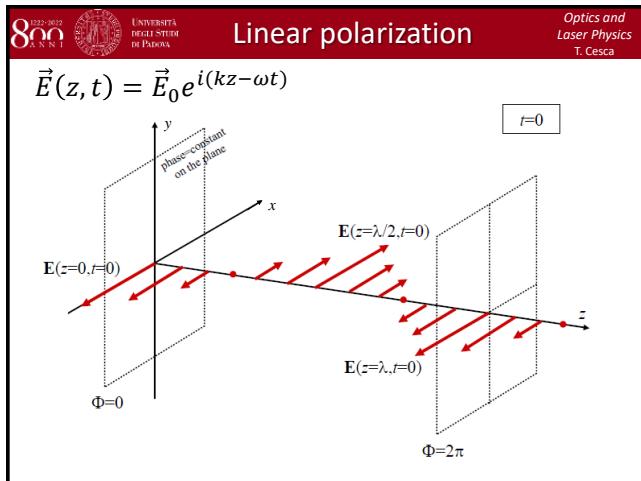


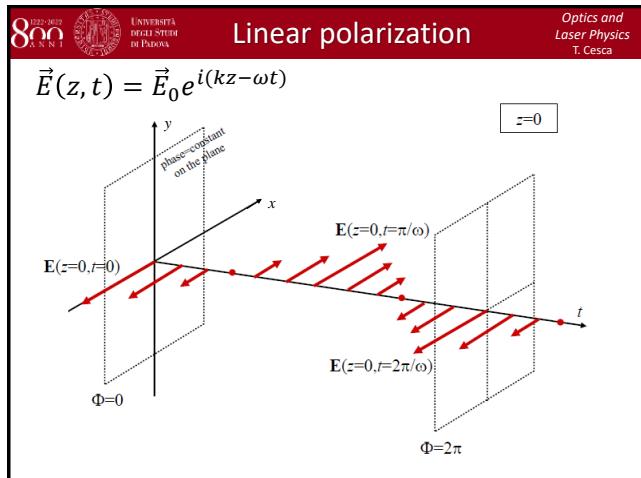
1 Lecture 2

Slide 1



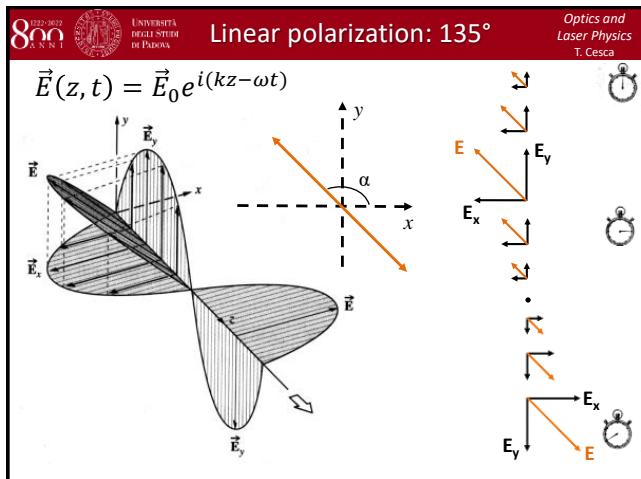
Now, we will talk about different kinds of polarization that we have. Let us start with the **linear polarization**: if the amplitude of the electric field is a real vector, we have a linear polarized wave, so the orientation of that vector represents the direction of polarization of your linearly polarized way. For instance, this is a snap of the electromagnetic way at time $t = 0$. For the different positions, the electric field is still oriented along the x axis.

Slide 2



This is the same wave at position $z = 0$ as a function of time. It is oscillating but maintains the oscillations along the x axis. Conventionally, when we talk about polarization we refer to the orientation of electric field.

Slide 3



For a linearly polarized way, the electric field always maintains the direction with respect of the axis. In this case, we have a linearly polarized wave forming an angle of 135° with respect to the x axis. The amplitude changes because it is still oscillating along this axis. To recap: if the vector that describes the electric field amplitude \vec{E}_0 is a real one, we have a linearly polarized wave and the angles define the orientation of the polarization.

