Physics (PHYS2500J), Unit 6 Wave Optics: 1. The nature and propagation of Light

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How do we treat the problems in optics?

The two personalities of light

Until Newton:
Particle (straight propagation)

1665 – early 19th century:
Evidence of wave

1873,
Maxwell predicted EM wave.

Newton even explained Snell's law with particle hypothesis.

Most convincing is Thomas Young's double slits interference

Propagation of light

Existence of light

1887,
Hertz experimentally proved EM wave.

Early 20th century, Plank, Einstein,
Modern concept of Photon

Blackbody radiation theory and Photoelectric effect.

Interaction with material world

Light has to be treated like wave (when considering the propagation) and particle (when considering interaction with material)

So is other particles (de Broglie)

Basic properties of light as particles

Energy of a single photon

$$\mathcal{E}_p = h\nu$$

Plank constant: 6.63×10^{-37} Js

Frequency of the EM wave

Or, $$\mathcal{E}_p = \hbar\omega$$

$$\hbar = \frac{h}{2\pi} \qquad \omega = 2\pi\nu$$

Also called Plank constant

Angular frequency

Momentum of a photon

$$\vec{P}_p = \frac{\mathcal{E}_p}{c}\hat{p} = \frac{h\nu}{c}\hat{p}$$

How do we treat the problems in optics?

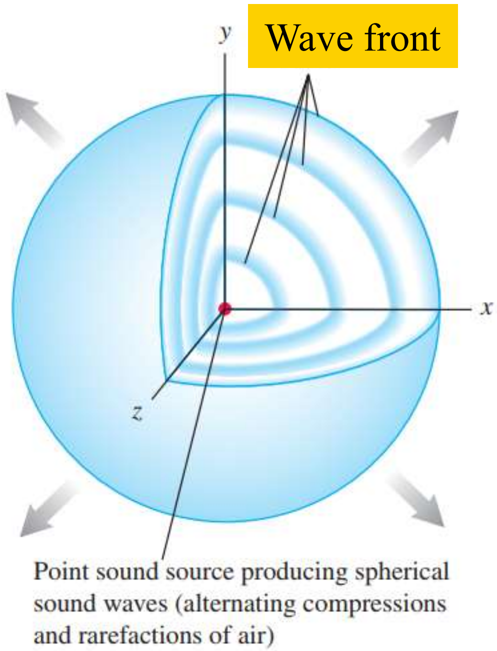
Feynman’s lecture:

A lot of photons. When the aperture is large (much larger than the wavelength), light can be treated as straight lines (ray, beam) —— geometrical optics

When the size of apertures (and other optical devices) is comparable to the wavelength, light needs to be treated as wave —— wave optics

Just a few or even one photon (weak light), energy of photon is comparable to the resolution of detector, light needs to be treated as particles —— quantum optics.

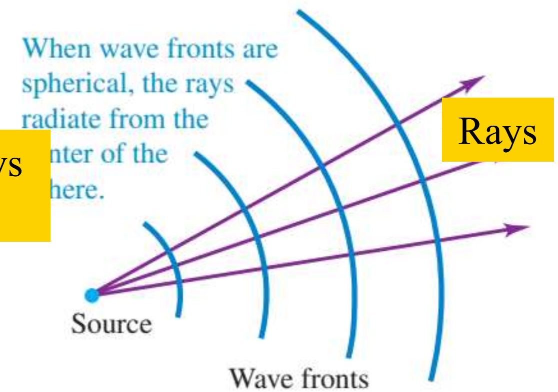
Terms for propagation of light



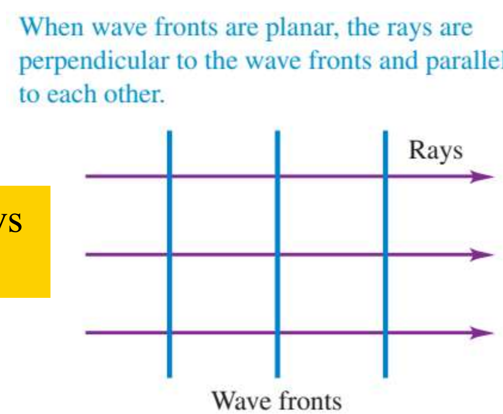
Wave front is the surface perpendicular to the propagation direction of light (similar to equipotential surface relative to electric field).

Wave front is actually the “equi-phase” surface.

Wave front and rays of spherical wave.



