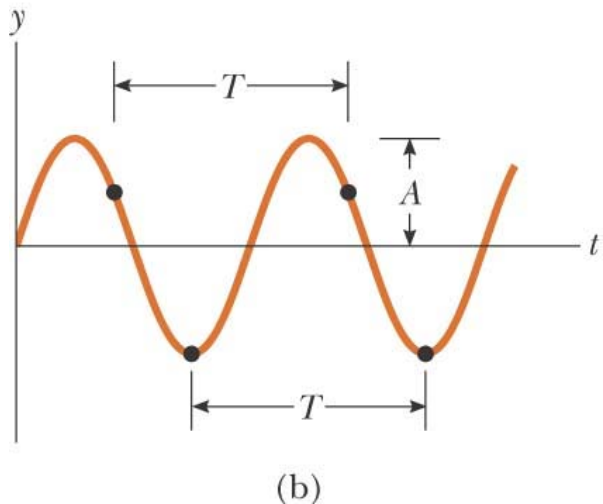
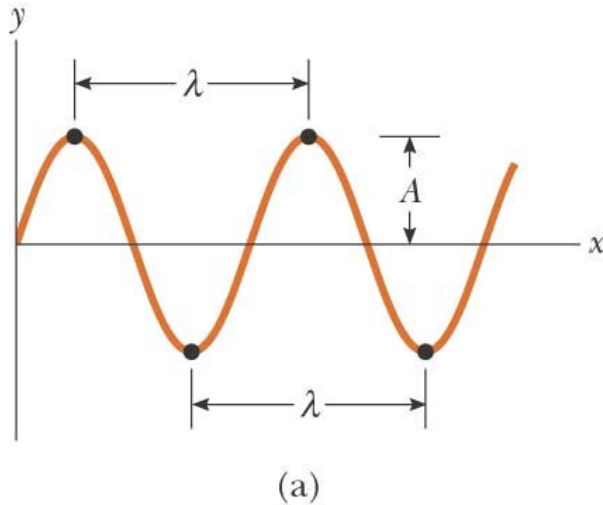


Optical Analytical Techniques for Thin Film Characterization

Nature of Light

- Light as wave
 - The propagation of light can best be described as a travelling wave.
 - It really is a coupled electric and magnetic field that oscillate together in time and space (electromagnetic wave).
 - The speed of the wave is constant in free space ($c = 3 \times 10^8$ m/s).
- Light as particle
 - The interaction of light with matter is best described as a massless particle called a photon.
 - The energy of the photon determines its frequency.
 - The number of photons in a beam determines the total energy in that beam.

Light as a Wave



$$y = A \cos(kx - \omega t)$$

$c = 3 \times 10^8 \text{ m/s}$ Speed of Light

$\omega = 2\pi f$ Angular Frequency

$$c = \frac{\omega}{k}$$

$k = \frac{2\pi}{\lambda}$ Wavenumber

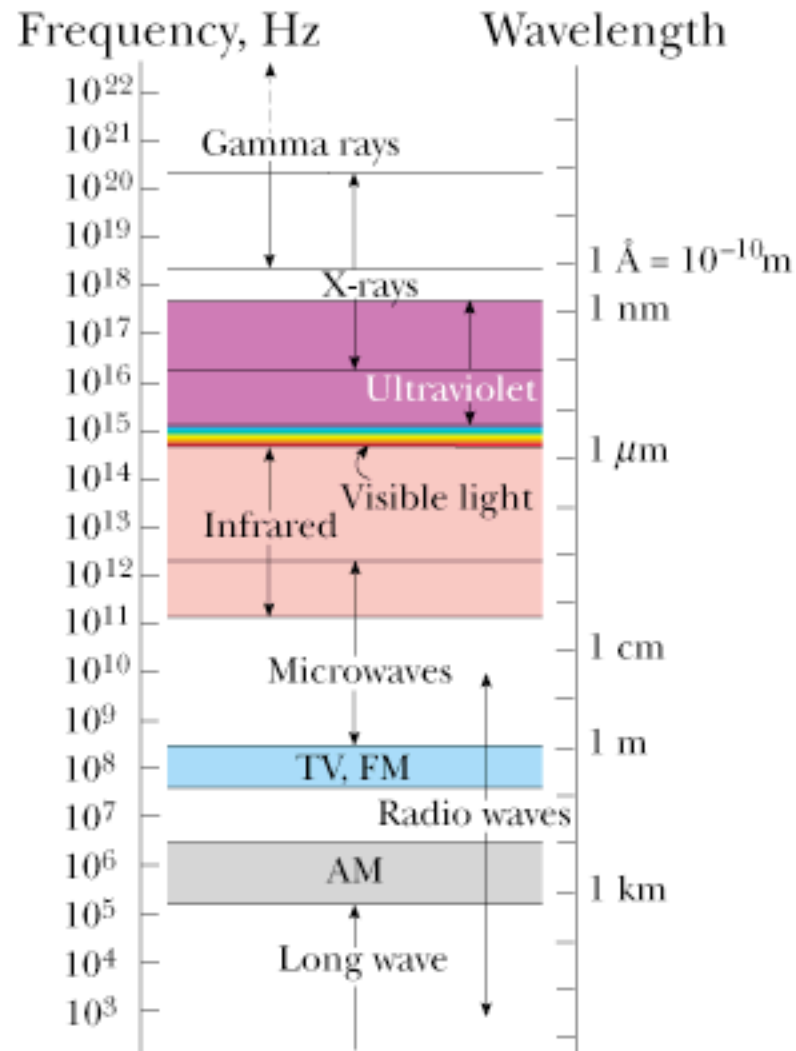
T Period (s)

λ Wavelength (m)

$f = \frac{1}{T}$ Frequency (Hz)

$$c = \lambda f$$

Electromagnetic Spectrum

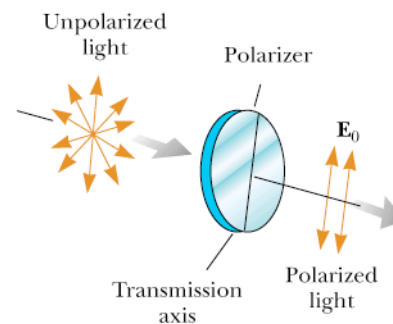
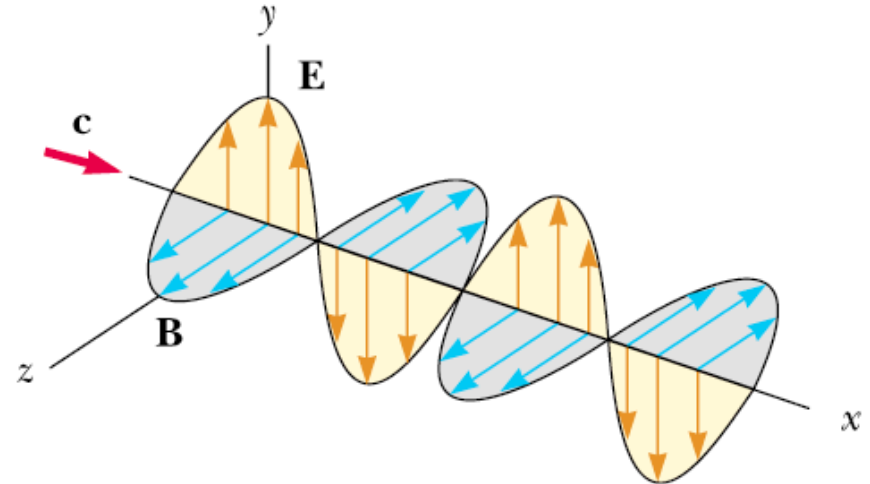


