Polarizers

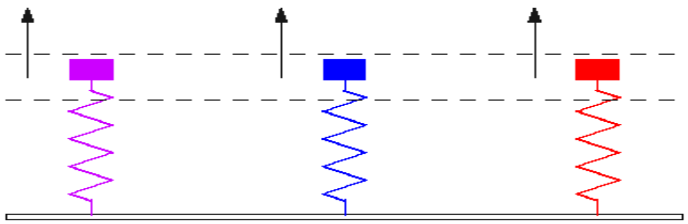
Reading – Shen and Kong – Ch. 3

Outline

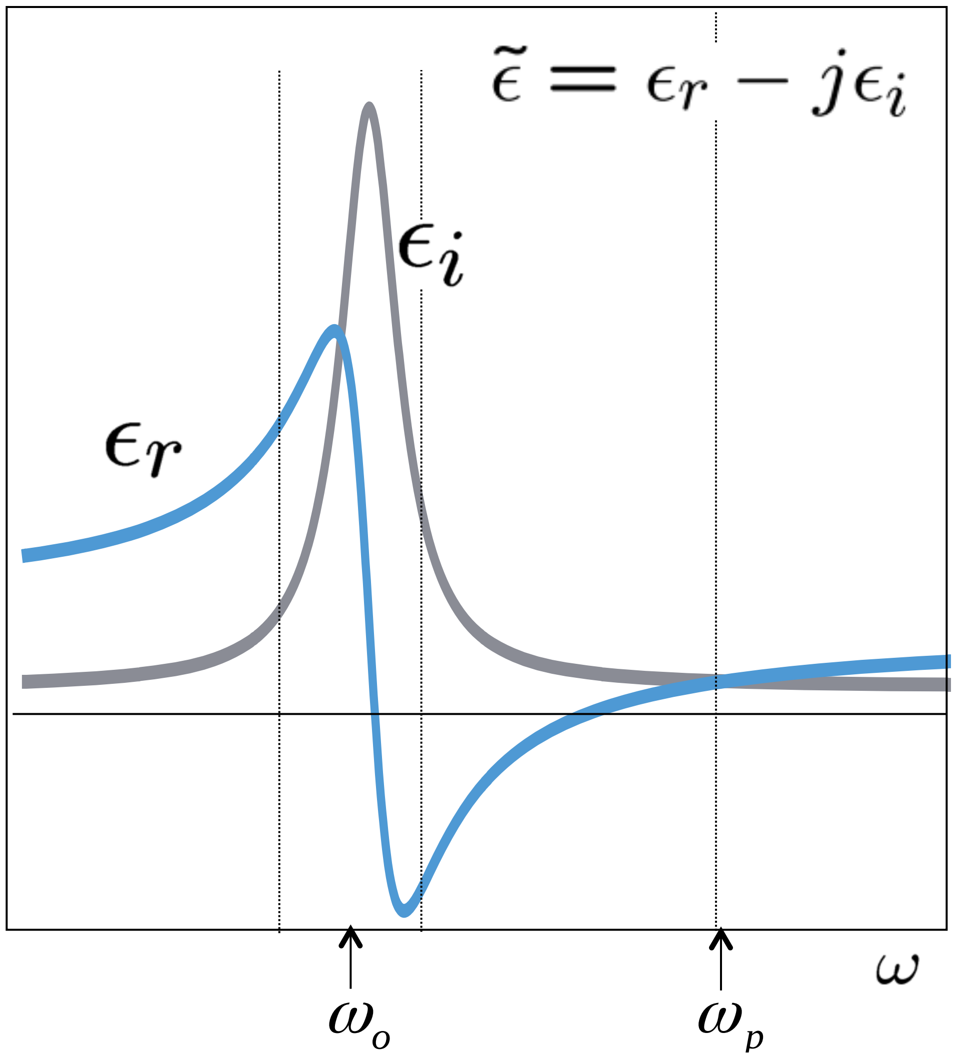
Review of the Lorentz Oscillator
Reflection of Plasmas and Metals

Polarization of Scattered Light
Polarizers
Applications of Polarizers

Microscopic Lorentz Oscillator Model



$$\epsilon = \epsilon_o \left(1 + \frac{\omega_p^2}{\omega_o^2 - \omega^2 + j\omega\gamma} \right)$$

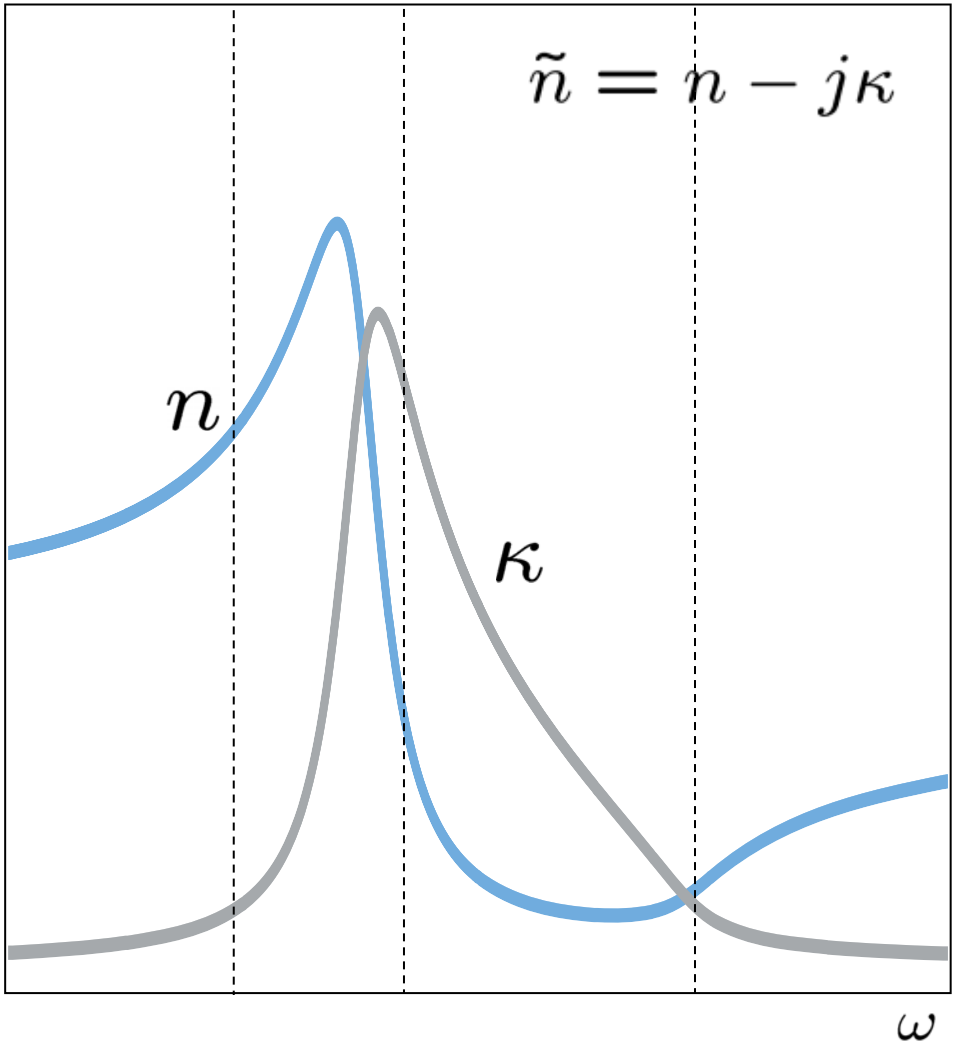


$$\omega_p^2 = \frac{Nq^2}{\epsilon_o m}$$

$$\omega_o^2 = \frac{k_{spring}}{m}$$

Complex Refractive Index

Note: we just changed notation from n to nr



$$\frac{\tilde{\epsilon}}{\epsilon_o} = \tilde{n}^2$$
$$= (n - j\kappa)^2$$
$$= n^2 - \kappa^2 - 2jn\kappa$$

$$\frac{\epsilon_{real}}{\epsilon_o} = n^2 - \kappa^2$$ (real)

$$\frac{\epsilon_{imag}}{\epsilon_o} = 2n\kappa$$ (imaginary)

$$v_p = \frac{1}{\sqrt{\mu\epsilon}} \qquad n \equiv \frac{c}{v_p} = \frac{\sqrt{\mu\epsilon}}{\sqrt{\mu_o\epsilon_o}} \approx \frac{\sqrt{\epsilon}}{\sqrt{\epsilon_o}}$$

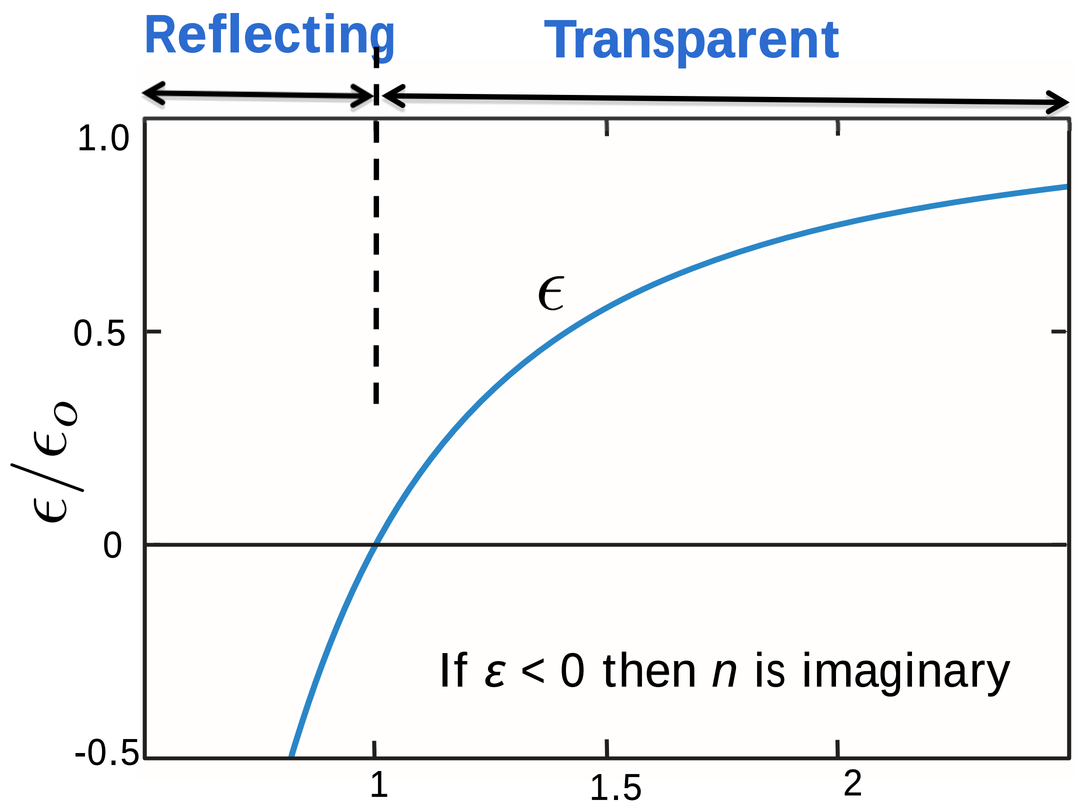
<u>Plasmas</u> (which we will assume to be lossless, $\gamma = 0$ *)*
... have no restoring force for electrons, $\omega_o = 0$

$$\epsilon = \epsilon_o \left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

$$\sqrt{\frac{\tilde{\epsilon}}{\epsilon_o}} = n - j\kappa$$

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \text{ for } \omega > \omega_p$$

$$\kappa = \sqrt{\frac{\omega_p^2}{\omega^2} - 1} \text{ for } \omega < \omega_p$$