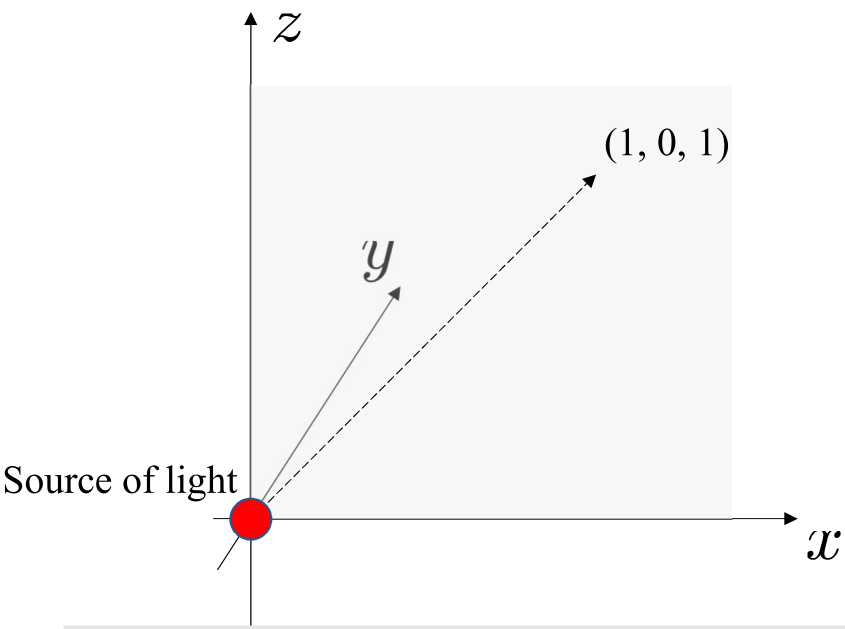
Wave front and rays of plane wave.



Example problem

Look at the picture. If flux of red light photon (760 nm) through a 1 cm^2 square at point (1, 0, 1) (unit m) is 10^{20}/s. What is the electric field at the same point?

In reality, should ask what is the rms value of the light or specify the polarity.



Step 1, get the intensity of the light from photon flow rate.

$$I = \frac{d\mathcal{E}}{dt}\frac{1}{S} = \frac{10^{20} \times h\nu}{1\times 10^{-4}} = 2.6 \times 10^5 \ \mathrm{W/m^2}$$

Step 2, Calculate properties of EM wave from intensity

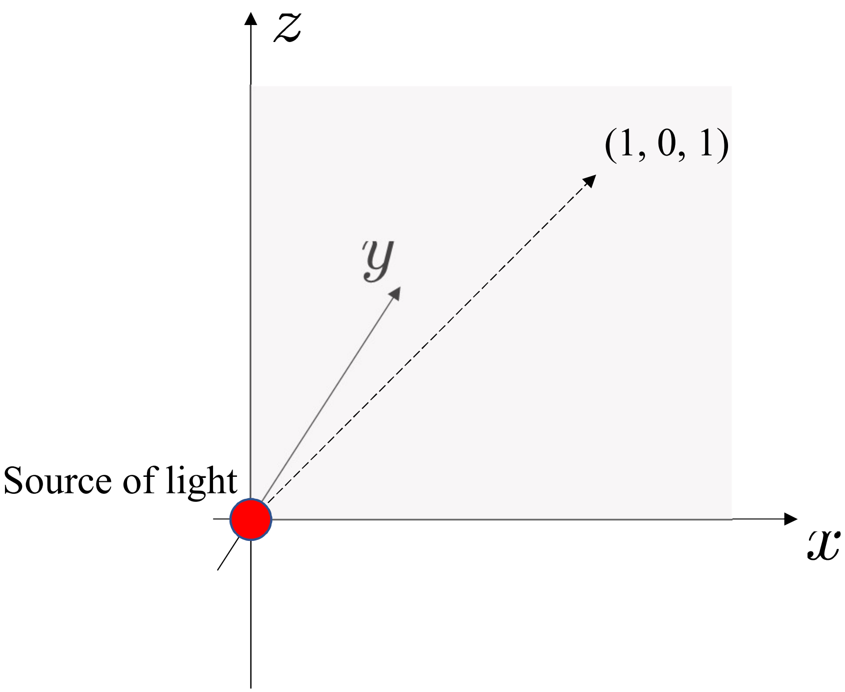
$$I = \overline{S} = \overline{E \times H} = \frac{\overline{E^2}}{c\mu_0}$$

$$E_{rms} = \sqrt{\overline{E^2}} = \sqrt{Ic\mu_0} = 9.9 \ \mathrm{kV/m}$$

It can be understood as a circular polarized light, where $|E|$ is a constant.

Example problem

What about at point (2, 0, 2)?



Energy conservation determines that the intensity of light is inverse proportional to distance square.

$$I_{202} = \frac{I_{101}}{4}$$

The relation between electric field and intensity determines the electric field is inverse proportional to distance.

