Lecture 7
Polarization and Modulation of Light II

ECE 325

OPTOELECTRONICS

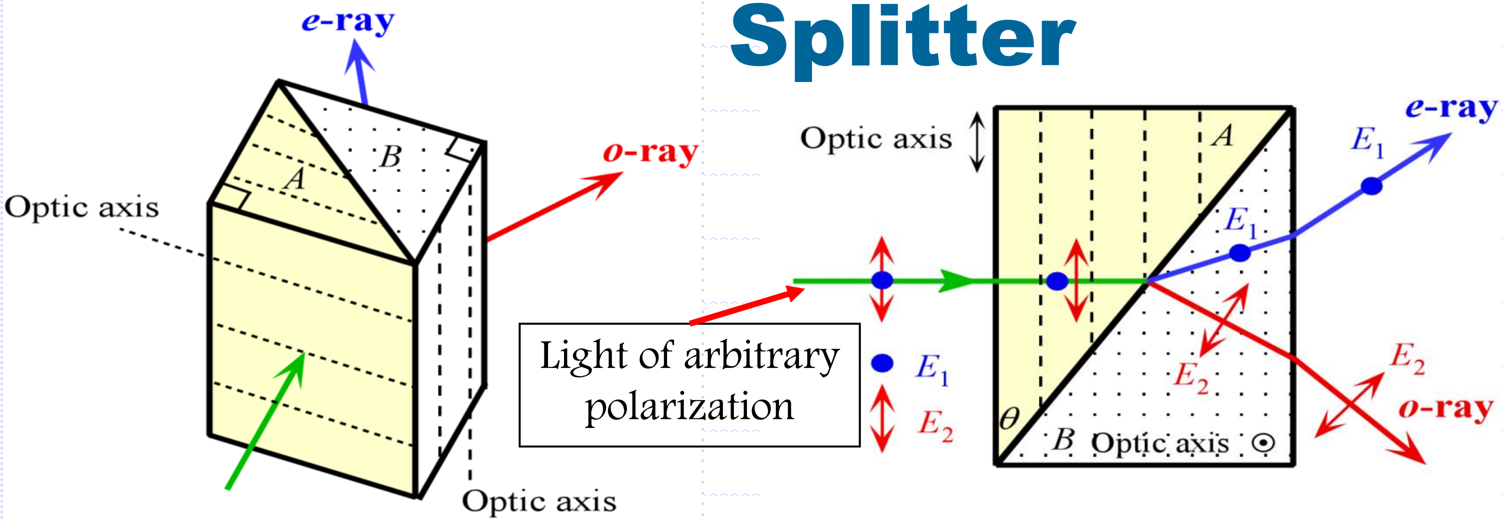
Menoufia University

Kasap–6.4, 6.5, 6.6 and 6.7

March 27, 2019

Ahmed Farghal, Ph.D.
ECE, Menoufia University

Wollaston Prism – Polarizing Beam-Splitter

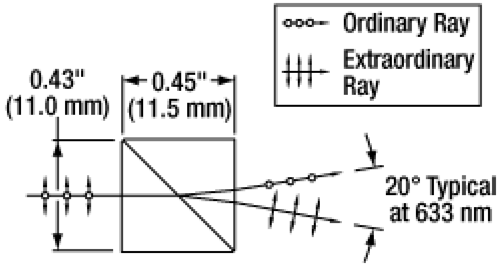


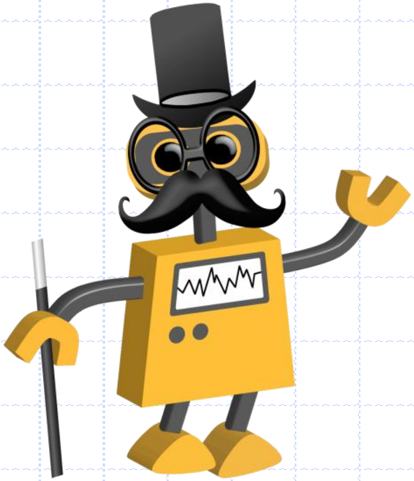
The o-ray becomes the e-ray and vice-versa as the rays traverse from the first to the second section.

For calcite, $n_e = 1.486$, $n_o = 1.658$ ($n_e < n_o$)

- The Wollaston prism is a **beam polarizing splitter** in which the split beam has orthogonal polarizations.
- Two **calcite** ($n_e < n_o$) right-angle prisms A and B are placed with their diagonal faces touching to form a rectangular block.
- The two prisms have their optic axes mutually orthogonal.
- The optic axes are parallel to the prism sides.
- E_1 is orthogonal to the plane of the paper and also to the optic axis of the first prism. E_2 is in the plane of the paper and orthogonal to E_1 (|| optic axis).