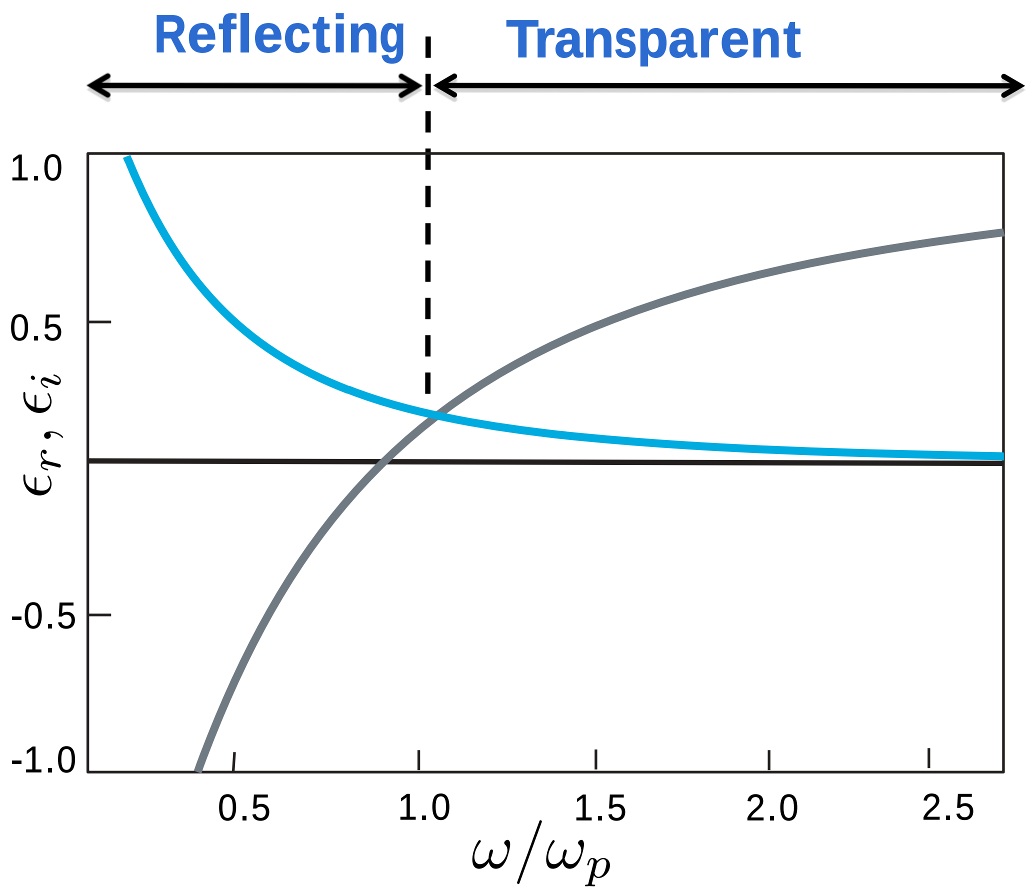


Metals are Lossy
... and have no restoring force for electrons $\omega_o \rightarrow 0$

$$\epsilon = \epsilon_o \left(1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}\right) = \epsilon_r - j\epsilon_i$$

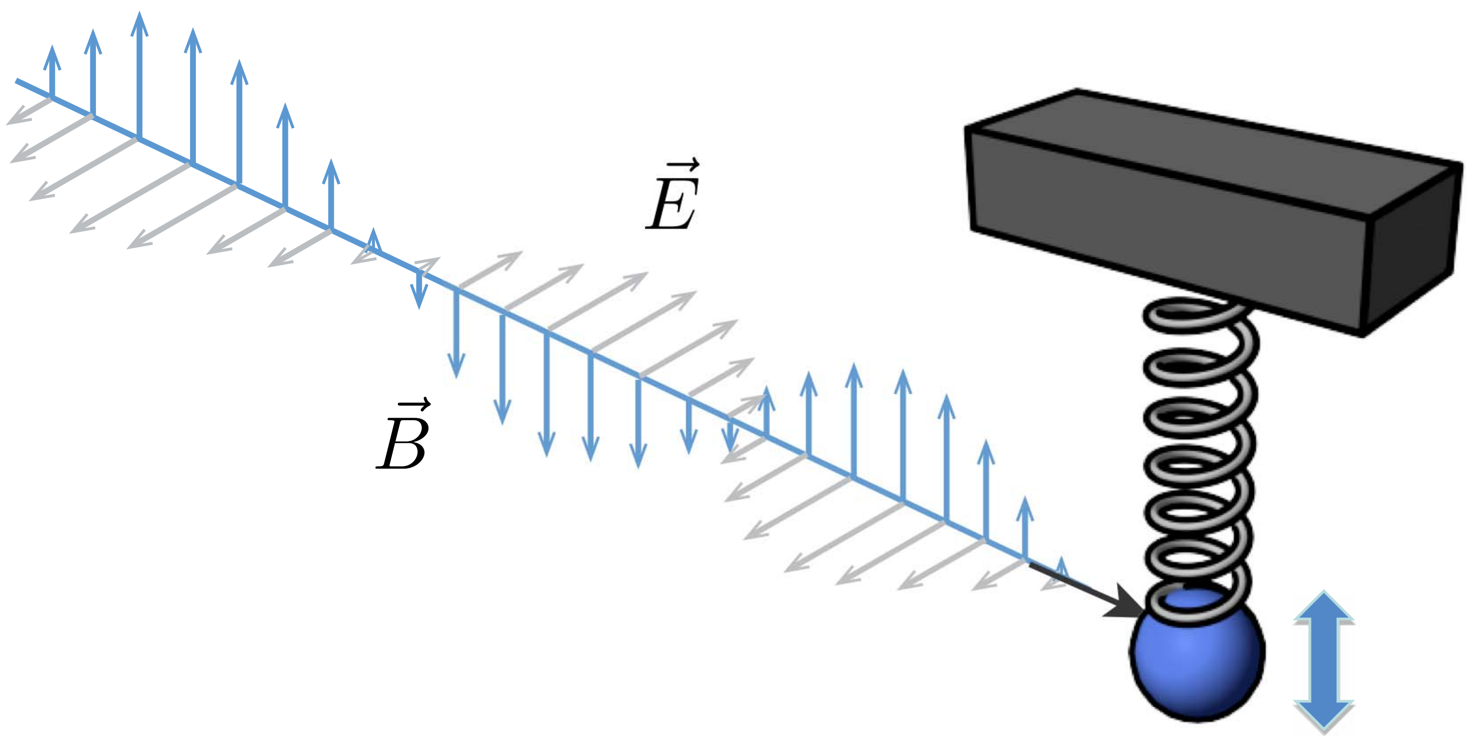
$$\epsilon_r = \epsilon_o \left(1 - \frac{\omega_p^2}{\omega^2 + \gamma^2}\right)$$