Wave Properties of Light

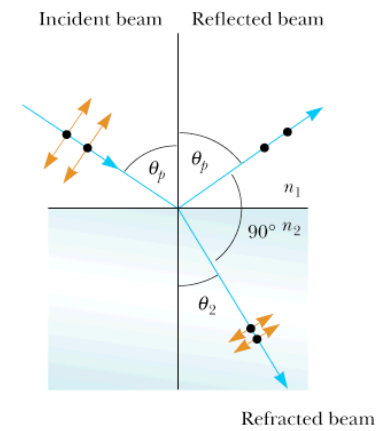
- Polarization
 - Direction of oscillation
- Interference
 - Interaction of two coherent waves
- Diffraction
 - Interaction of a wave with itself

Polarization

- We said that light is a wave with an electric and a magnetic field. These fields are **vector** quantities, which means they have a direction as well as an amplitude.
- The direction of the electric field associated with the EM wave is called its **polarization**.
- Light can be linearly (horizontal or vertical) or circularly (clockwise or counter cw) polarized or unpolarized (random polarization).
- Laser light is generally polarized while sunlight and light from light bulbs are unpolarized.
- Unpolarized light can be turned in to polarized light by a polarizer.
- A polarizer can work by;
 - selective absorption (polaroid films, sunglasses)
 - selective scattering (blue skies, red sunsets)
 - reflection (Brewster's angle, ellipsometry)
 - double refraction (calcite crystals)



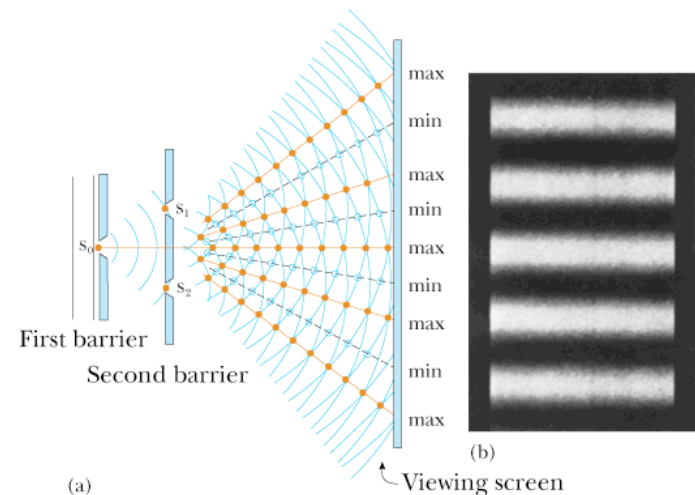
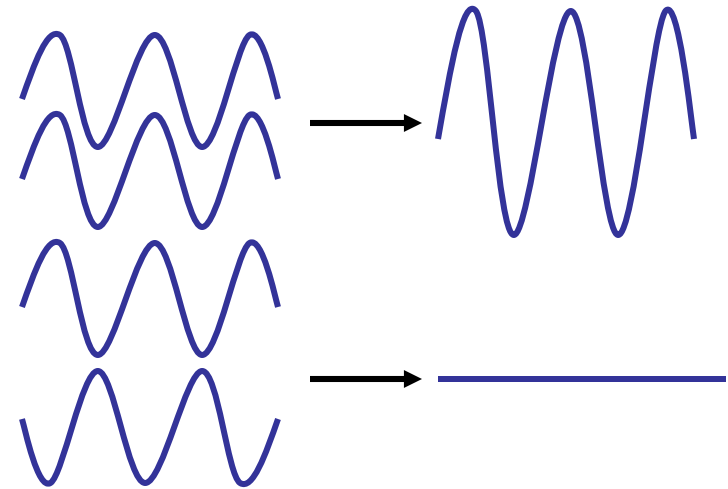
Selective Absorption



Reflection

Interference

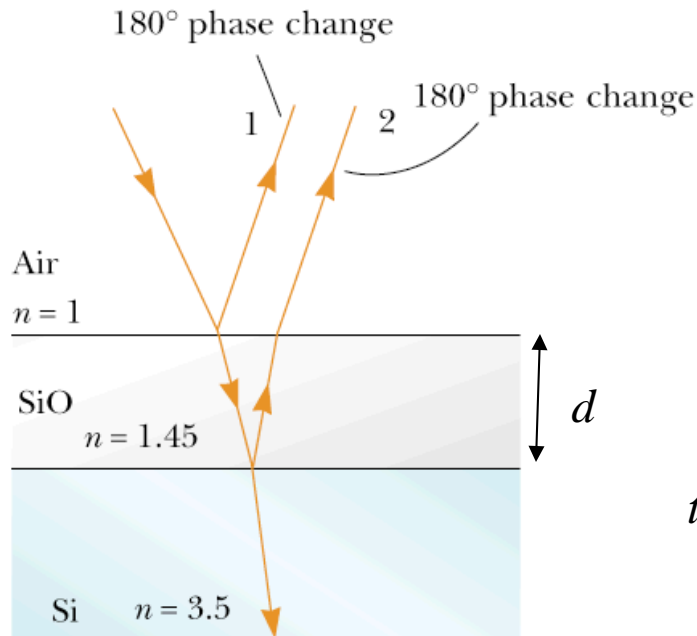
- If the waves are emitted from a single source, we can adjust the synchronicity of the waves by adjusting their arrival times.
- If one wave arrives half a period of oscillation after the other, then it will be completely out of sync with the earlier one and they will cancel each other out – **destructive interference**.
- The same is true for any wave that arrives 1.5 periods later and 2.5 periods later, etc.
- If one wave arrives exactly a period later then it will be again completely in sync with the earlier one and they will add to each other – **constructive interference**.
- Same is true for all waves arriving 2 periods, 3 periods, etc. later.



Thin Film Interference

- Consider a thin film that is at least partially transparent to light.
- If light is incident from the top, some of the light will be reflected and some will be transmitted in to the film.
- Similarly, as the transmitted light tries to exit the film at the bottom, there will be reflection and transmission.
- The waves that were reflected from the top of the film and the bottom of the film will interfere with each other.
- If the delay introduced by the thickness of the film matches an integer multiple of the period of light, there will be constructive interference.
- If it is half a period of delay, there will be destructive interference.
- One additional wrinkle is that waves that reflect off of a higher index medium will undergo a 180° phase change so that a delay of one period results in destructive interference and a delay of half a period results in constructive interference.