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Circular polarization

Optics and Laser Physics
T. Cesca

$$\vec{E} = iE_{0x}e^{i(kz-\omega t)} + jE_{0y}e^{i(kz-\omega t+\delta)}$$

Right-circularly polarized (**R**): $E_{0x} = E_{0y}$ $\delta = -\frac{\pi}{2}$

Clockwise rotation if looking from the receiver

Let us suppose that we overlap two linearly polarized way in orthogonal orientations. We are introducing a phase shift δ to the y component with respect to the x component. We obtain a **right-circularly polarized** (**R**) wave:

$$E_{0x} = E_{0y} \quad \delta = -\frac{\pi}{2}$$

The vector that describe the polarization, does not maintain the same orientation along the plane, but the tick of the arrow is rotating in the **clockwise** direction. It is still again a convention-

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Circular polarization

Optics and Laser Physics
T. Cesca

$$\vec{E} = iE_{0x}e^{i(kz-\omega t)} + jE_{0y}e^{i(kz-\omega t+\delta)}$$

Left-circularly polarized (**L**): $E_{0x} = E_{0y}$ $\delta = +\frac{\pi}{2}$

Counter-clockwise rotation if looking from the receiver

If the phase shift is:

$$E_{0x} = E_{0y} \quad \delta = +\frac{\pi}{2}$$

we have a **counter-clockwise** rotation (looking from the receiver).

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Elliptical polarization

Optics and Laser Physics
T. Cesca

$$\vec{E} = iE_{0x}e^{i(kz-\omega t)} + jE_{0y}e^{i(kz-\omega t+\delta)}$$

Right-elliptically polarized (**R**): $E_{0x} \neq E_{0y}$ $\delta = -\frac{\pi}{2}$

Left-elliptically polarized (**L**): $E_{0x} \neq E_{0y}$ $\delta = +\frac{\pi}{2}$

Clockwise (counter-clockwise) rotation if looking from the receiver

If we start with two linearly polarized waves but with different amplitudes and we have a given shift, we will end up with:

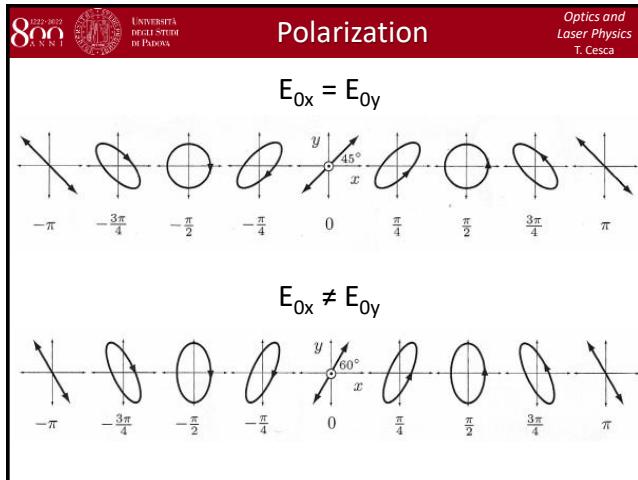
- **right-elliptically** polarized wave ((**R**)):

$$E_{0x} \neq E_{0y} \quad \delta = -\frac{\pi}{2}$$

- **left-elliptically** polarized wave ((**L**)):

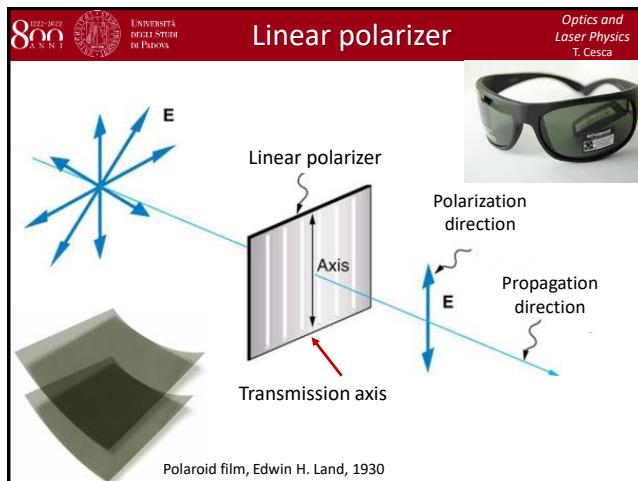
$$E_{0x} \neq E_{0y} \quad \delta = +\frac{\pi}{2}$$

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We can generalize this idea. In general, if we sum up two components, we can have different situations accordingly to the relative phase shift. If $E_{0x} \neq E_{0y}$, you cannot get circular polarized waves.