$$\epsilon_i = \epsilon_o \frac{\gamma\omega_p^2}{\omega(\omega^2 + \gamma^2)}$$

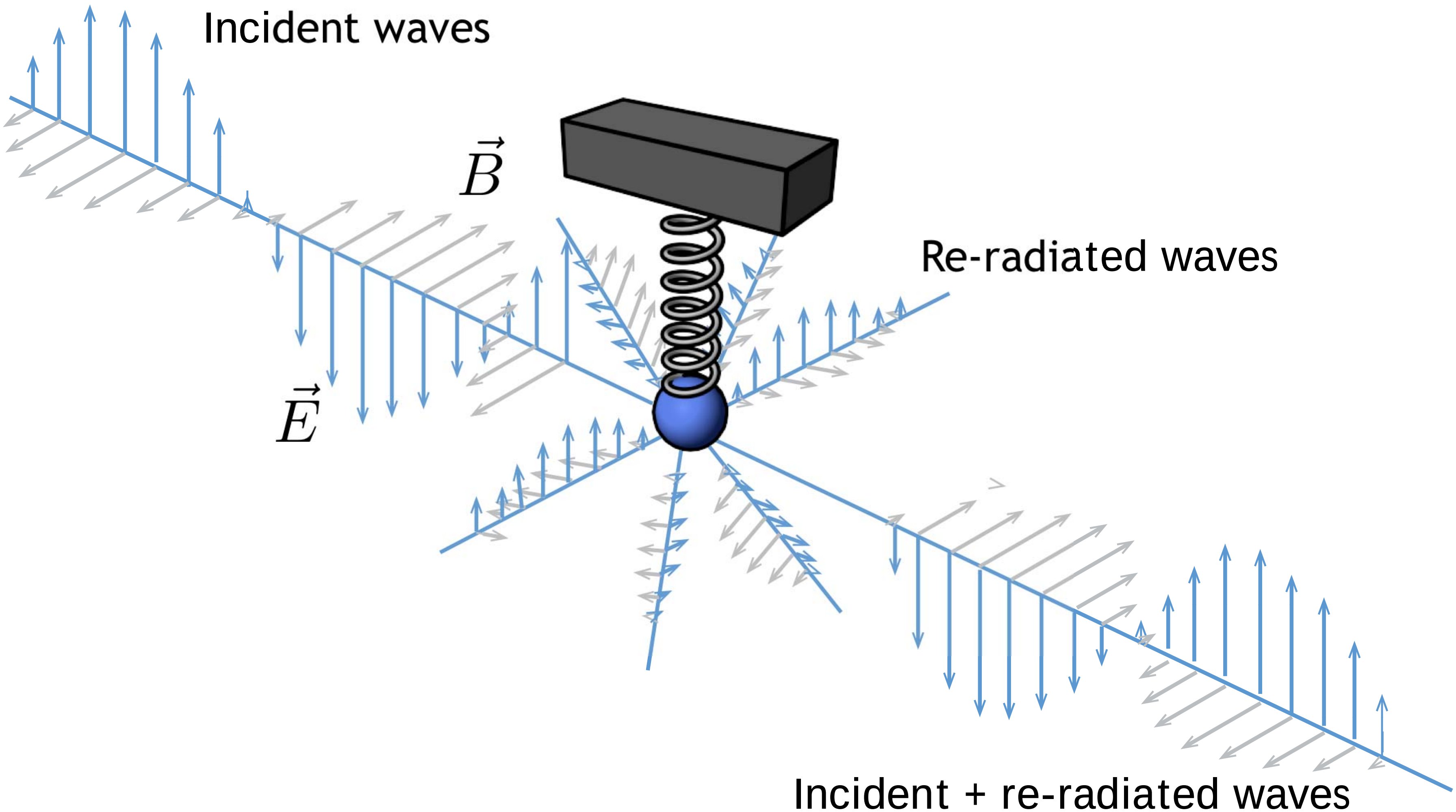


Give an argument that proves
that a truly invisible man would also be blind

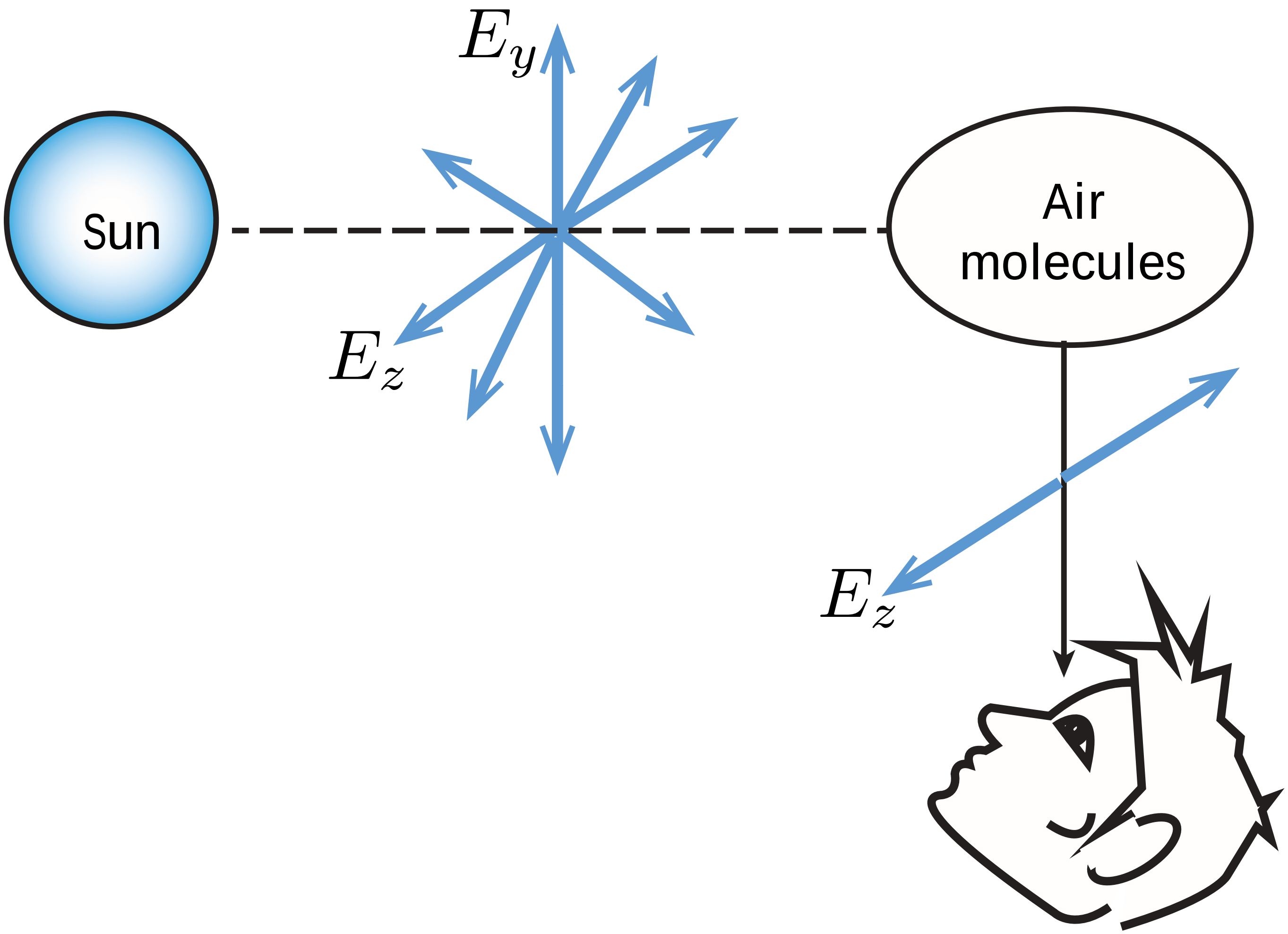
Effect of Sinusoidal E-field on a Hanging Charged Ball

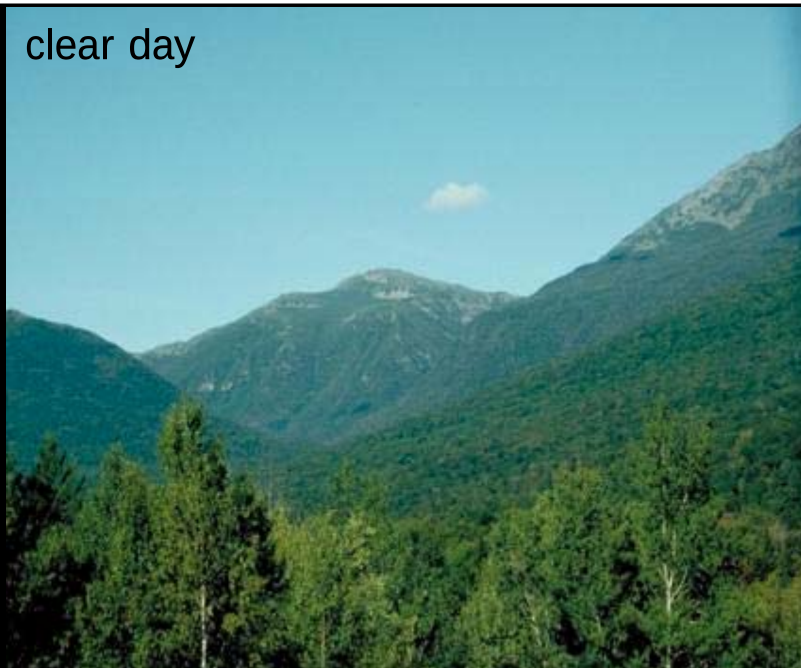


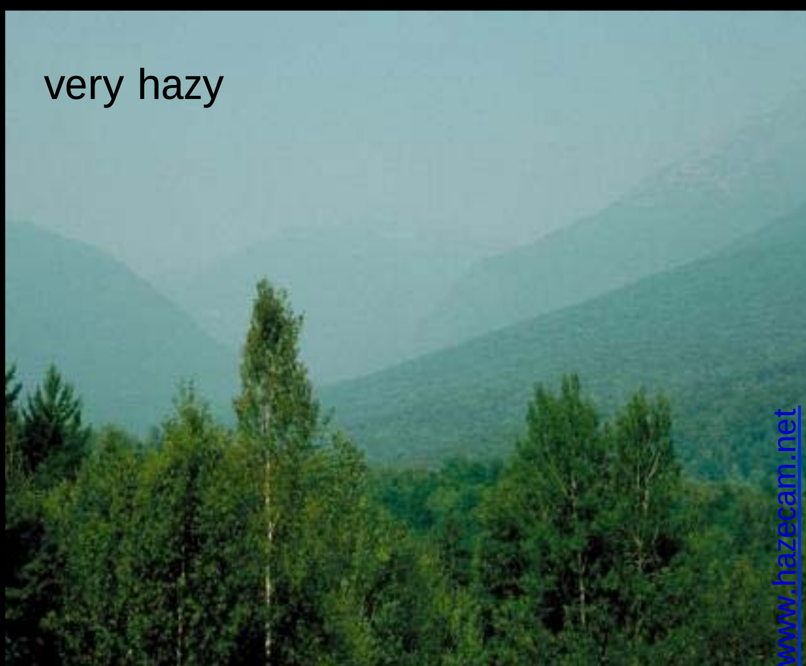
Radiation of a Moving Charge



Why is Skylight Polarized ?







Why did Mountains Turn Bluish ?

Because atmosphere preferentially scatters blue light

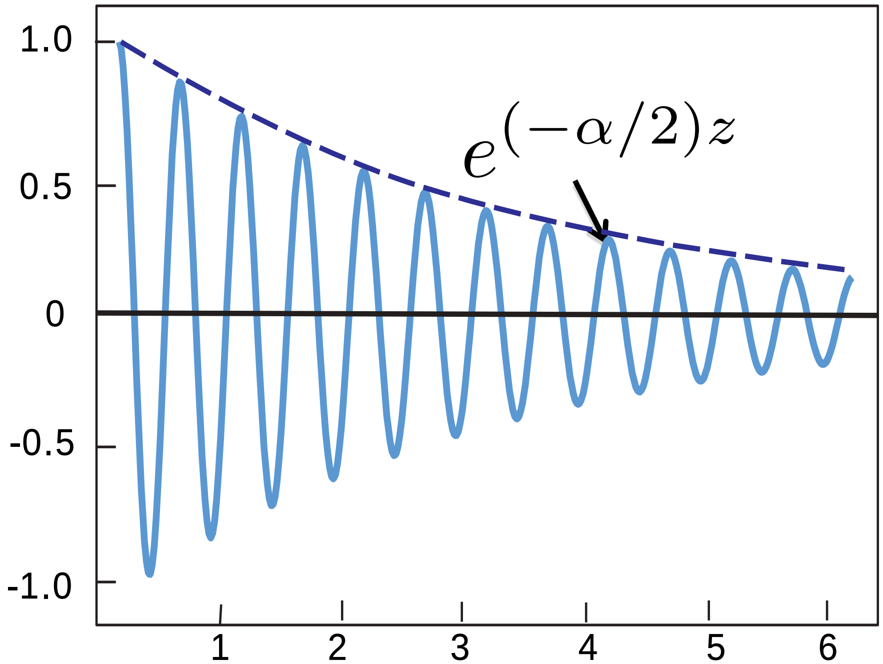
Behavior of Plane Waves in Lossy Materials

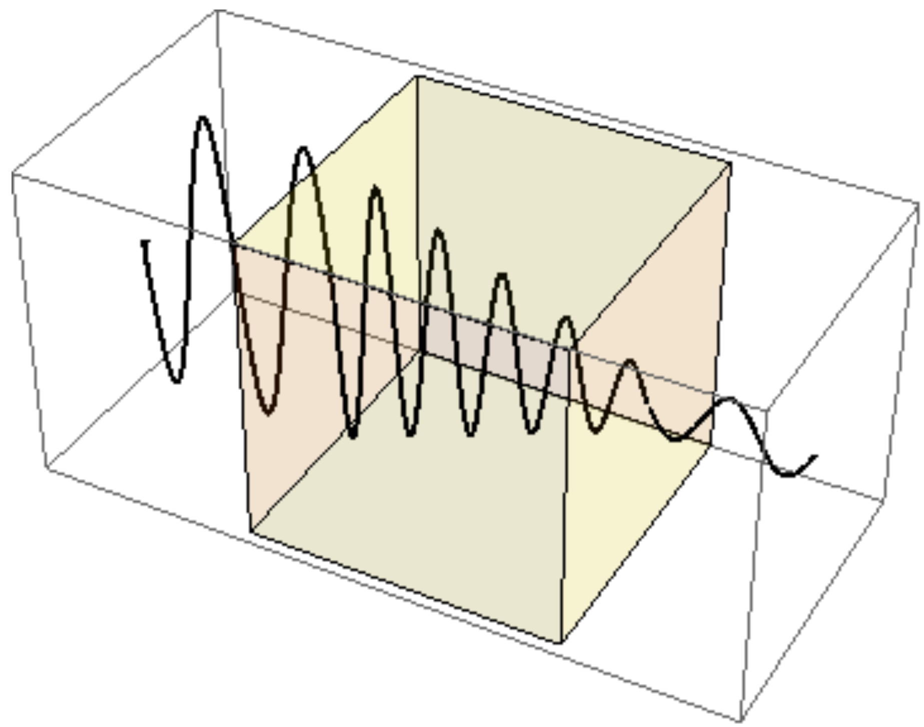
... can help us understand polarizers

$$E_y = Re\left(A_1 e^{j(\omega t - kz)}\right) + Re\left(A_2 e^{j(\omega t + kz)}\right)$$

$$E_y(z,t) = A_1 e^{-(\alpha/2)z} cos(\omega t - kz) + A_2 e^{+(\alpha/2)z} cos(\omega t + kz)$$