Thin Film Example – Anti-Reflective Coating



If the extra time the 2nd wave spends in the SiO layer is an integer multiple of the period, then there will be constructive interference, otherwise destructive interference.

$$t = \frac{2d}{c/n_{SiO}} = \frac{2dn_{SiO}}{c}$$

Extra time spent in SiO

$$t = T = \frac{\lambda}{c} = \frac{2dn_{SiO}}{c} \rightarrow \lambda = 2dn_{SiO}$$

Condition for constructive interference

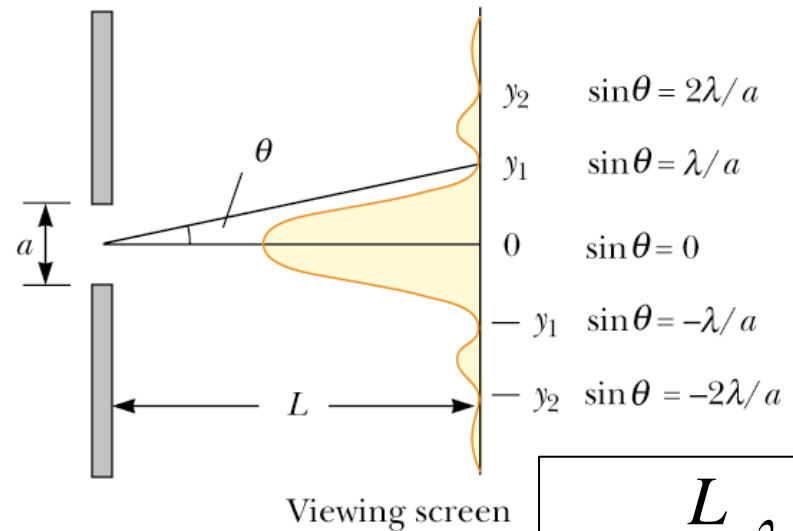
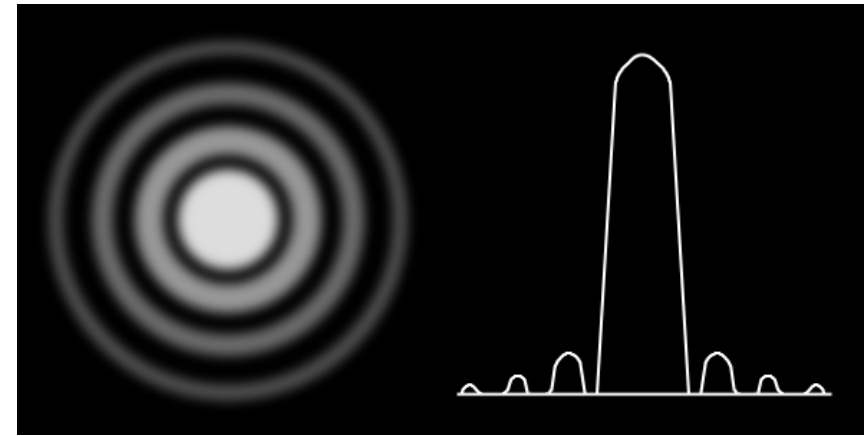
$$t = \frac{T}{2} = \frac{\lambda}{2c} = \frac{2dn_{SiO}}{c} \rightarrow \lambda = 4dn_{SiO}$$

Condition for destructive interference

If you want a film that does not reflect red light (~620 nm), you would make the film thickness, $d = 107$ nm

Diffraction

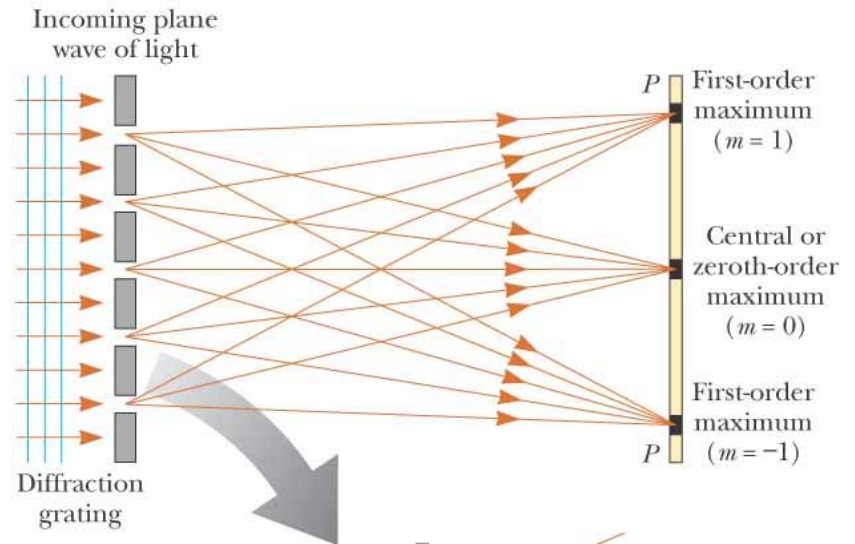
- Diffraction occurs because light waves that go through an opening (or around an obstruction) interfere with themselves.
- This results in a series of constructive and destructive interference bands.
- Most of the light intensity is in the central bright band.
- The width of the band is inversely proportional to the width of the opening and directly proportional to the wavelength of the light.



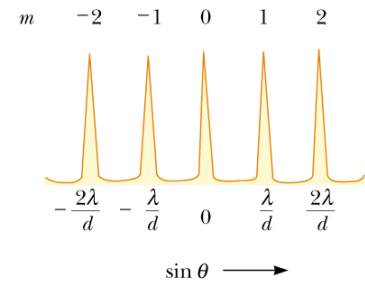
$$y_1 \approx \frac{L}{a} \lambda$$

Diffraction Gratings

- A series of finely spaced slits creates a multiple slit interference pattern of sharp bright spots.
- The location of the spots depend on the wavelength of light.
- Such a device is used to separate light in to its spectral components.

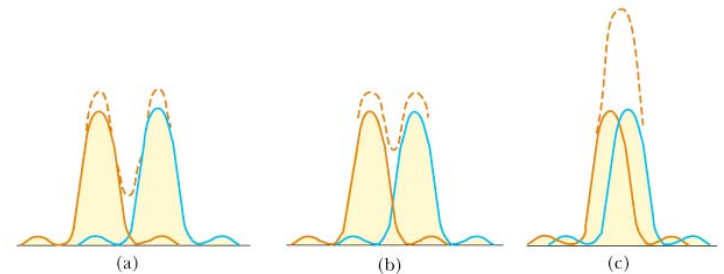
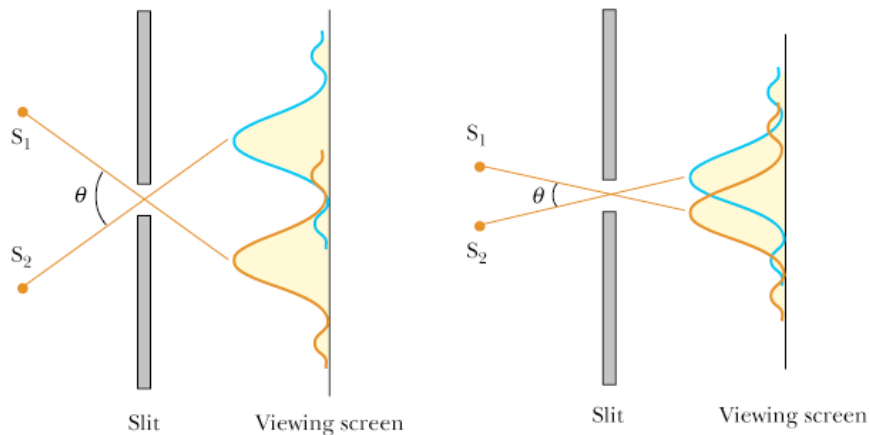


$$d \sin \theta = m \lambda$$



Optical Resolution

- When light from two different sources pass through an aperture, their diffraction patterns will overlap.
- If the overlap is severe, the two sources will not be resolved.



