quad B_{ij} = B_{ji} = B$$

“Einstein B coefficient”

The rate constants of stimulated absorption and emission are equal

$$I = \frac{\frac{A}{B}}{e^{\frac{\Delta E}{kT}} - 1}$$

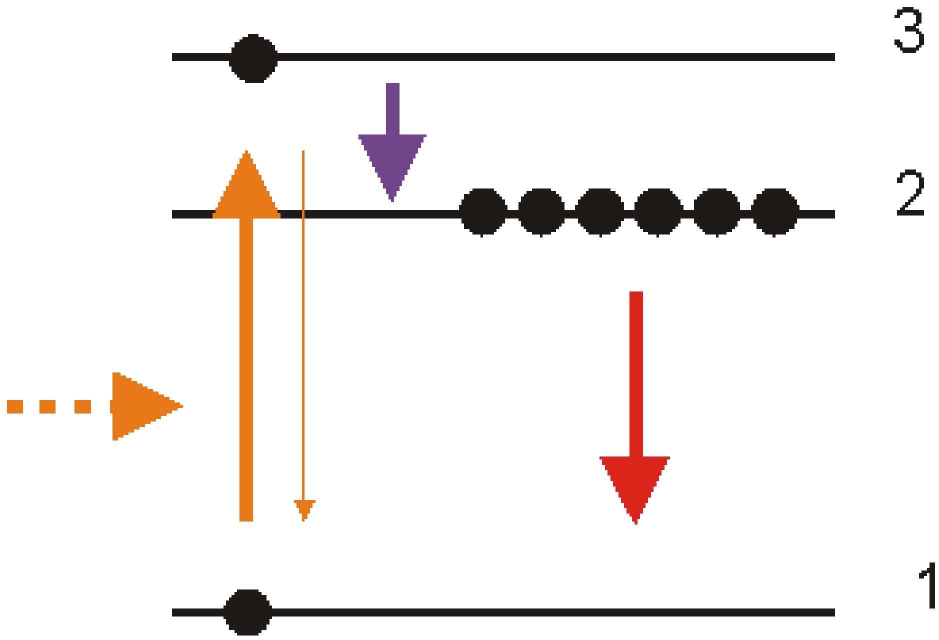
Population inversion is not possible in a 2-state system



Low Light High Light

As excited state becomes well populated, the excitation and de-excitation probability becomes equal because the Einstein coefficients for up and down are equal

Population inversion is possible in a 3-state system



Population inversion can be created if:

(1) Spontaneous decay rate to from state 3 to state 2 is the fastest
(2) Stimulated excitation rate from state 1 to state 3 is faster or comparable to the decay rate from state 2 to state 1
(3) Population inversion is created between state 1 and 2
(4) Increasing “pump” power (orange) do not cause stimulated emission from state 2