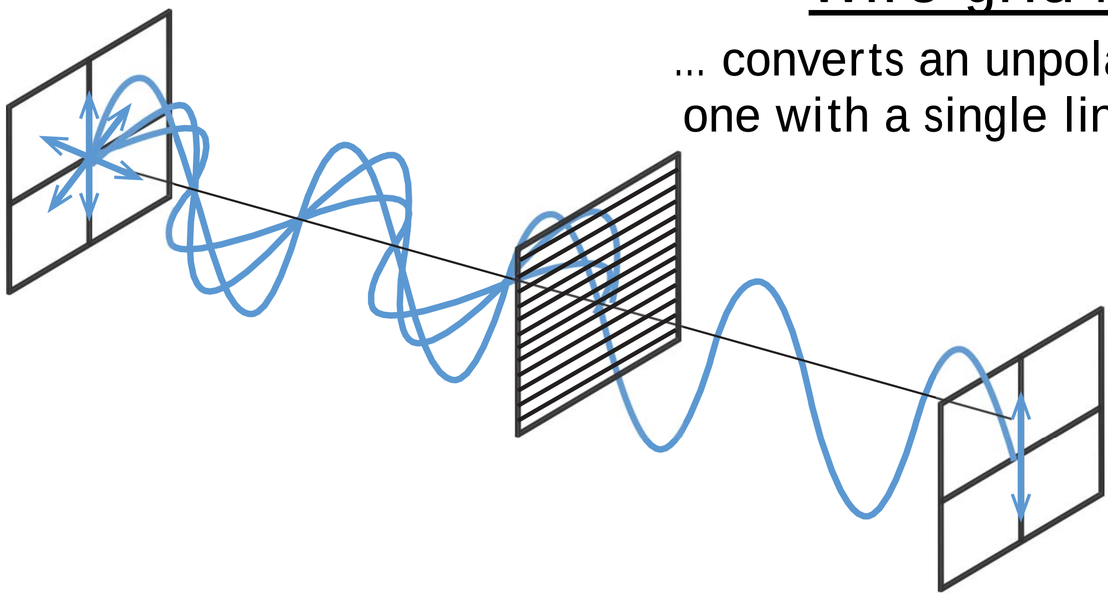
$$\alpha = \frac{2\kappa\omega}{c} = \frac{4\pi\kappa}{\lambda}$$





Wire-grid Polarizer

... converts an unpolarized beam into one with a single linear polarization



The *wire-grid polarizer* consists of a regular array of parallel metallic wires, placed in a plane perpendicular to the incident beam.

Electromagnetic waves with electric fields aligned parallel to the wires induce the movement of electrons along the length of the wires. Since the electrons are free to move, the polarizer behaves in a similar manner as the surface of a metal when reflecting light; some energy is lost due to Joule heating in the wires, and the rest of the wave is reflected backwards along the incident beam.

Electromagnetic waves with electric fields aligned perpendicular to the wires, the electrons cannot move very far across the width of each wire; therefore, little energy is lost or reflected, and the incident wave is able to travel through the grid.

Therefore, the transmitted wave has an electric field purely in the direction perpendicular to the wires, and is thus linearly polarized.

Image by zygzee http://www.flickr.com/photos/zygzee/324322772/ on flickr

Dichroism of Materials

dichroic glass jewelry

Dichroism in materials refers to the phenomenon when light rays having different polarizations are absorbed by different amounts.

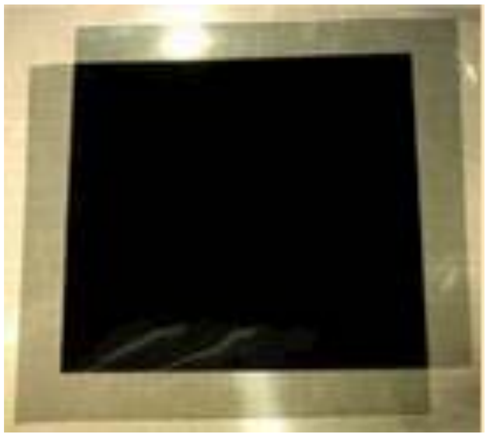
Polaroid sheet polarizers were developed by Edwin Land in 1929 using herapathite. Herapathite, or iodoquinine sulfate, is a chemical compound whose crystals are dichroic and thus can be used for polarizing light.

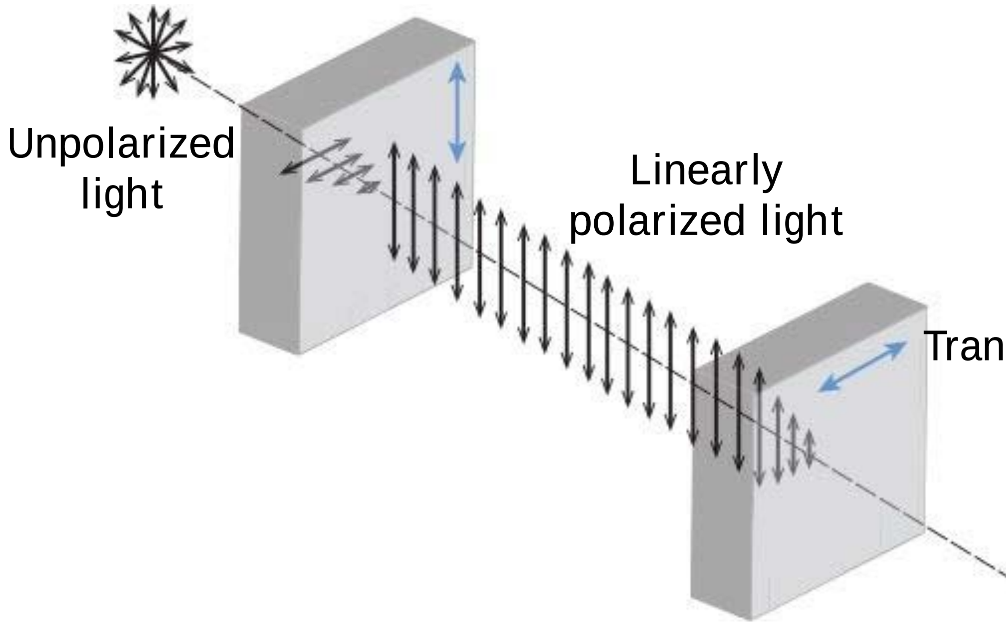
According to Edwin H. Land, herapathite was discovered In 1852 by William Herapath, a doctor in Bristol. One of his pupils found that adding iodine to the urine of a dog that had been fed quinine produced unusual green crystals. Herapath noticed while studying the crystals under a microscope that they appeared to polarize light.

Land in 1929 to construct the first type of Polaroid sheet polarizer. He did this by embedding herapathite crystals in a polymer instead of growing a single large crystal. Land established Polaroid Corporation in 1937 in Cambridge, Massachusetts. The company initially produced Polaroid Day Glasses, the first sunglasses with a polarizing filter.

Crossed Polarizers

In practice, some light is lost in the polarizer and the actual transmission of unpolarized light will be somewhat lower than this, around 38% for Polaroid-type polarizers.

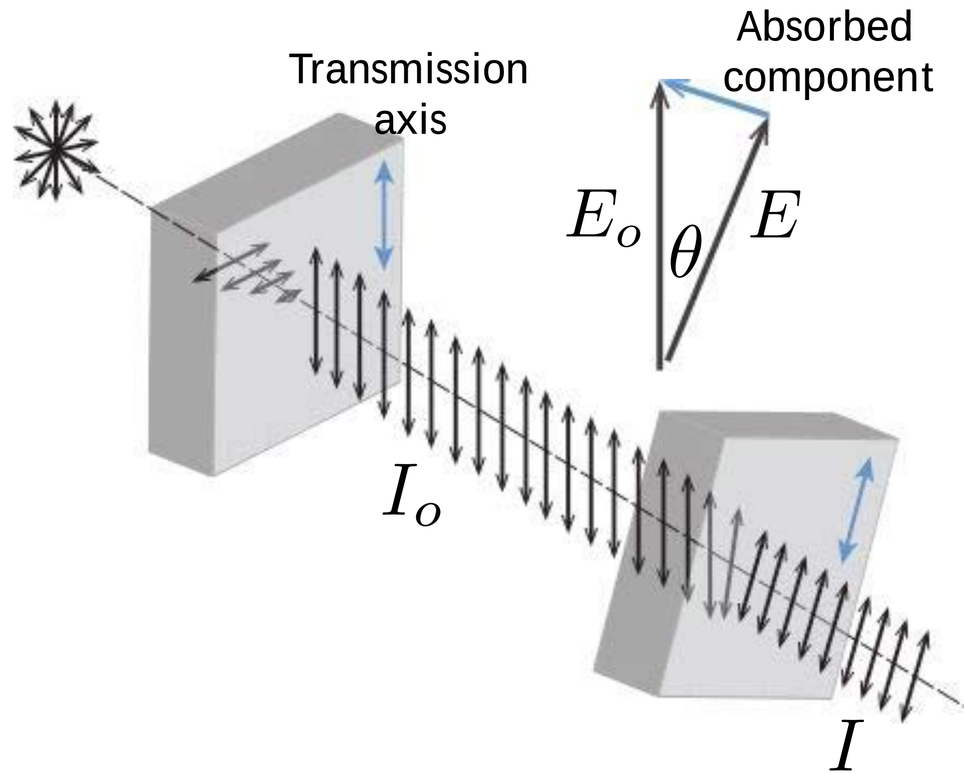




If two polarizers are placed one after another (the second polarizer is generally called an *analyzer*), the mutual angle between their polarizing axes gives the value of θ in Malus' law. If the two axes are orthogonal, the polarizers are *crossed* and in theory no light is transmitted, though again practically speaking no polarizer is perfect and the transmission is not exactly zero (for example, crossed Polaroid sheets appear slightly blue in color).

Real polarizers are also not perfect blockers of the polarization orthogonal to their polarization axis; the ratio of the transmission of the unwanted component to the wanted component is called the *extinction ratio*, and varies from around 1:500 for Polaroid to about $1:10^6$ for Glan-Taylor prism polarizers.

Malus' law, discovered experimentally by Etienne-Louis Malus in 1809, says that when a perfect polarizer is placed in a polarized beam of light, the intensity, *I*, of the light that passes through is given by



$$I = I_o cos^2\theta$$

Where I_o is the initial intensity, and θ is the angle between the light's initial plane of polarization and the axis of the polarizer.

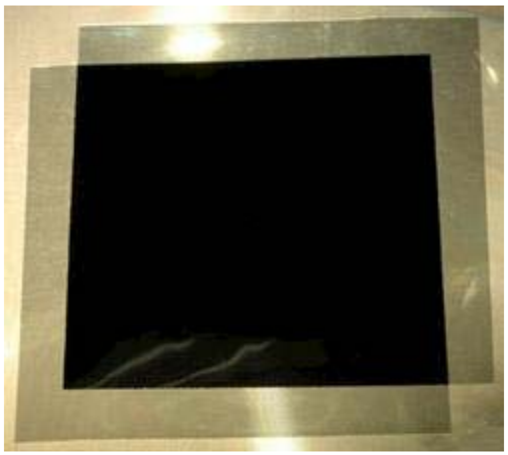
Question:

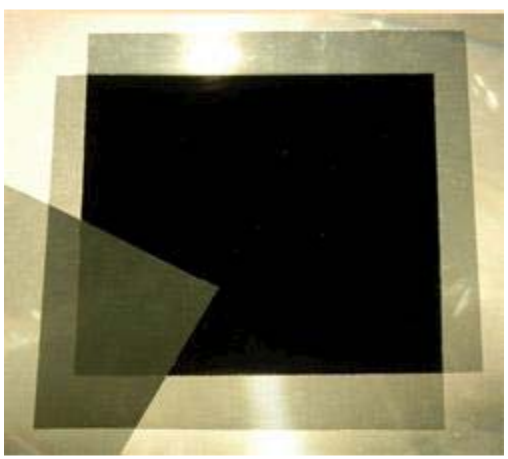
Two polarizing sheets have their polarizing directions parallel, so that the intensity of the transmitted light is maximized (with value I_{max}). Through what angle, θ, must either sheet be turned, if the transmitted light intensity is to drop to ½ I_{max} ?