$$\theta_{\min} = 1.22 \frac{\lambda}{D}$$

Rayleigh's criterion for optical resolution

Light as a Particle

- In its interactions with matter (atoms and/or molecules), light can be described as a particle called a photon.

$$c = \lambda f$$

$$c = 3 \times 10^8 \text{ m/s}$$

Speed of Light

$$E = hf$$

$$h = 6.6262 \times 10^{-34} \text{ J}\cdot\text{s}$$

Planck's Constant

$$1\text{eV} = 1.6 \times 10^{-19} \text{ J}$$

electron-volt

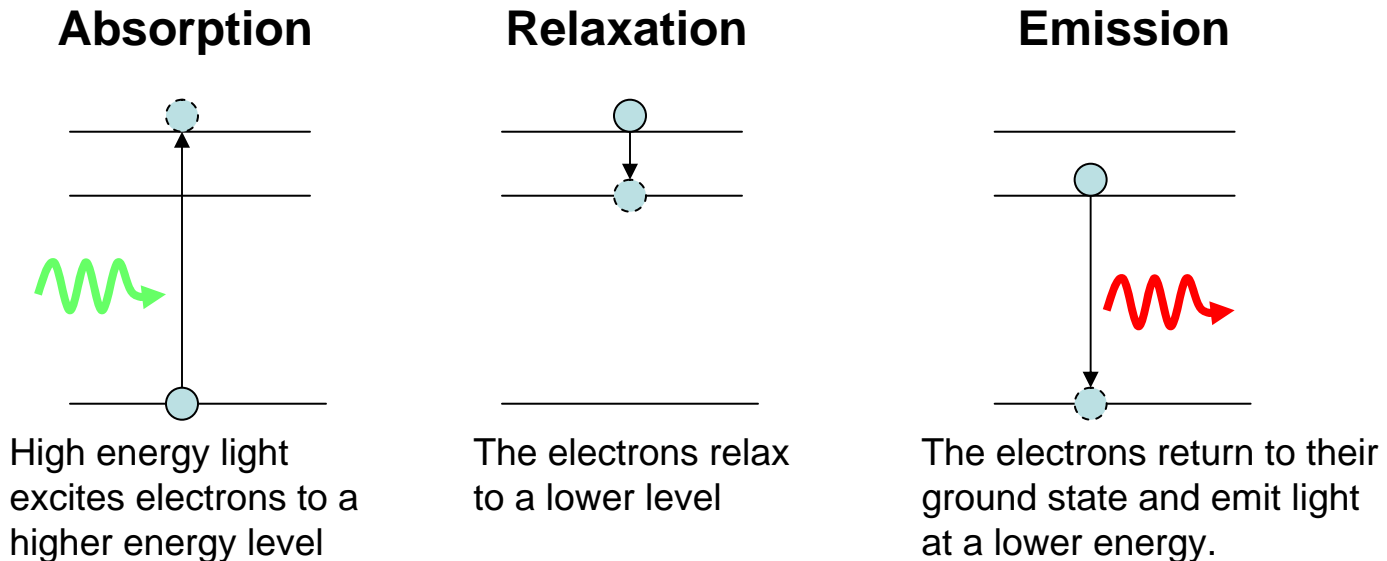
$$E\lambda \approx 1240$$

Light
energy
in eV

Light
wavelength
in nm

Absorption and Luminescence

- External energy can be supplied to a material by
 - electrical current (electroluminescence)
 - optical excitation (photoluminescence)
 - electrical discharge (cathodoluminescence)
- When external energy is absorbed in a material, the excited electrons can return to their ground states by releasing the absorbed energy as light.
- This light can come from direct level to level transitions or from defects.

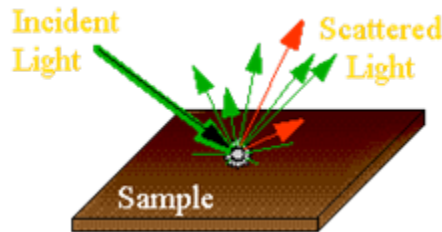


Lattice Vibrations

- Atoms making up a crystal lattice can vibrate or rotate in their place.
- These oscillations can be thought of individual entities, called **phonons**, that have a characteristic oscillation frequency and energy ($E = hf$).
- The energy of the vibration is dependent on the composition of the crystal and the chemical bonds.
- Lattice vibrations are also how sound waves propagate through materials.
- If the vibrations are in the direction of the lattice, they are called longitudinal vibrations.
- If they are in perpendicular to the direction of the lattice, they are transverse vibrations.
- Transverse vibration energies are in the order of tens of meV.

Raman Scattering

- The Raman effect arises when the incident light excites molecules in the sample which subsequently scatter the light.
- While most of this scattered light is at the same wavelength as the incident light, some is scattered at a different wavelength.
- This *inelastically* scattered light is called Raman scattering.
- The main medium for this energy change are the lattice vibrations.



Non-linear Optics

- When light passes through a material, it interacts with the atoms around it.
- The electric field associated with the light wave will distort the electrons in their orbits creating a polarized state.
- The material polarization in turn affects the light propagating through it.
- For low intensity light, this polarization is linearly dependent on the electric field and only the intensity of the light changes.
- However, for high intensity light waves, the dependence becomes non-linear.
- The non-linearity creates harmonics of the light wave.

The incident electric field

$$E = E_0 \cos \omega t$$

The polarization response of the material

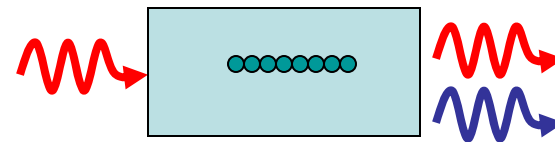
$$P = a_1 E + a_2 E^2 + a_3 E^3 + \dots$$