$$\left(\frac{E_{202}}{E_{101}}\right)^2 = \frac{I_{202}}{I_{101}}$$

$$E_{202} = \frac{E_{101}}{2}$$

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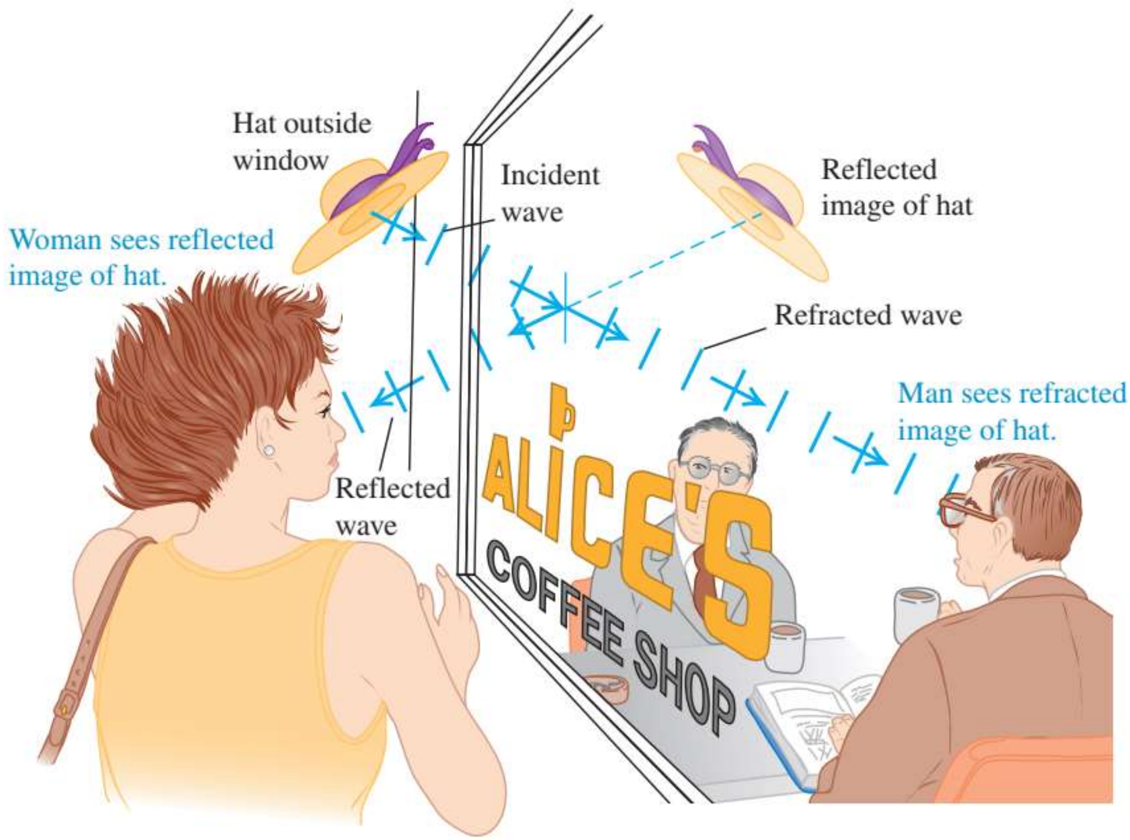
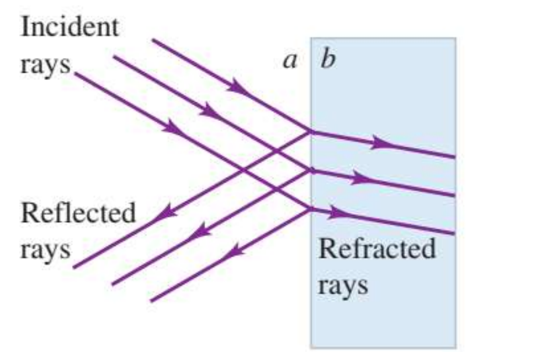
Refraction and reflection

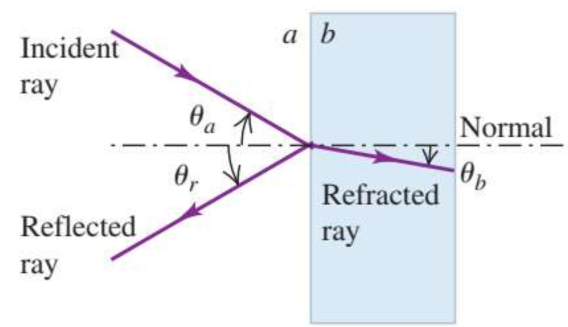
(a) Plane waves reflected and refracted from a window



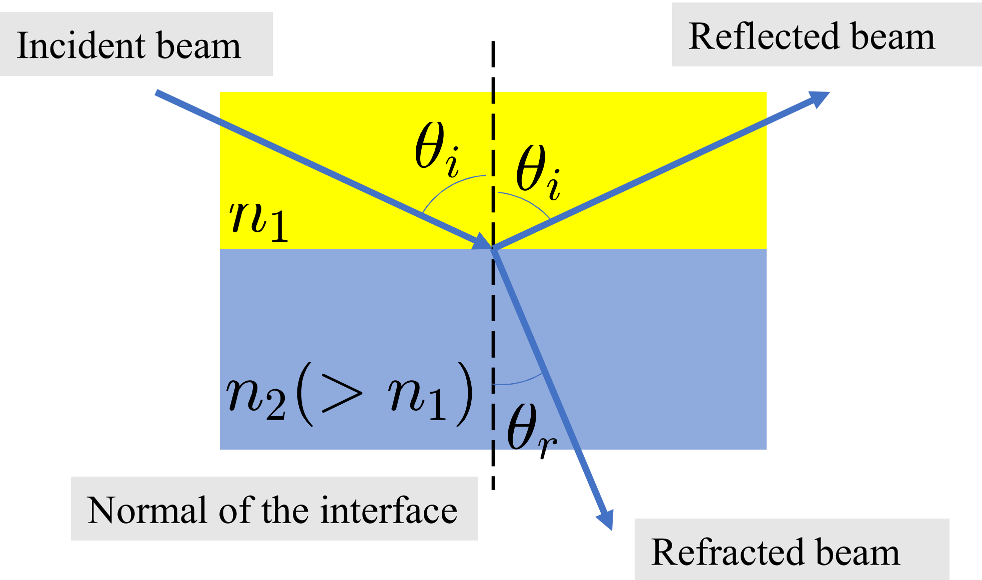
It is natural to have the multiple ray step, which is not shown in a lot of books.