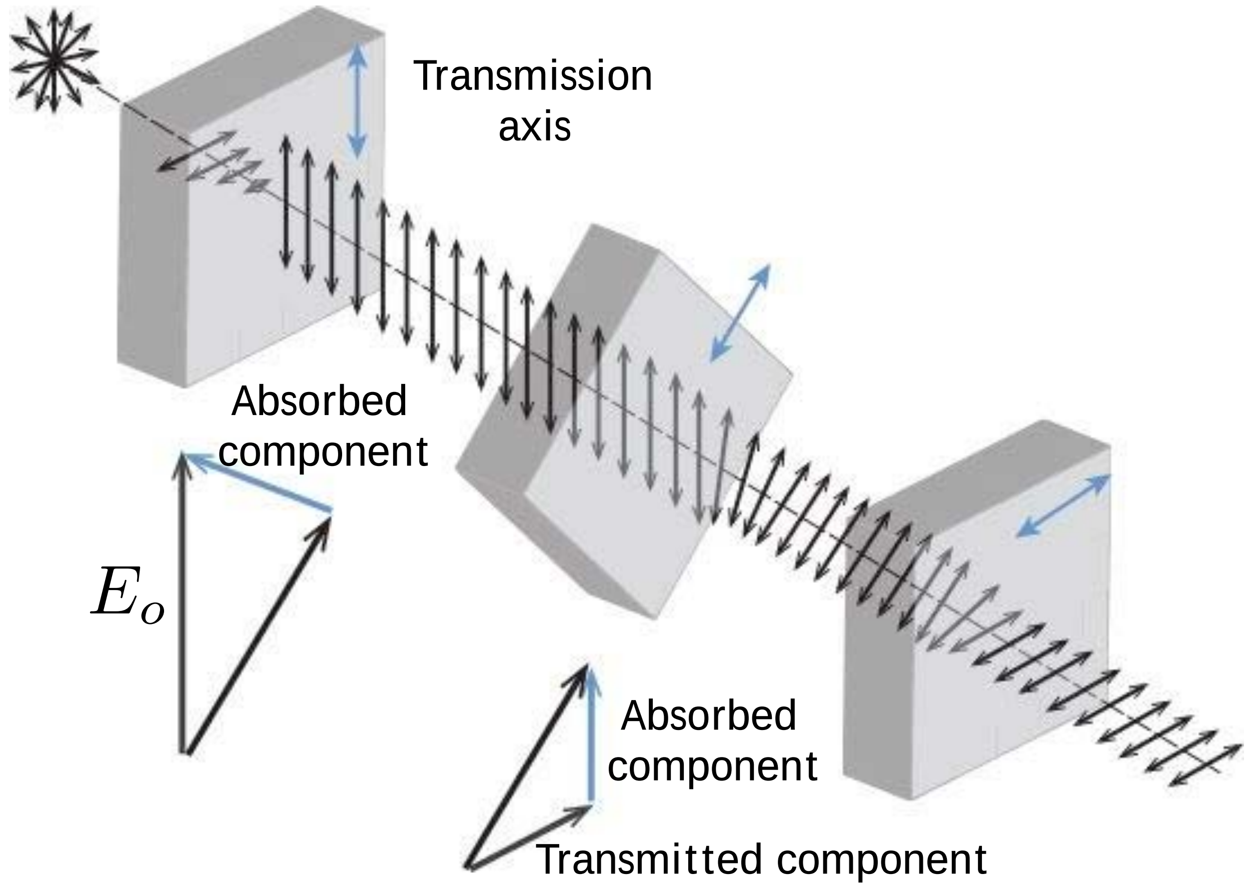
θ = ______________

Polarizer Puzzle

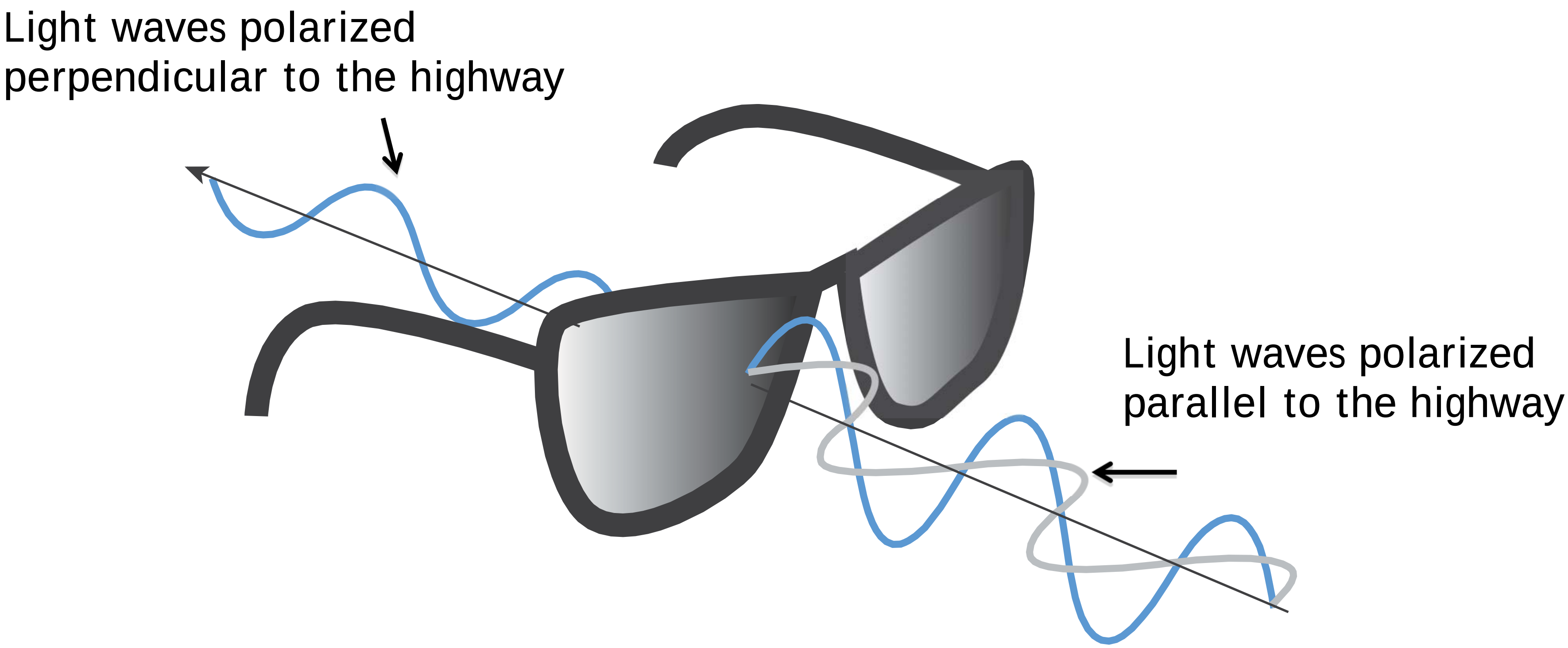
If crossed polarizers block all light, why does putting a third polarizer at 45° between them result in some transmission of light?