Second Harmonic Generation

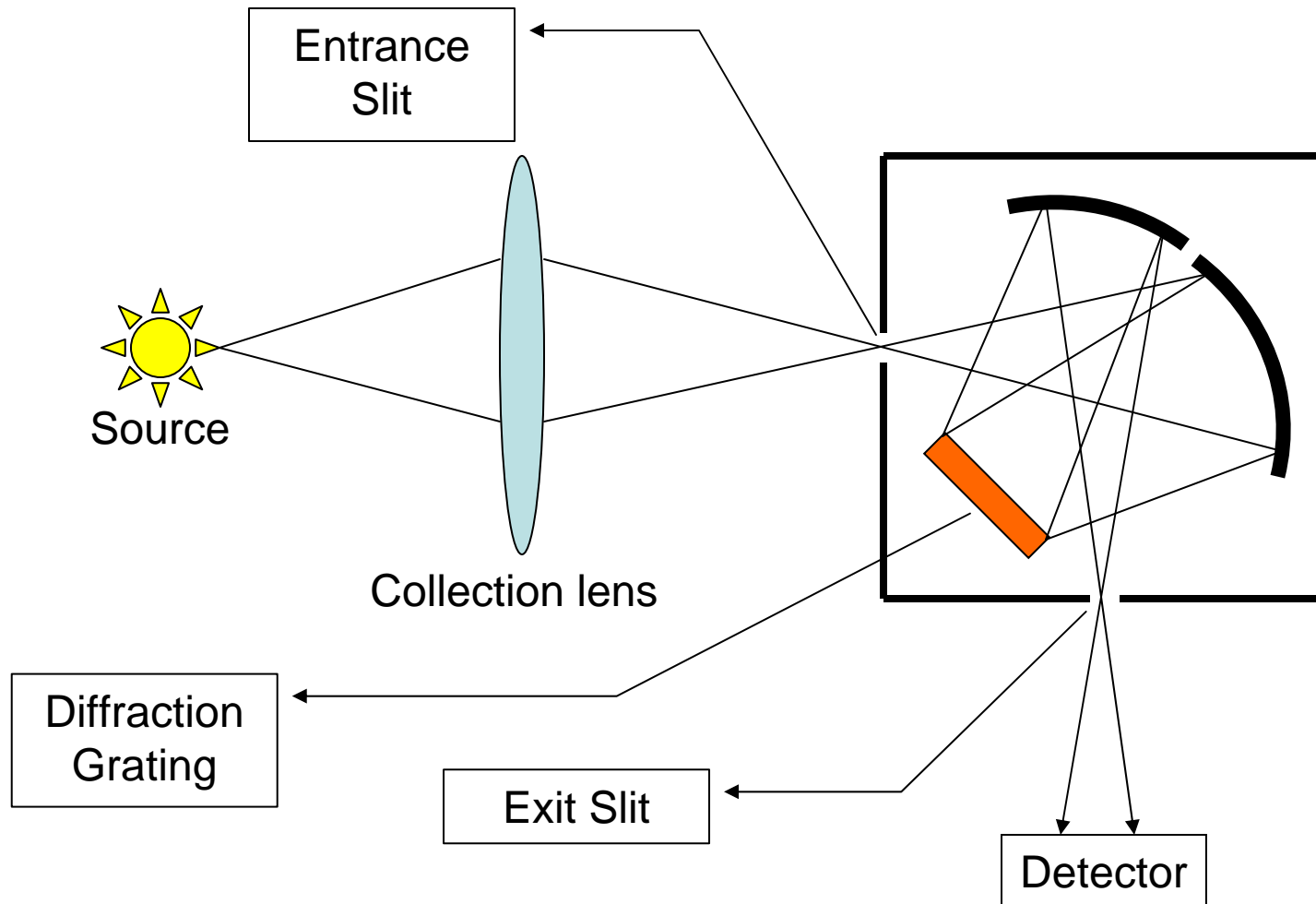
$$P = a_2 E^2 = a_2 (E_0 \cos \omega t)^2$$

$$P = a_2 E_0^2 \cos^2 \omega t = a_2 E_0^2 (1 + 2 \cos 2\omega t)$$

2nd Harmonic at 2ω

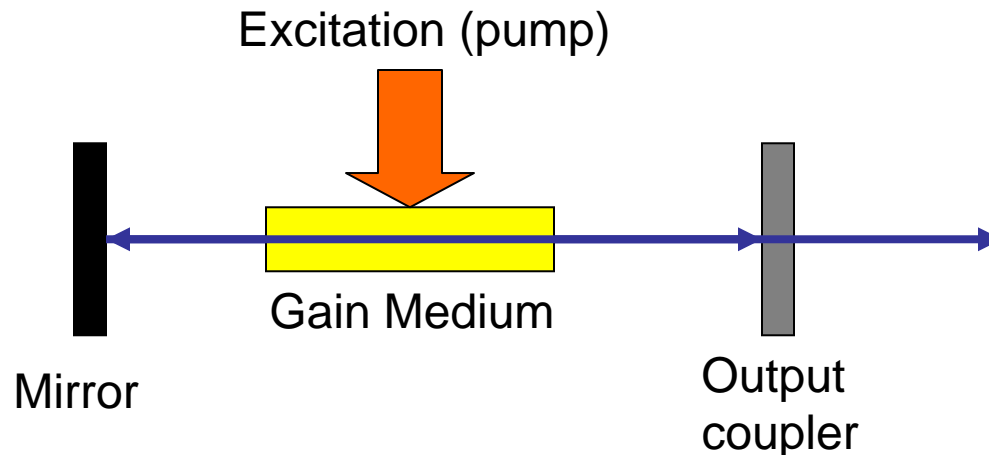


Spectrometers



Lasers

- Consider a gain medium sandwiched between two mirrors.
- The gain medium can absorb external energy and convert it to light.
- The light emitted by the gain medium will be reflected from the mirrors back in to the medium, resulting in more absorption and light generation.
- If the number of excited electrons in the gain medium exceed the number of ground state electrons, the process can become self sustaining (inversion).



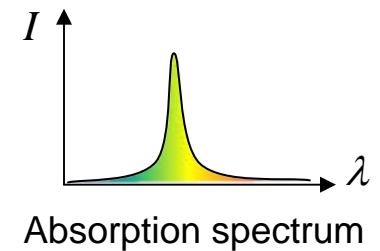
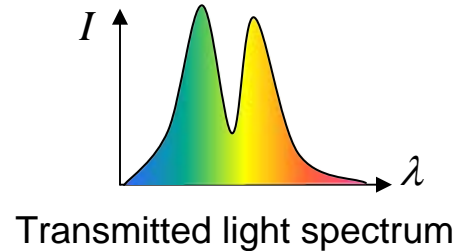
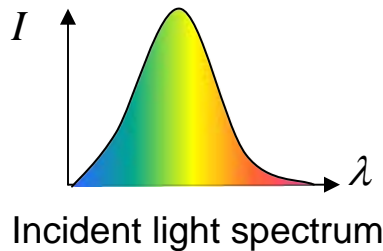
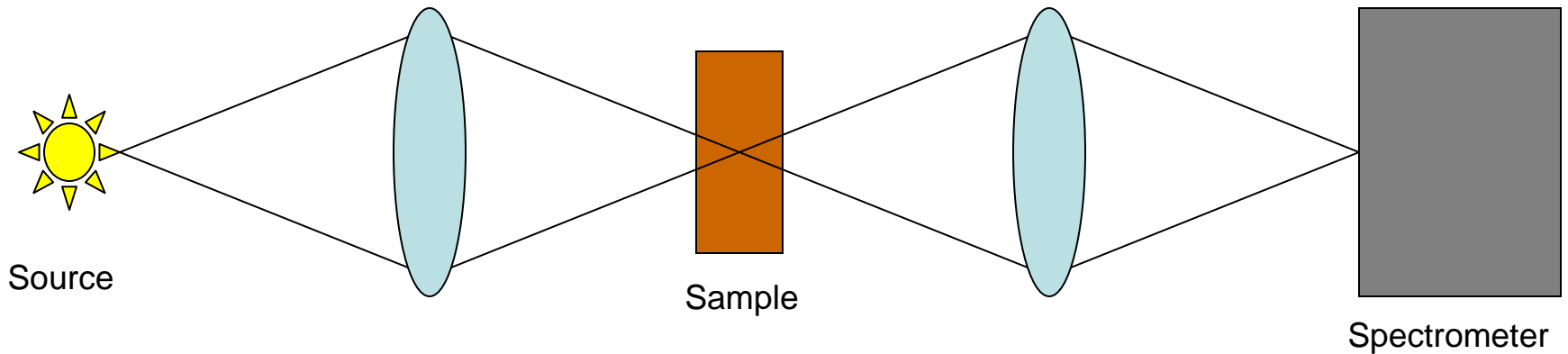
Some Details