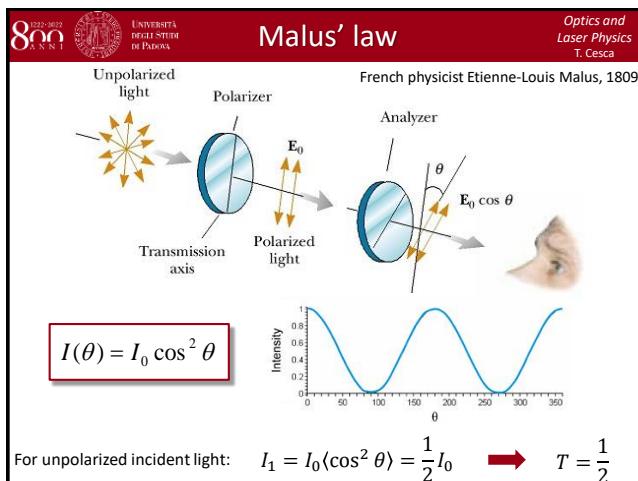
Slide 8



How is it physically possible to obtain a linear polarized wave? Let us consider the sun's light (which we consider *unpolarized* and that is represented by a convolution of arrows along all directions). A **Linear polarizer** gives you a linearly polarized wave along the **trasmission axis** (it blocks completely all the waves that are linearly polarized along the orthogonal direction of the trasmission axis).

In reality, the most cheap object is the **polaroid film**, which contains molecules which have an absorbtion which select highly to the orientation. They work perfectly as a linear polarizer. Sunglasses are made with polaroid films.

Slide 9



Let us suppose to have non polarized ligh, a polarizer and then we use the second polarizer as an analyzer (we rotate it with respect to the trasmission axis of the first polarizer). We are just making the projection of the beam along the polarizer. The component we obtain is $I(\theta) = I_0 \cos^2(\theta)$ (where θ is the relative angle between the two trasmission axis). The **Malus law** (1809) is:

$$I(\theta) = I_0 \cos^2(\theta)$$

which is the intensity coming from an analyzer. If we use just one polarizer, (**unpolarized beam**) we can describe this still using Malus law: in this case we are taking an average over all the possible orientations:

$$I = \frac{1}{2} I_0 \rightarrow T = \frac{1}{2}$$

Slide 10

Partial polarization

French physicist Etienne-Louis Malus, 1809

Unpolarized light → Polarizer → Polarized light E_0 → Analyzer → Linearly polarized light

$G_p = \frac{I_{POL}}{I_{POL} + I_{NON-POL}} = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$

Polarization degree (for partially linearly polarized light)

We can consider also the situation in we have a partial degree of linear polarization and we can quantify the **degree of polarization**, by using a polarizer. If you want to determine G experimentally, you have the analyzer rotating in front of your beam and you measure the maximum and the minimum.

Slide 11

Determine the **transmitted intensity** and the **final polarization state** of a beam of unpolarized light with intensity I_0 impinging on 3 coaxial ideal linear polarizers; the transmission axis of the first polarizer is vertical, at 45° for the second and horizontal for the third.

Unpolarized light I_0

$I_1 = T I_0 = \frac{1}{2} I_0$ $T = \frac{1}{2}$ Transmission factor of an ideal linear polarizer for unpolarized light

$I_2 = I_1 \cos^2 45$

$I_3 = I_2 \cos^2 45 = I_1 \cos^2 45 \cos^2 45 = \frac{1}{2} I_0 \left(\frac{\sqrt{2}}{2}\right)^2 \left(\frac{\sqrt{2}}{2}\right)^2 = \frac{I_0}{8}$

If we remove the second polarizer, the transmitted intensity is 0!

Let us try to make an example using the linearly polarized beam.

Slide 12

A real linear polarizer with vertical transmission axis is made in such a way that it can transmit a fraction $f = 0.248$ of the intensity transmitted for vertical polarization when a beam with horizontal polarization is impinging on it.

Determine the **degree of polarization** of the output beam from this polarizer when the input beam is unpolarized.