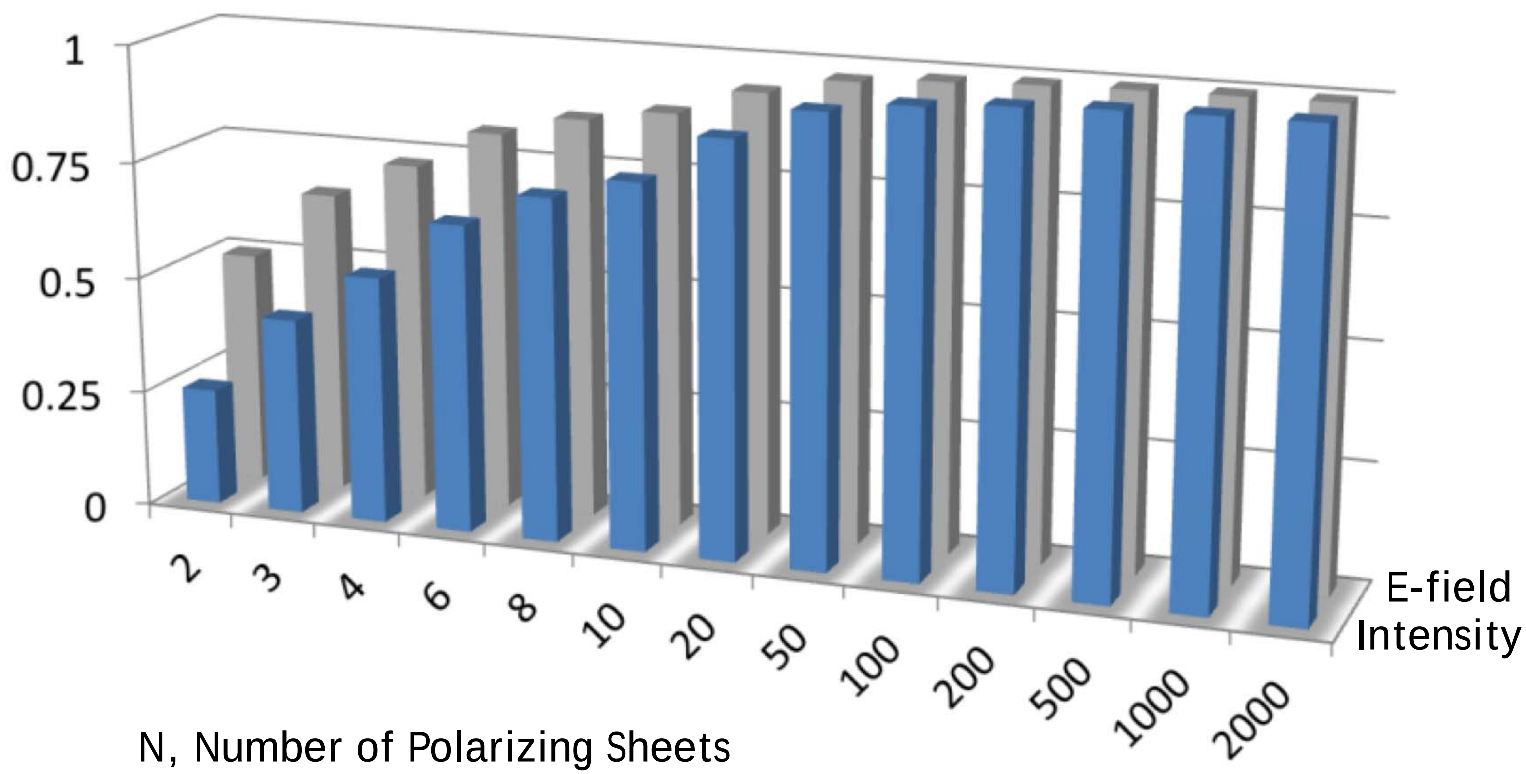
Polarized Sunglasses



Reduce glare off the roads while driving

Transmission Through a Stack of Polarizing Sheets

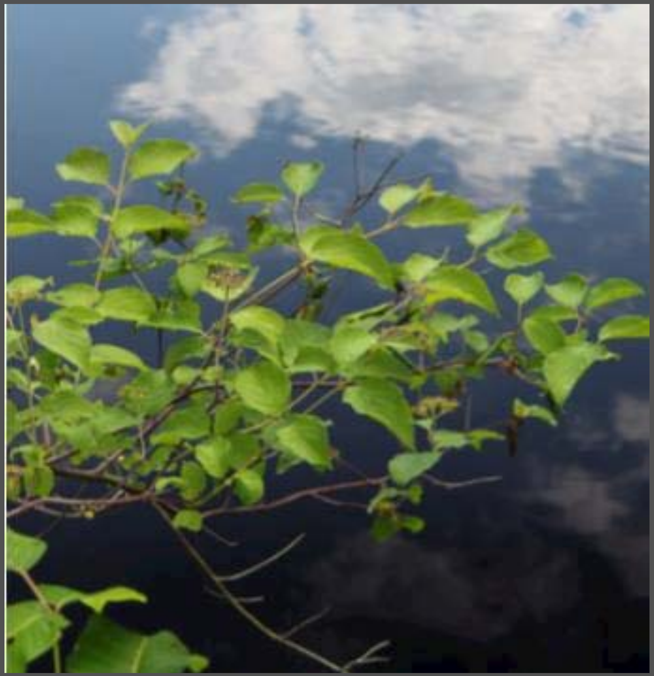
We assumed that these polarizers have no absorption



N, Number of Polarizing Sheets
Polarization of each is turned by π/(2N)
with respect to the previous one in a stack

Polarization Photography

Without Polarizer



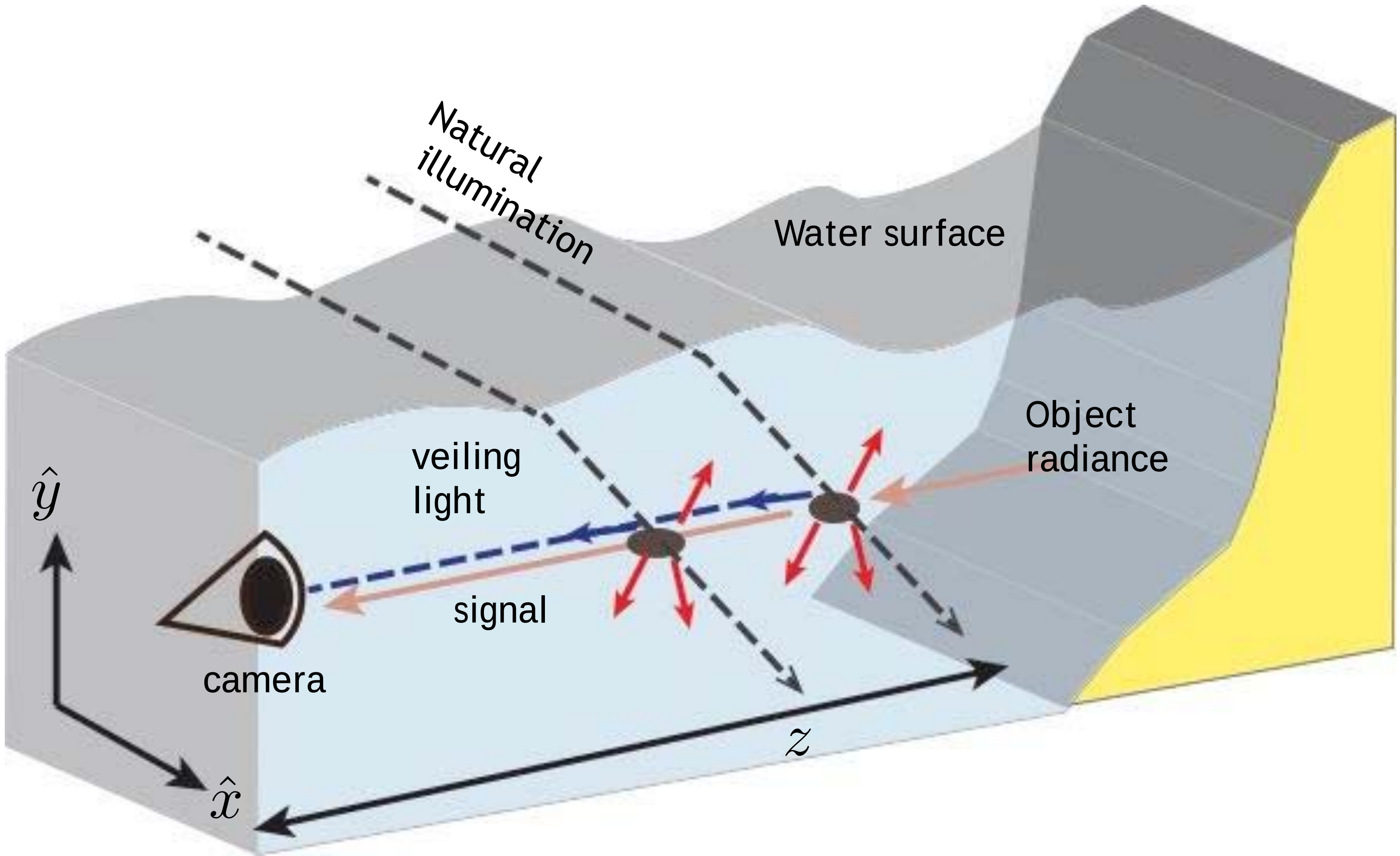
With Polarizer

- Reduces Sun Glare
- Reduce Reflections
- Darkens Sky
- Increase Color Saturation
- Reduces Haze

Polarization Photography : Reflections

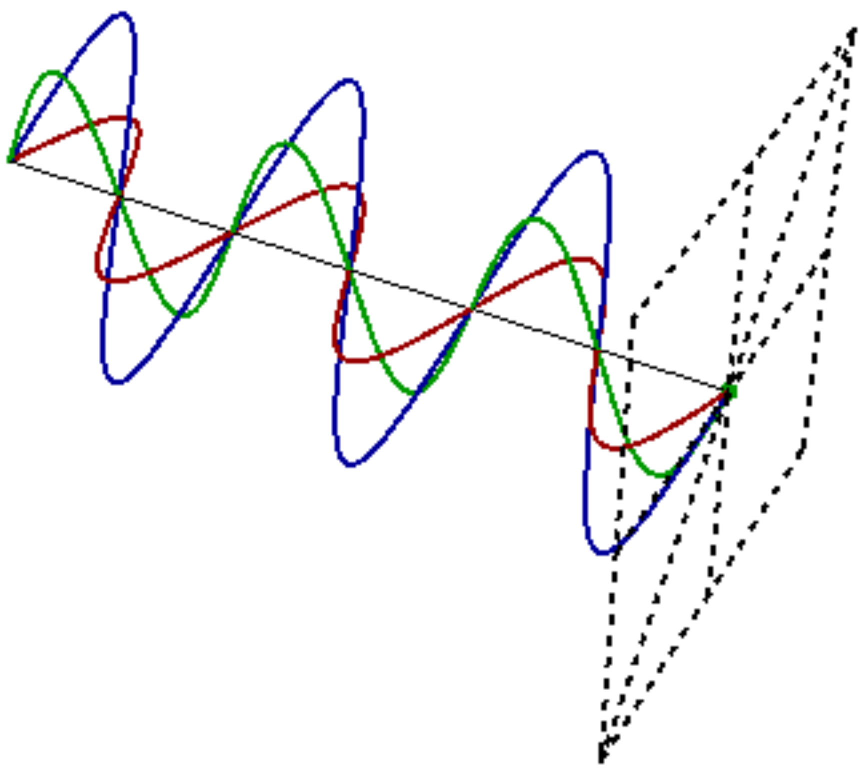
Reduce Reflections

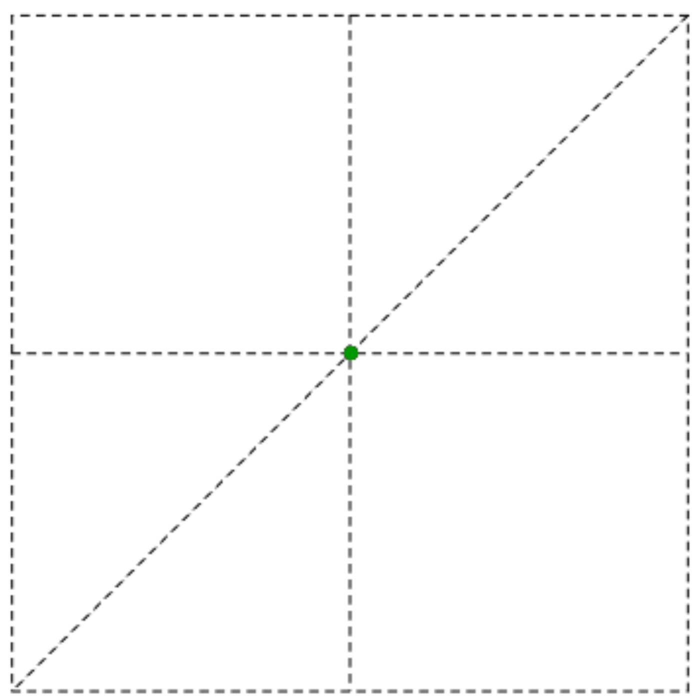
Polarization Photography : Underwater



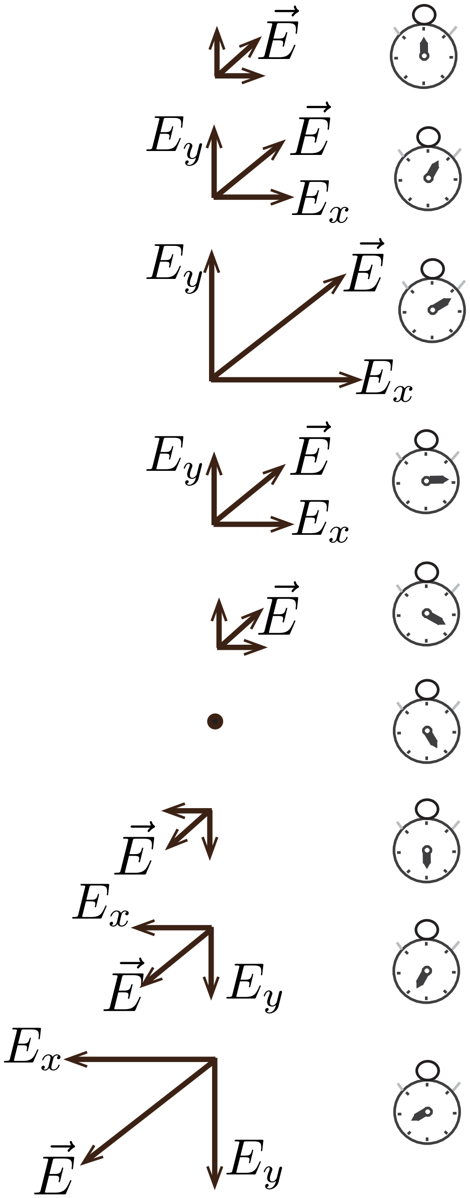
Superposition of Sinusoidal Uniform Plane Waves

$$\overline{E} = A\left(\cos(\omega t - kz)\,\widehat{y} + \cos(\omega t - kz)\,\widehat{x}\right)$$