- The gain medium can be;
 - a crystal (YAG, Ti: Sapphire)
 - a dye (Rhodamine, LDP)
 - a gas (Argon, HeNe, CO₂)
 - a plasma (ArF)
 - a semiconductor (GaAs, GaN)
- The excitation can be;
 - electric current (semiconductor diode lasers)
 - optical (dye lasers)
 - electric discharge (gas lasers)

Properties of Laser Light

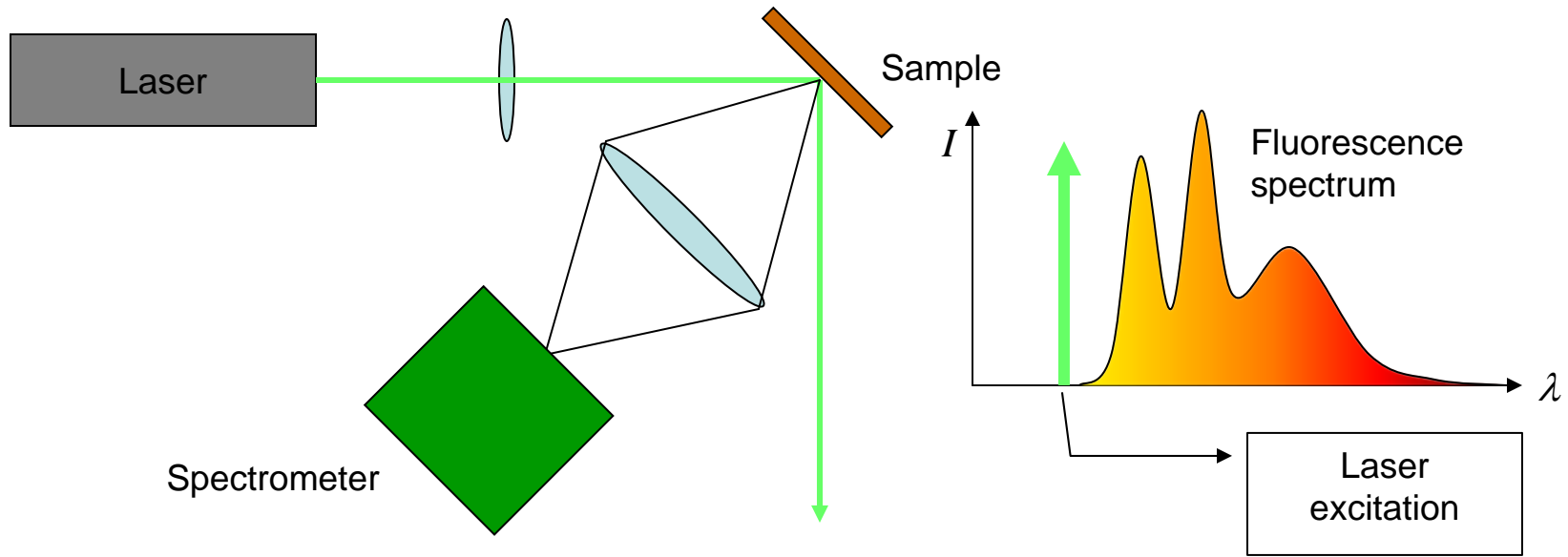
- Laser light is coherent.
 - All the waves emitted by the laser oscillate in phase (unlike incoherent light from the sun or a light bulb).
- Laser light is monochromatic.
 - Since the emitted light is the result of a particular electronic transition, it only has a single wavelength.
- Laser light is directional.
 - The gain medium and the “cavity” formed by the mirrors determine the direction of the emitted light.

Absorption Spectroscopy



- Measures the absorption coefficient.
- The result is a combination of a number of processes that go on in the sample.

Fluorescence Spectroscopy



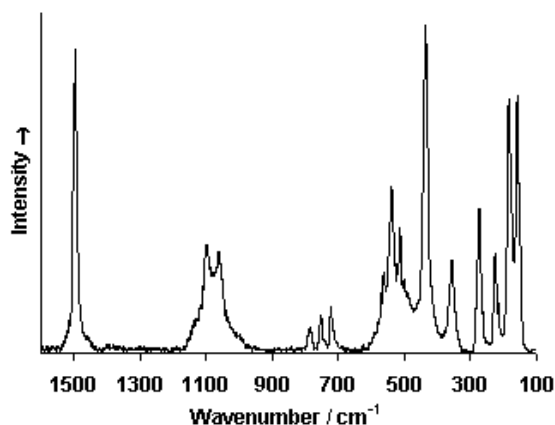
- The laser excites an electronic transition.
- Light at various wavelengths are emitted as the electrons relax and return to their ground states.
- It is sensitive to electronic transitions.

Excitation Spectroscopy

- Same setup but now change the excitation wavelength and detect at a single wavelength.
- Used for precision measurement of molecular absorption lines.

Raman Spectroscopy

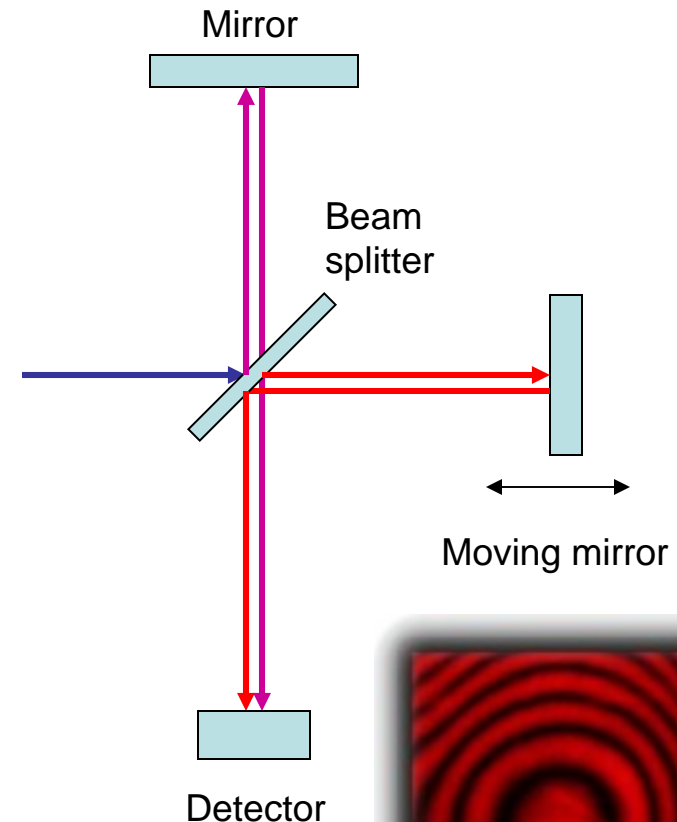
- The setup is similar to fluorescence spectroscopy.
- However, since the Raman scattering lines are very close to the laser excitation, narrow band lasers, precision filters and double monochromators are used.
- Raman scattering results from the change of the excitation laser wavelength by lattice vibrations.
- The lattice vibrations are sensitive to the chemical bonds in the sample.
- It is used in chemical analysis, process control and thin film quality measurements.
- The units are in wavenumbers ($k = 2\pi/\lambda$)