(c) The representation simplified to show just one set of rays



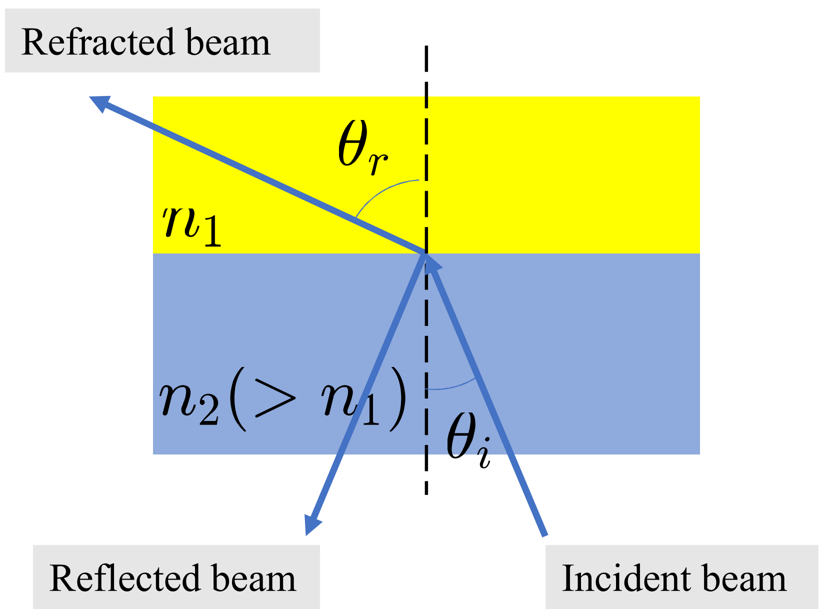
Snell's law



Snell's law

$$n_1 \sin\theta_i = n_2 \sin\theta_r$$

Total internal reflection



1. Reverse the light path in the last page. Light hits the interface from the denser medium.

2. Increase the incident angle, the refracted angle is also going to increase.

$$\sin\theta_r = \frac{n_2}{n_1}\sin\theta_i$$

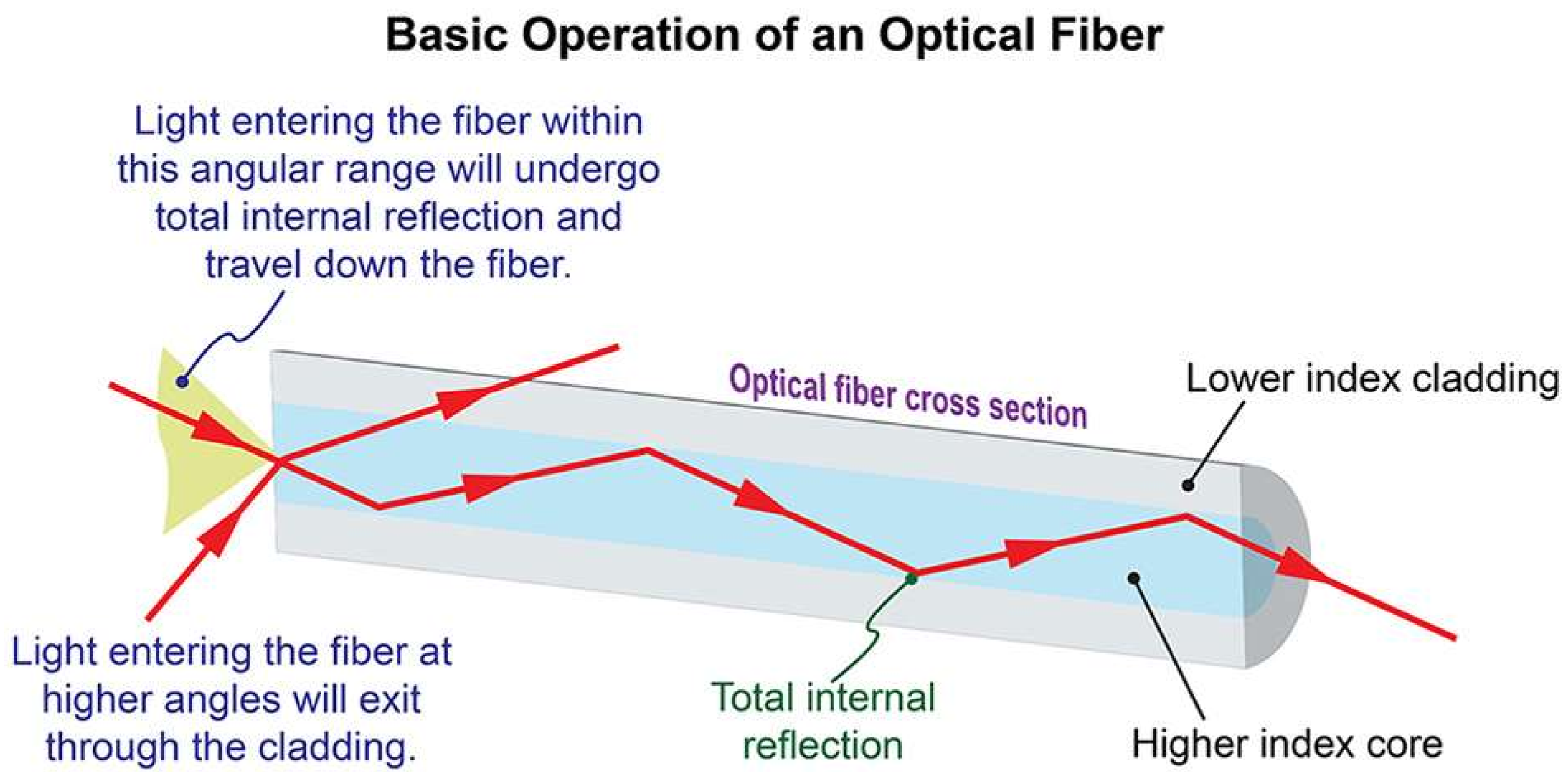
3. Until the incident beam increased to $\operatorname{asin}(\frac{n_1}{n_2})$