Unpolarized light I_0

$I_y = T I_0 = \frac{1}{2} I_0$

since the input beam is unpolarized

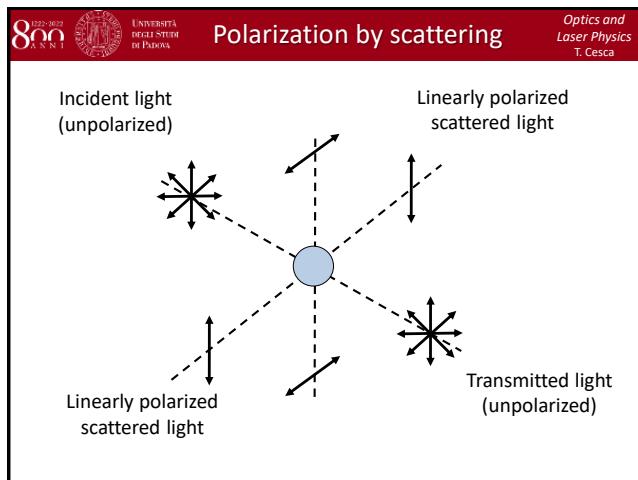
$I_x = f I_y = 0.248 I_y = \frac{0.248}{2} I_0$ according to the text of the exercise

$I_{MAX} = I_y = \frac{1}{2} I_0 \quad \rightarrow \quad G_p = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}} = \frac{I_y - 0.248 I_y}{I_y + 0.248 I_y} = 0.603$

$I_{MIN} = I_x = \frac{0.248}{2} I_0 \quad 60.3\%$

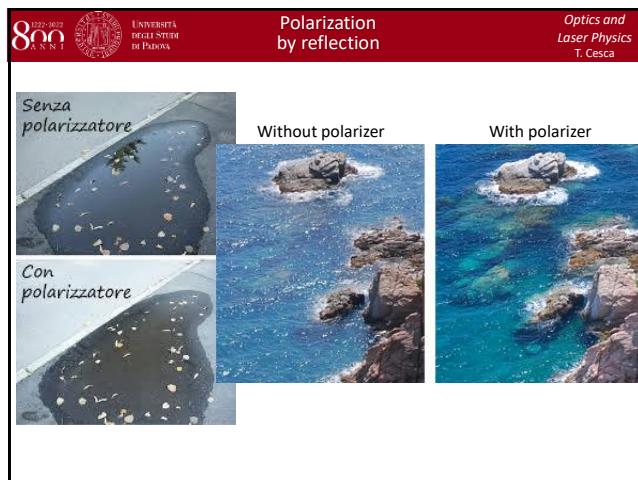
Let us do a different exercise.

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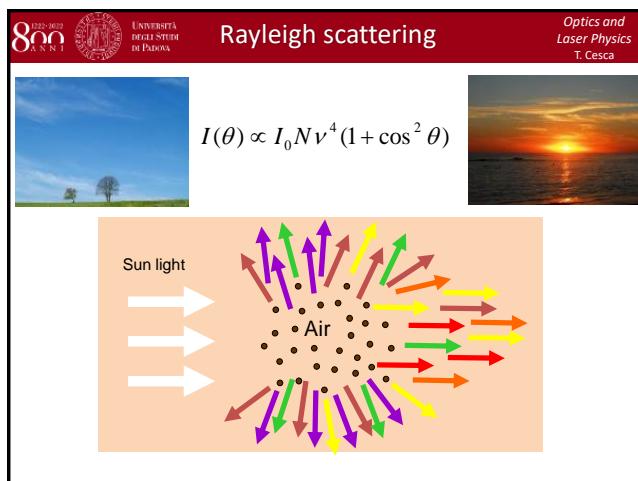
In reality, when is it possible to get a polarized beam? The simplest situation is light scattered from the atmosphere (so light coming from the sun is not completely unpolarized, it has a degree of polarization by scattering with molecules of the atmosphere). With a very simple description we consider molecules of the atmosphere as electric dipoles. Like for electric dipoles, the degree of polarization will be maximum along the direction perpendicular to the direction of light. We start from unpolarized incident light, the transmitted light along the same direction is still unpolarized. But in the orthogonal direction, you will get the maximum degree of polarization.

Slide 14



Sunglasses are polarized because you can reduce a lot the reflection components (the reflected beam is typically partially polarized).

Slide 15



Let us consider particles that compose atmosphere. Why is the sky blue? The reason is related to scattering. The intensity scattered by molecules on the atmosphere has this dependence (see equation) from the angle (of the light) and the frequency. Light is scattered from atmosphere from all the possible orientation: the intensity is strongly dependent on ν^4 . The highest intensity is for the component with the highest frequency (blue region). That is why when we are averaging over all the possible orientation, the components which we receive most are the component on the blue region.

The situation is completely different if we look at the sky during sunset (sun is close to horizon): the light is moving parallel to the surface. Actually, light which reaches our eyes is on the component which is not scattered in different directions, i.e. yellow.

Hence, the intensity of the component that are scattered in different direction are much higher for blue components than for the red component.