Raman spectrum of
Malachite Green

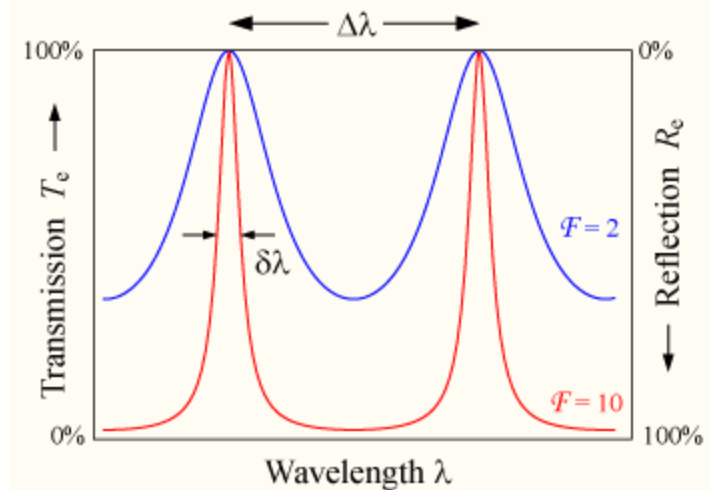
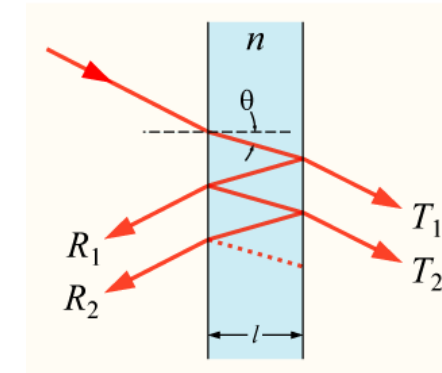
Michelson Interferometer

- The idea is to detect the difference in the arrival times of two beams by their interference.
- The arrival time is also equivalent to path length.
- This technique can be used to test surface quality and flatness.



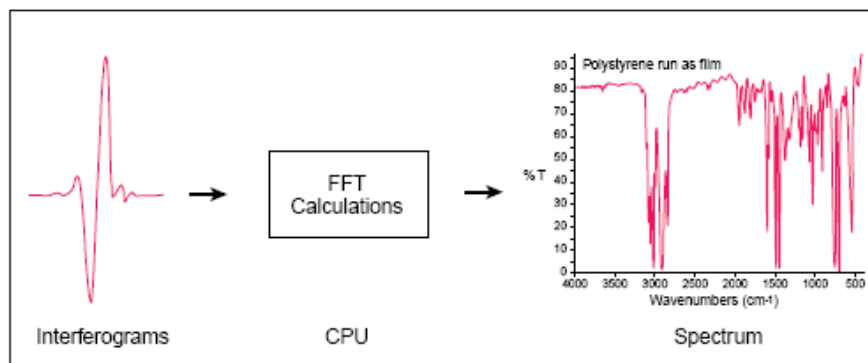
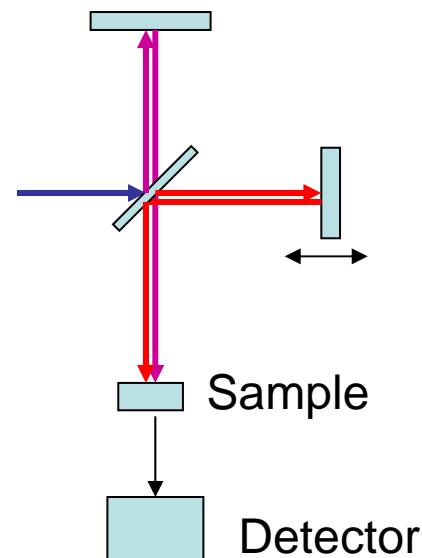
Fabry-Perot Interferometer

- It is based on thin film interference.
- Since constructive and destructive interference is dependent on the wavelength of the light and the length of the interferometer, it can be a very precise method of wavelength measurement.
- The reflectivities of the surfaces determine the *finesse* of the interferometer (the sharpness of the transmitted lines)



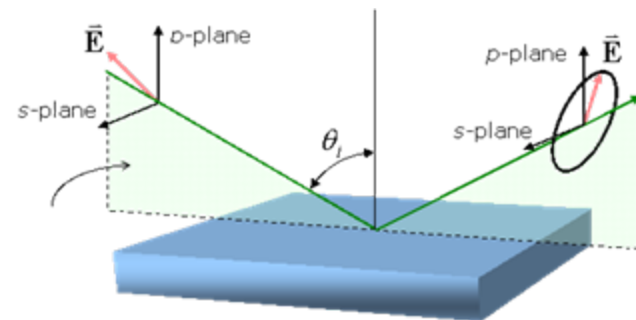
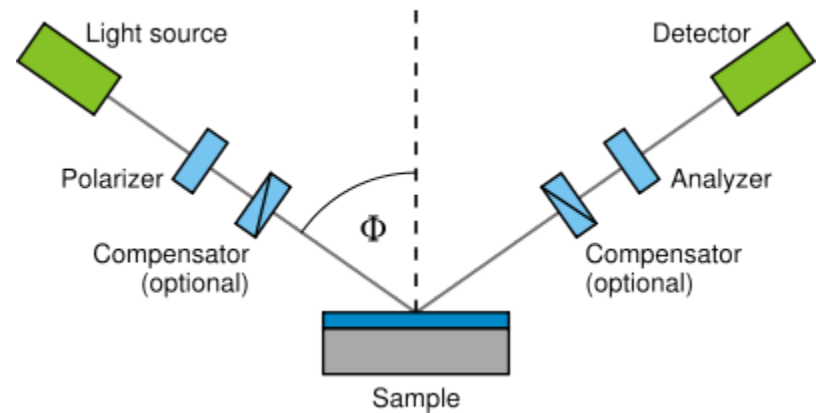
FTIR Spectroscopy

- Fourier Transform Infra-Red Spectroscopy
- It is a combination of IR absorption spectroscopy and a Michelson interferometer.
- The absorption is recorded as a function of time (as the mirror in one of the interferometer arms is moved).
- The resulting interferogram is then Fourier transformed in to frequency space to obtain an absorption spectrum.
- The spectrum is sensitive to the vibrations of the molecular bonds of the sample material.



Ellipsometry

- Ellipsometry measures the change of the polarization of a beam upon reflection or transmission.
- Using equations that relate reflection coefficients to polarization, the technique gives direct measurement of the complex dielectric constant of the sample which includes information about the index of refraction and the absorption coefficient.
- Both of those quantities will depend on the surface composition, thickness and morphology.
- One can measure thicknesses much less than the wavelength of the light used.