$$\theta_r = \frac{\pi}{2}$$

4. Further increase of incident angle, Snell's condition can not be satisfied. No refraction beam. It is called total (internal) reflection.

Optical fiber is based on the principle of total internal reflection

https://www.coherent.com/news/glossary/optical-fibers



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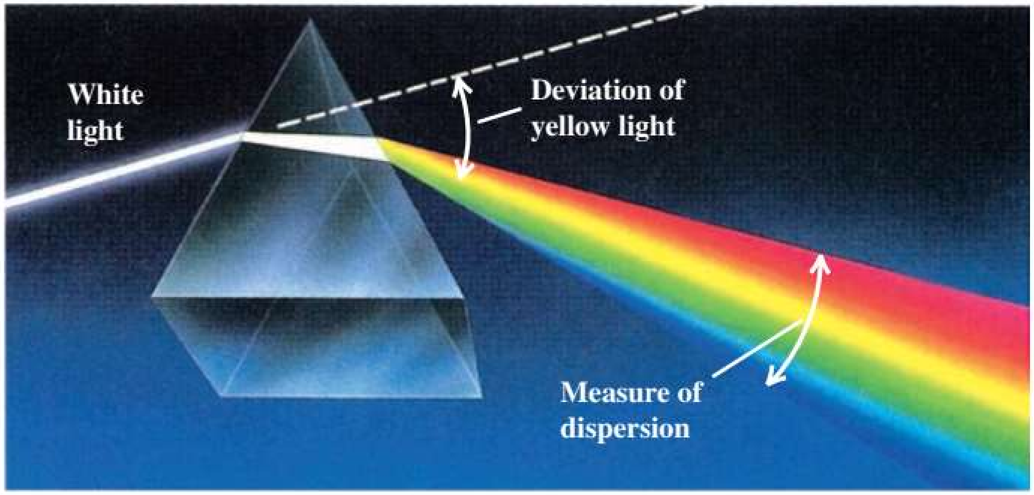
dispersion

33.18 Dispersion of light by a prism. The band of colors is called a spectrum.



1. Ordinary white light contains light of multiple wave lengths.

2. Dispersion is caused by different refraction indices for light of different wavelength.

3. In the left figure, which wavelength has higher refraction index, red or violet?

Violet

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Polarization (偏振)

1. Transverse wave: limited the direction of Electric field (as a vector) in the yoz plane.

$$\vec{E} = E_y \hat{y} + E_z \hat{z}$$

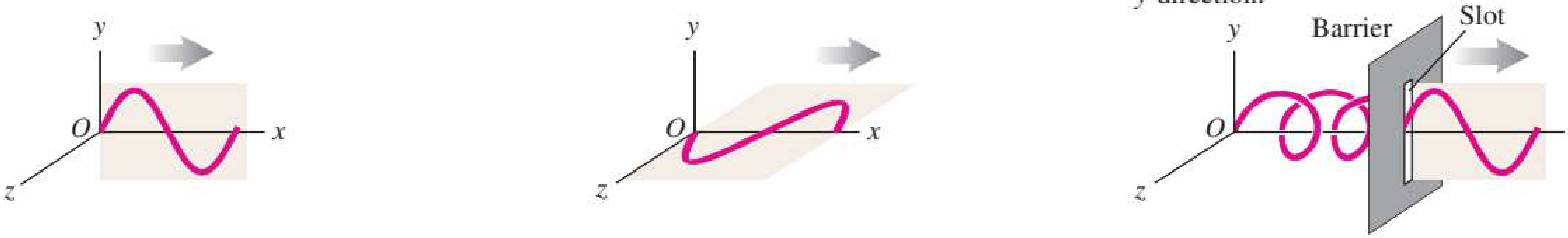
2. Polarization: further requirements on E_y and E_z