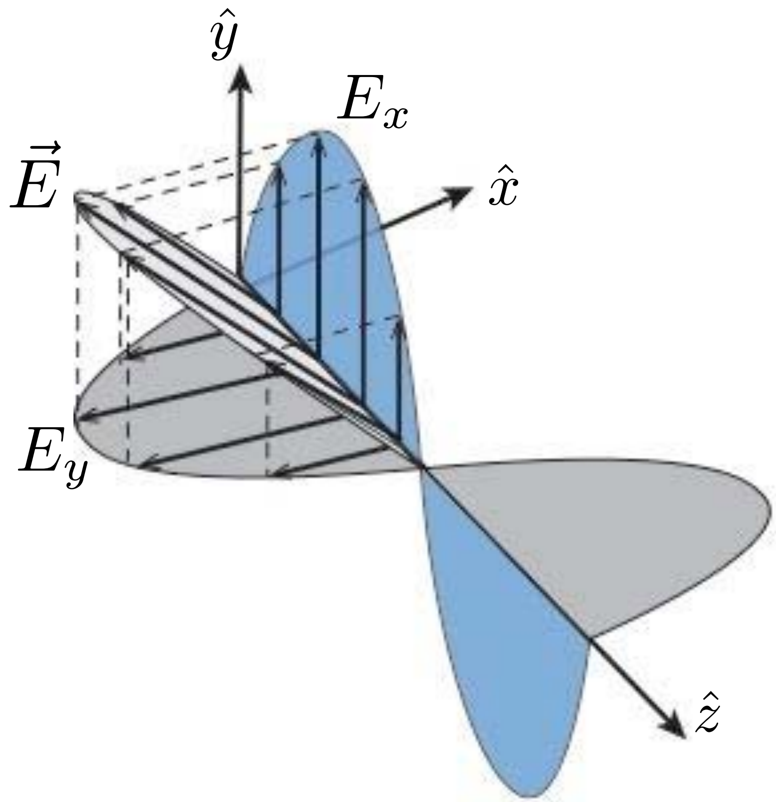


45° Polarization



$$E_x(z,t) = \hat{x} Re\left(\tilde{E}_o e^{j(\omega t - kz)}\right)$$

$$E_y(z,t) = \hat{y} Re\left(\tilde{E}_o e^{j(\omega t - kz)}\right)$$



The complex amplitude, $\tilde{E}_o$,is the same for both components.

Therefore E_x and E_y are always in phase.

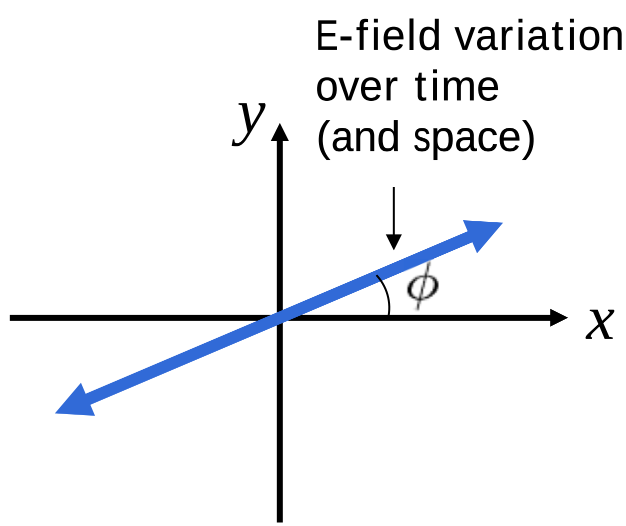
Where is the magnetic field?

Arbitrary-Angle Linear Polarization

$$E_x(z,t) = \hat{x}\, Re\{\tilde{E}_o\, cos(\phi)\, exp[j(\omega t - kz)]\}$$

$$E_y(z,t) = \hat{y}\, Re\{\tilde{E}_o\, sin(\phi)\, exp[j(\omega t - kz)]\}$$

Here, the *y*-component is **in phase** with the *x*-component, but has **different magnitude**.



Arbitrary-Angle Linear Polarization

$$E_x(z,t) = \hat{x}\, Re\{\tilde{E}_o\, cos(\phi)\, exp[j(\omega t - kz)]\}$$

$$E_y(z,t) = \hat{y}\, Re\{\tilde{E}_o\, sin(\phi)\, exp[j(\omega t - kz)]\}$$

Specifically:

0° linear (*x*) polarization: $E_y/E_x = 0$

90° linear (*y*) polarization: $E_y/E_x = \infty$

45° linear polarization: $E_y/E_x = 1$

Arbitrary linear polarization:

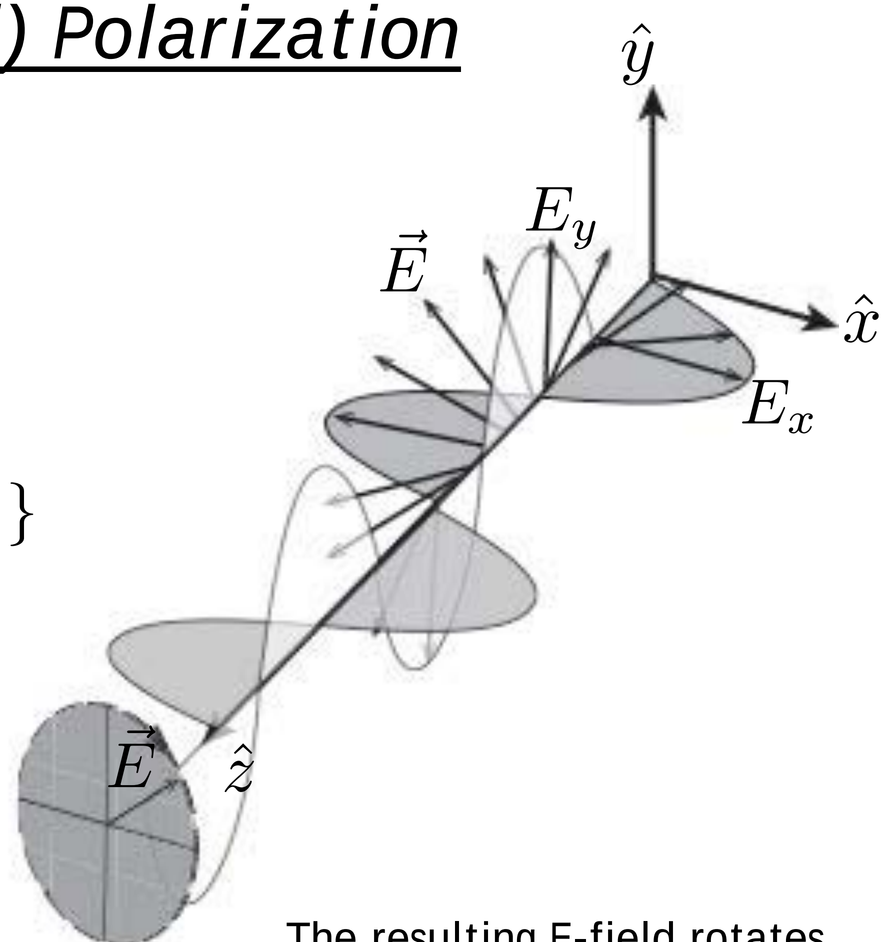
$$\frac{E_y(z,t)}{E_x(z,t)} = \frac{sin(\phi)}{cos(\phi)} = tan(\phi)$$

Circular (or Helical) Polarization

$$E_x(z,t) = \hat{x}\tilde{E}_o sin(\omega t - kz)$$
$$E_y(z,t) = \hat{y}\tilde{E}_o cos(\omega t - kz)$$

... or, more generally,

$$E_x(z,t) = \hat{x}Re\{-j\tilde{E}_o e^{j(\omega t - kz)}\}$$
$$E_y(z,t) = \hat{y}Re\{j\tilde{E}_o e^{j(\omega t - kz)}\}$$



The complex amplitude of the *x*-component is ***-j*** times the complex amplitude of the *y*-component.

***E**$_x$* and ***E**$_y$* are always **90˚ out of phase**

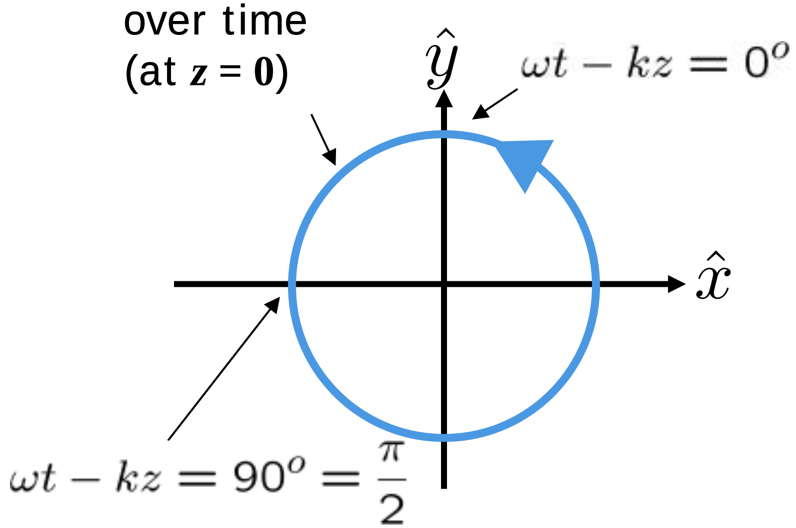
The resulting E-field rotates **counterclockwise** around the propagation-vector (looking along *z-axis*).

If projected on a constant z plane the E-field vector would rotate **clockwise !!!**

Right vs. Left Circular (or Helical) Polarization

$$E_x(z,t) = -\hat{x}\tilde{E}_o sin(\omega t - kz)$$
$$E_y(z,t) = \hat{y}\tilde{E}_o cos(\omega t - kz)$$

E-field variation over time (at $z = 0$)