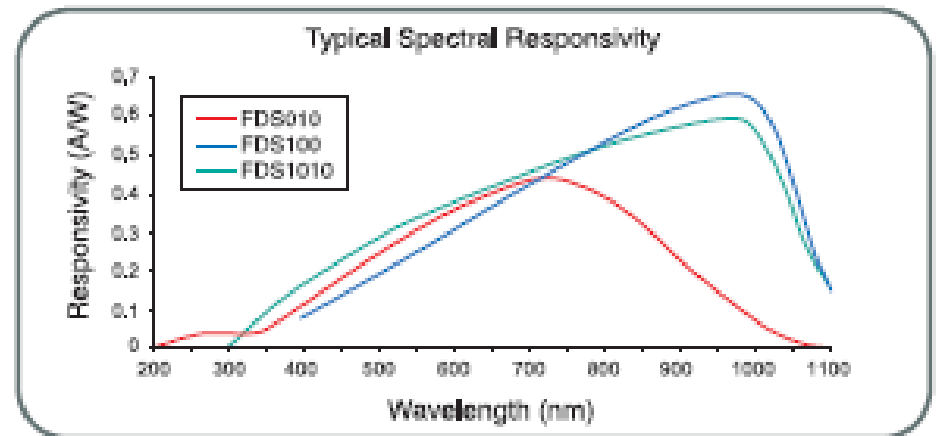


Detectors

- Photodiodes
- Avalanche Photodiodes
- Photovoltaic cells
- CCDs
- Photomultipliers

Photodiodes

- Uses an active, undoped layer sandwiched between a p- and an n-type semiconductor.
- Light incident on the undoped layer excites electrons and holes.
- Under bias, electrons are swept to the p-type layer and holes to the n-type and create a current that is proportional to the incident light intensity.
- Light has to be absorbed in order for current to be created, so the wavelength range of a PD is in its absorption region.
 - Si: 200 - 1100 nm
 - Ge: 400 – 1700 nm
 - InGaAs: 800 - 2600 nm



Typical Si Photodiode response curves

Avalanche Photodiodes

- Under high reverse bias, a photodiode can show high gain.
- Basically, each excited electron has enough excess energy to excite another electron which in turn can excite another, etc.

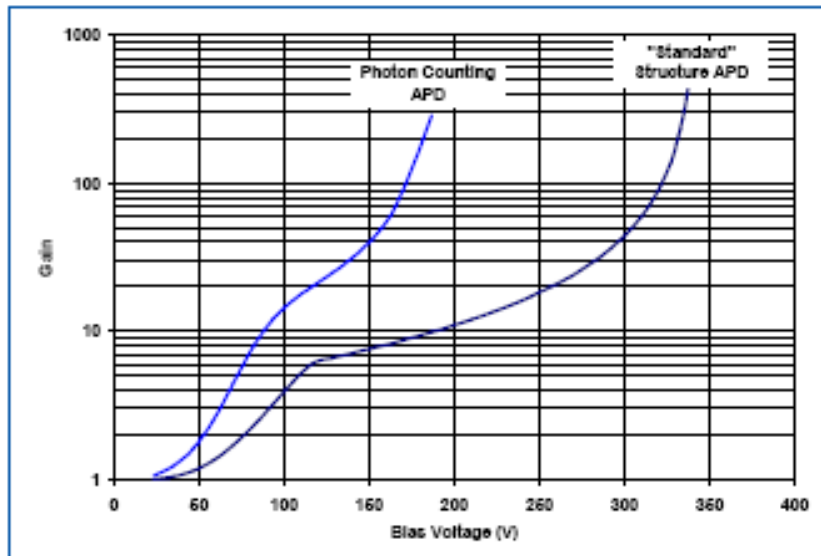
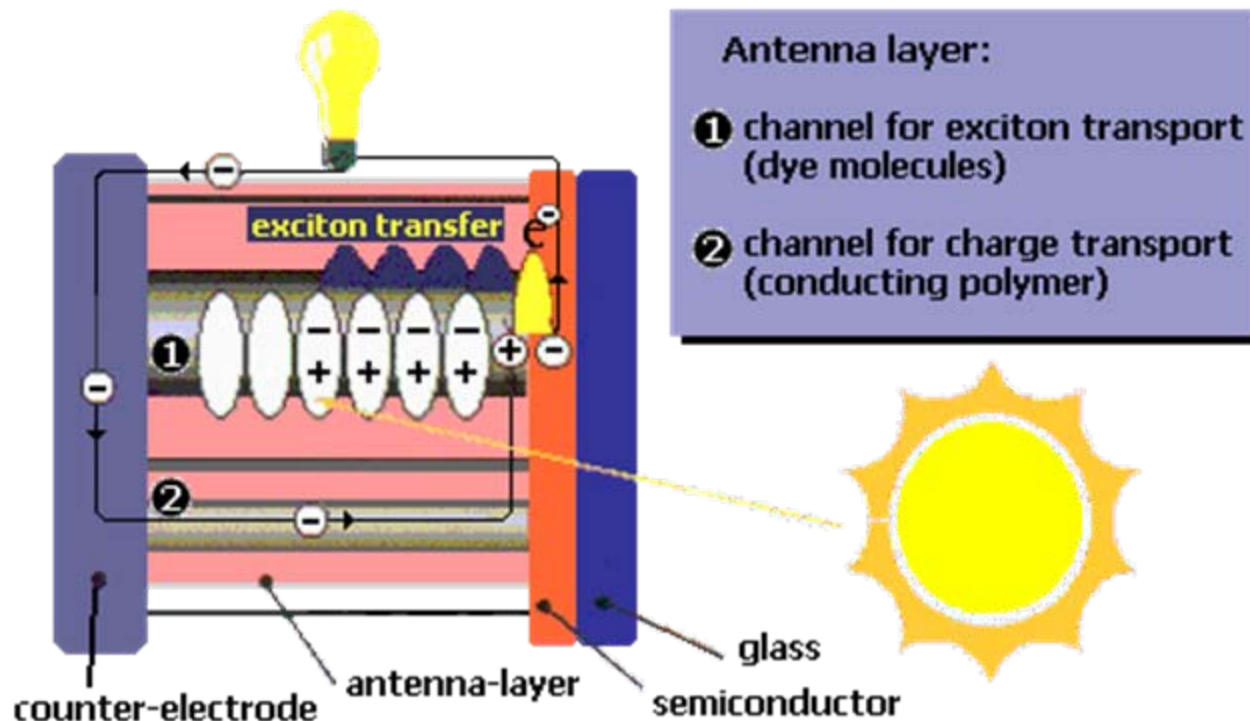


Figure 2 Gain vs Bias voltage

The Gain as a function of the bias voltage varies with the structure of the APD

Photovoltaic Cells

- Same principle as a PD but no n- or p-type layers.



CCDs

- CCD stands for Charge Coupled Device.
- It is a combination of a light sensor array (such as a photodiode array) and a capacitively coupled read out mechanism that allows sequential reading of the optical signal at each element of the array with the aid of a clock signal.
- Since they can be fabricated in to large 2 D arrays and have excellent gain and background noise characteristics, they are used as image sensors.

Photomultiplier Tubes

- A vacuum tube houses a series of dynodes and an anode.
- Photons incident on the cathode generate photoelectrons.
- These electrons are amplified in successive dynode stages by secondary electron emissions.
- Gains up to 10^8 can be achieved, enabling single photon detection.
- PMTs are sensitive in the UV and visible ranges.