3. Example, analogy in mechanical wave, where E_z=0

(a) Transverse wave linearly polarized in the y-direction

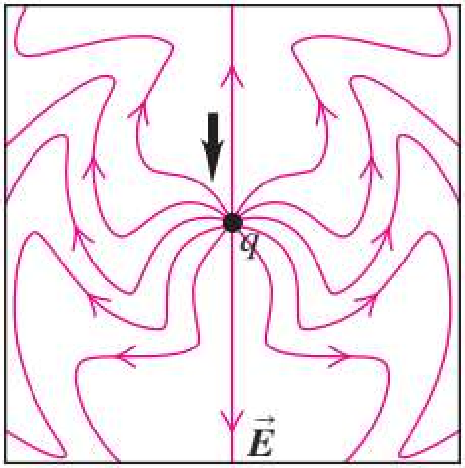
(b) Transverse wave linearly polarized in the z-direction

(c) The slot functions as a polarizing filter, passing only components polarized in the y-direction.



For cases of E_y=0, or E_z =0, or E_y/E_z = constant, which is actually the same if the coordinate system is rotated about x-axis, it is called a linear polarization.

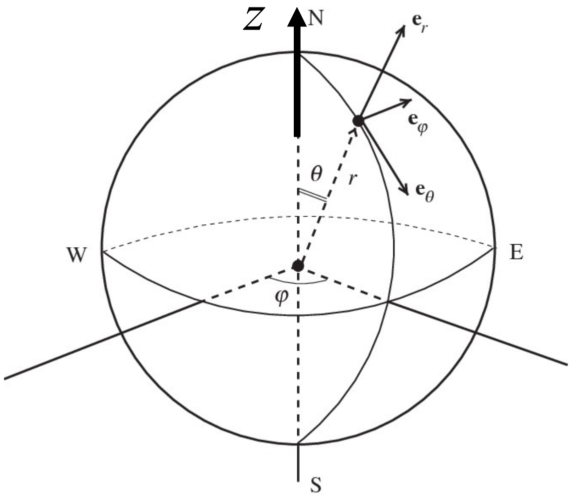
Polarization light source



A single oscillator is a (linearly) polarized source.

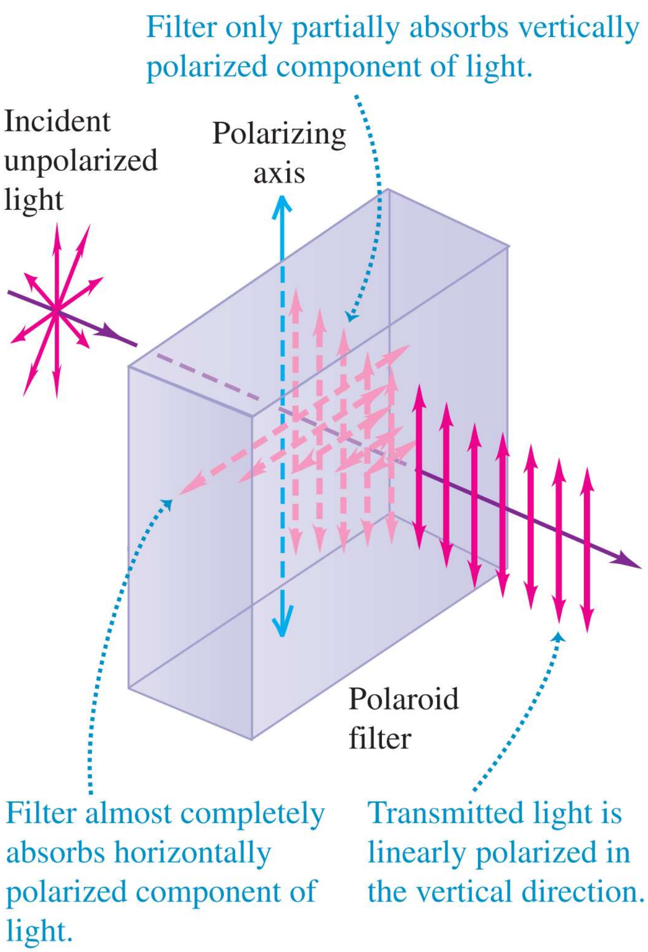
A light bulb is an unpolarized source.

An oscillator vibrates in z direction, the E field of light is in θ direction in spherical coordinate system. No r or φ components.