... or, more generally,

$$E_x(z,t) = \hat{x}Re\{+j\tilde{E}_o e^{j(\omega t - kz)}\}$$

$$E_y(z,t) = \hat{y}Re\{j\tilde{E}_o e^{j(\omega t - kz)}\}$$

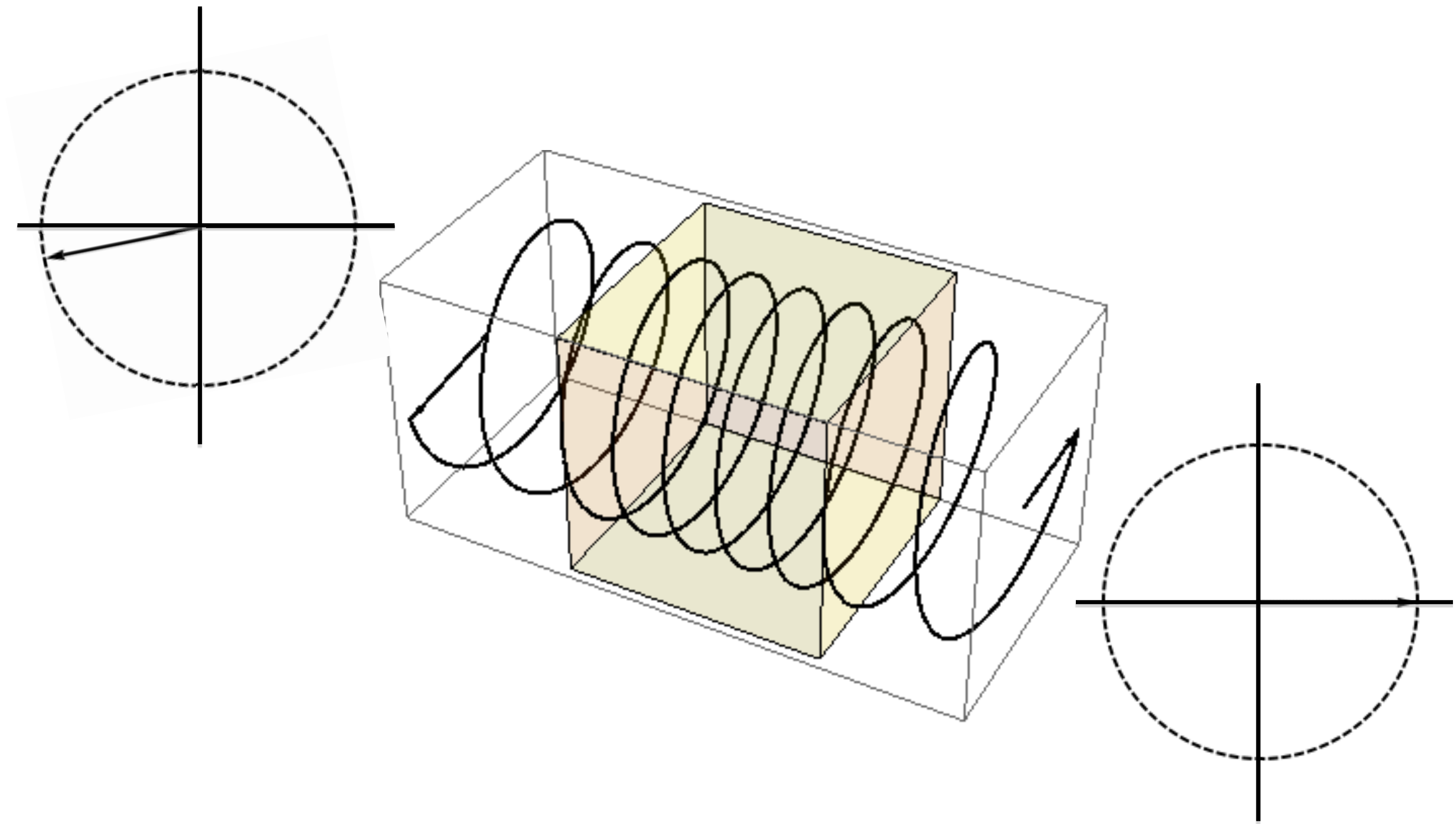
Here, the complex amplitude of the x-component is ***+j*** times the complex amplitude of the y-component.

So the components are always **90° out of phase, but in the other direction**

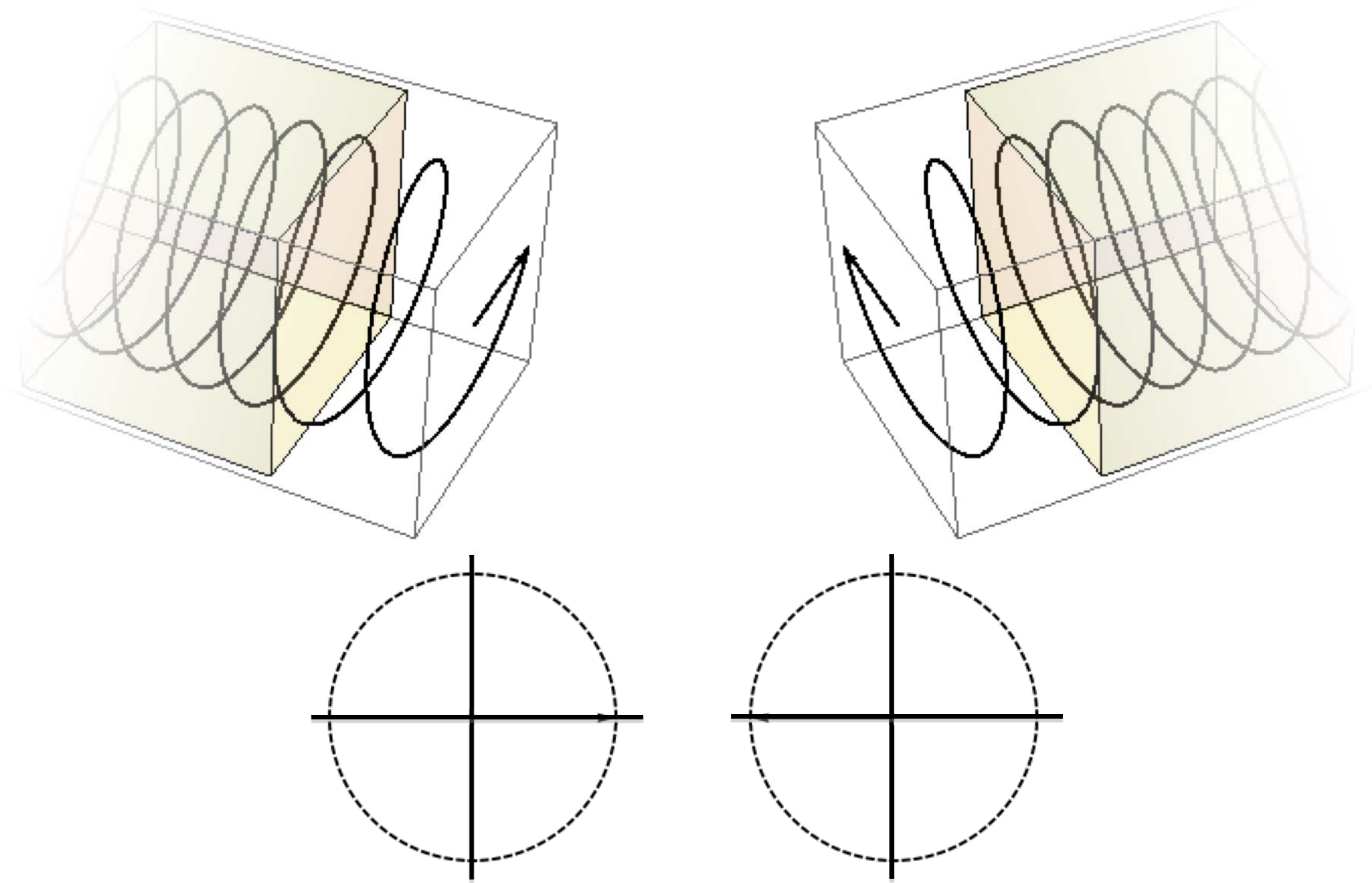
The resulting E-field rotates **clockwise** around the propagation-vector (looking along *z-axis*).

If projected on a constant z plane the E-field vector would rotate **counterclockwise !!!**

Effect of the refractive index of the medium on circularly polarized radiation



A linearly polarized wave can be represented as a sum of two circularly polarized waves

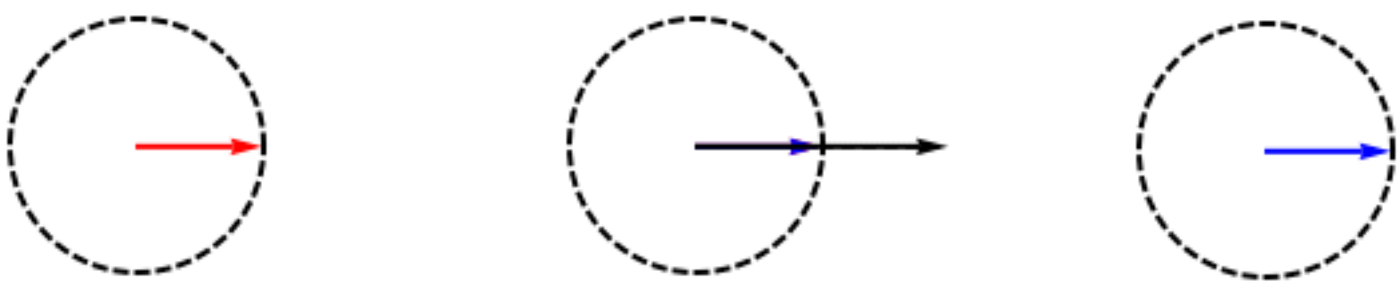


A linearly polarized wave can be represented as a sum of two circularly polarized waves

$$E_x(z,t) = \hat{x}\tilde{E}_o sin(\omega t - kz)$$
$$E_y(z,t) = \hat{y}\tilde{E}_o cos(\omega t - kz)$$

$$E_x(z,t) = -\hat{x}\tilde{E}_o sin(\omega t - kz)$$
$$E_y(z,t) = \hat{y}\tilde{E}_o cos(\omega t - kz)$$

CIRCULAR **LINEAR** **CIRCULAR**



*Unequal arbitrary-relative-phase components yield **elliptial polarization***

$$E_x(z,t) = \hat{x}E_{ox}cos(\omega t - kz)$$

$$E_y(z,t) = \hat{y}E_{oy}cos(\omega t - kz - \theta)$$

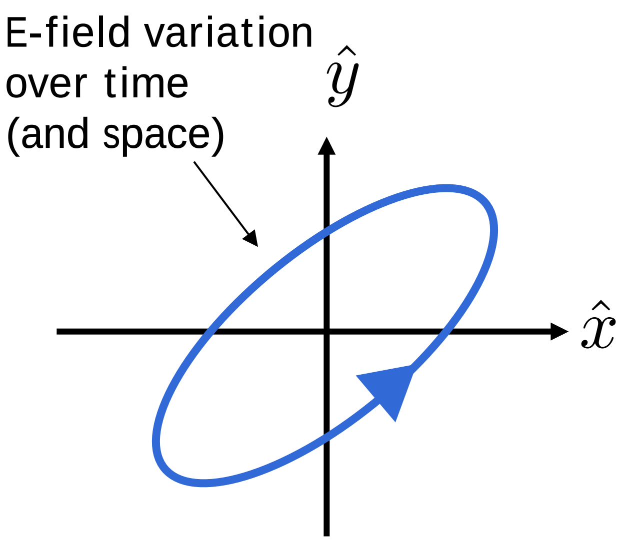
where $E_{ox} \neq E_{oy}$

... or, more generally,

$$E_x(z,t) = \hat{x}Re\{E_{ox}e^{j(\omega t - kz)}\}$$

$$E_y(z,t) = \hat{y}Re\{E_{oy}e^{j(\omega t - kz - \theta)}\}$$

... where $\tilde{E}_{ox}$ and $\tilde{E}_{oy}$ are arbitrary complex amplitudes



The resulting E-field can rotate clockwise or counter-clockwise around the k-vector (looking along k).

Key Takeaways

Plasmas – lossless, no restoring force
Metals – lossy, no restoring force
Dielectrics – lossy, with restoring force

EM Field of light causes vibration of the matter it interacts with. The mater is polarized along the same direction as the EM wave … leading to re-radiation of light by polarized matter. (This is why skylight is polarized.)

Malus' law: when a perfect polarizer is placed in a polarized beam of light, the intensity, *I*, of the light that passes through is given by

$$I = I_o cos^2\theta$$

where I_0 is the initial intensity, and θ is the angle between the light's initial plane of polarization and the axis of the polarizer.

EM Waves can be linearly, circularly, or elliptically polarized.

A linearly polarized wave can be represented as a sum of two circularly polarized waves.