Many electrons vibrates randomly in any direction. The radiation is symmetric in direction. No polarization found in the light. Similar for **direct** sun light.

Polarizing filters



1. A polarization filter is such a device that only light polarized in one direction can path it. That direction is called

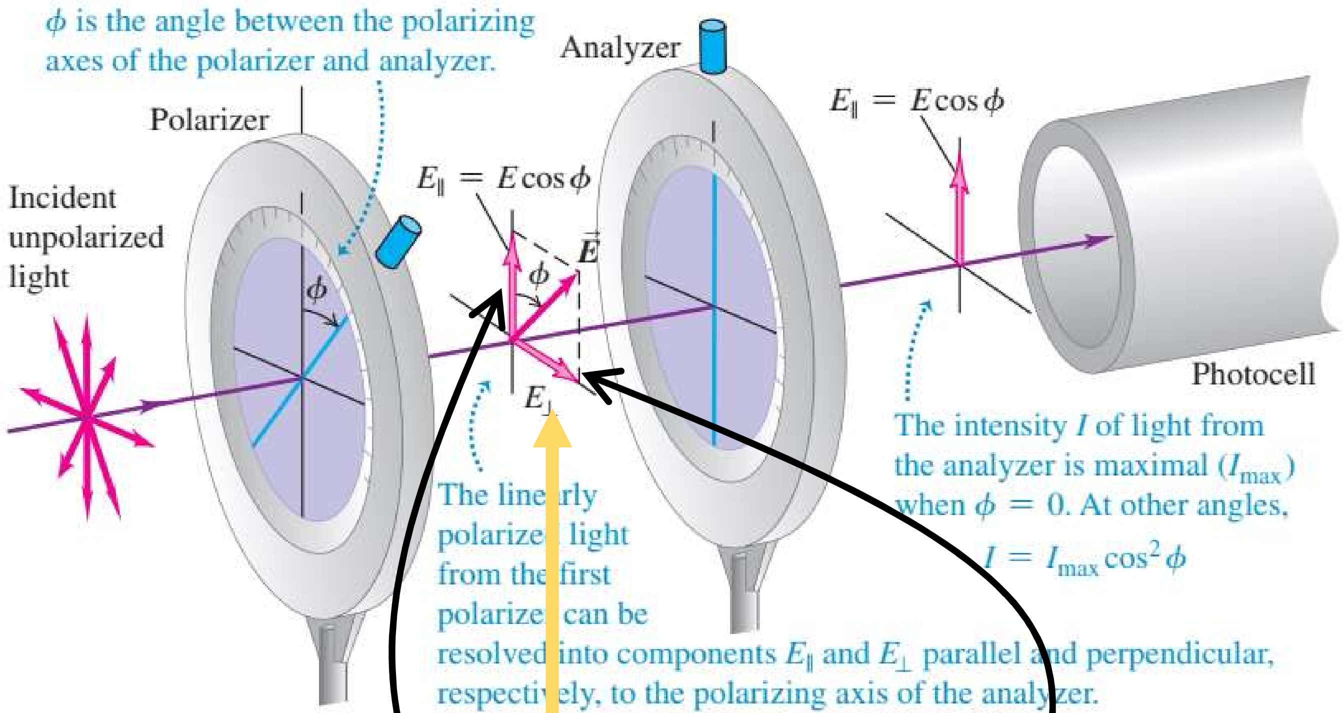
Polarizing axis

2. A natural light can be considered summation of light polarized in any direction (what do I mean by SUMMATION? Instead of superposition, related to the concept of coherence, will be answered in next topic)

3. After the filter only half of the intensity is kept. But the light is polarized now.

Why half?

Using the polarizing filters

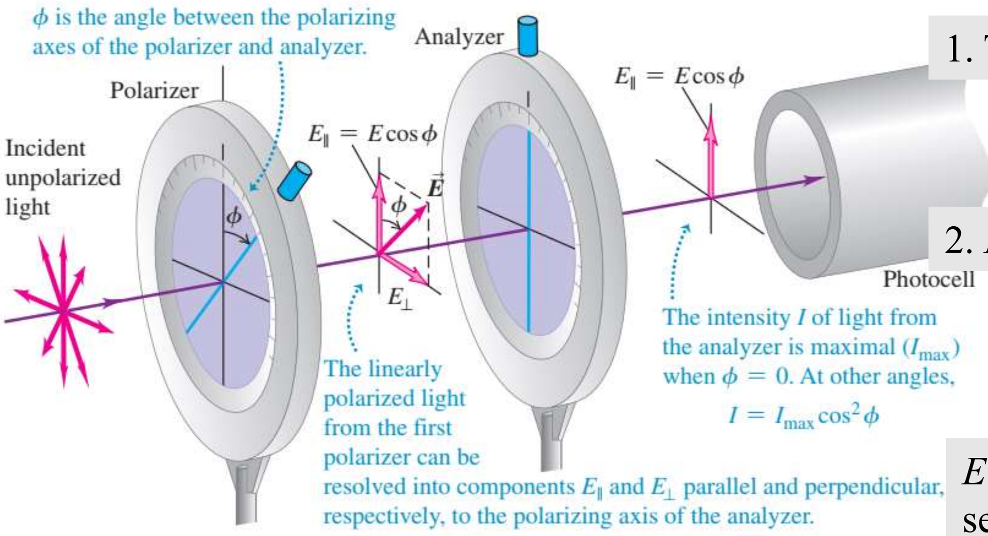


1. Using one polarizer to generated a polarized light, use another one (whose polarizing axis forms a φ angle with the first).

2. The polarized light can be considered superposition of two independent light. (superposition of electric field)

$$\vec{E} = E_y\hat{y} + E_z\hat{z}$$

Malus's law*



1. The intensity measured by the detector is proportional to

$$E \times H$$

2. H is proportional to E, so the intensity is proportional to

$$I \propto E^2 = (E_0 \cos\phi)^2$$

E is the field after the second polarization filter

φ is the angle between the two polarizing axis.

E_0 is the field between the two polarization filters

3. Malus's law (important)

$$I = I_{max} \cos^2 \phi$$

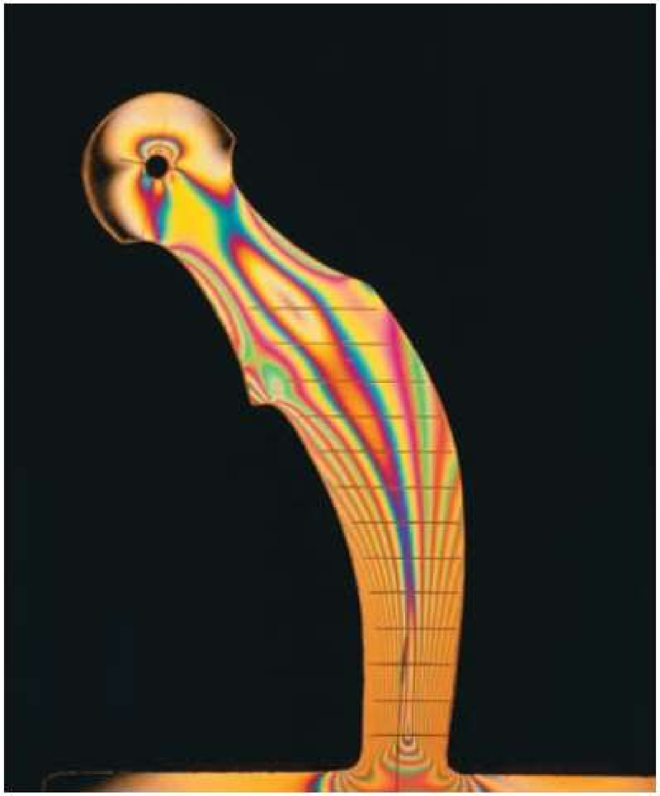
Maximum intensity is reached when φ=0 and intensity drops to 0 when φ=π/2.

Applications of polarization: 3D movies

Ugly bi-color 3D vs. polarized 3D screens

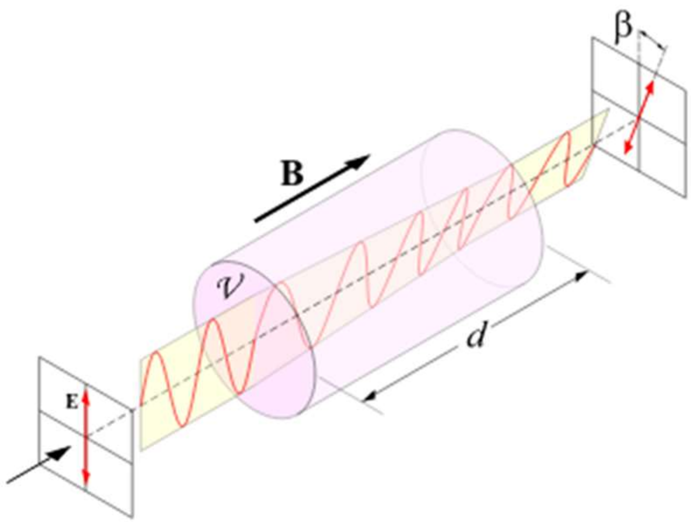
Birefringence introduced by stress: photoelasticity

33.30 This plastic model of an artificial hip joint was photographed between two polarizing filters (a polarizer and an analyzer) with perpendicular polarizing axes. The colored interference pattern reveals the direction and magnitude of stresses in the model. Engineers use these results to help design the actual hip joint (used in hip replacement surgery), which is made of metal.



It is not guaranteed any material will behave birefringence under stress

Magneto-optical Faraday’s effect



Magneto optical Faraday effect

The polarization direction rotated by MO crystal under longitudinal magnetic field.

It is not guaranteed material will rotate the polarization under magnetic field.

Polarized light microscope: Magneto-optical microscope

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Nucleation and propagation of thermomagnetic avalanches in thin-film superconductors (Review Article)

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