Wollaston Prism

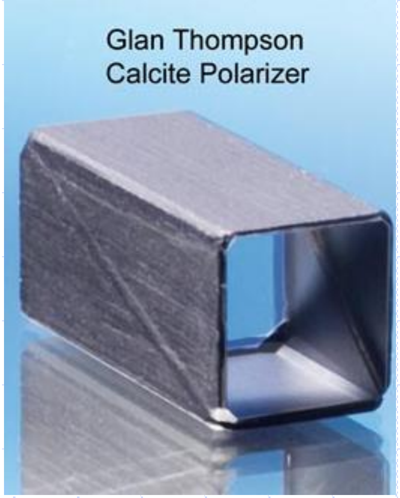




Courtesy of Thorlabs

Birefringent Polarizer

(mainly for high-power lasers) where we can't use polaroid sheet since it will melt.



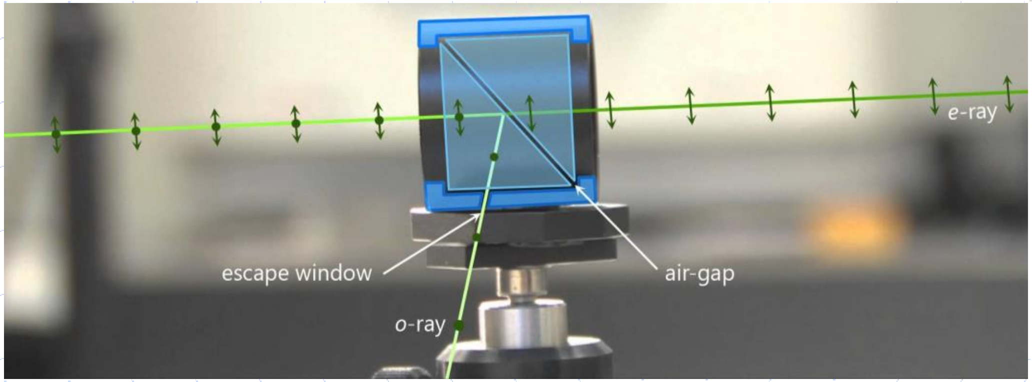
For calcite, n_e = 1.486, n_o = 1.658

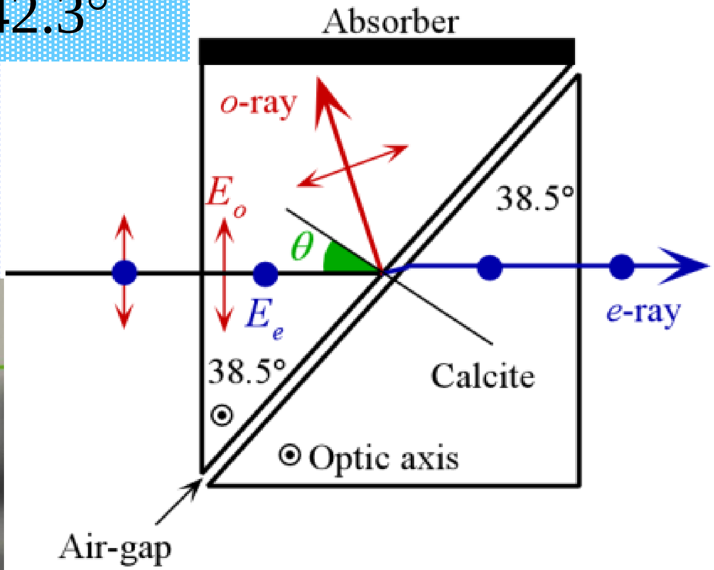
$$n_{o/e} \sin\theta_{i-o/e} = n_{air} \sin\theta_{r-o/e} \quad \text{and} \quad \sin\theta_{c-o/e} = \frac{n_{air}}{n_{o/e}}$$

$$\Rightarrow \quad \sin\theta_{c-o} = 1/n_o = 1/1.658 \quad \Rightarrow \quad \theta_{c-o} = 37.1°$$

$$\Rightarrow \quad \sin\theta_{c-e} = 1/n_e = 1/1.486 \quad \Rightarrow \quad \theta_{c-e} = 42.3°$$

Calcite-air interface: $\theta_{c\text{-}o} < \theta < \theta_{c\text{-}e}$
in order for the *o*-ray to experience TIR
The *e*-ray will not experience TIR.

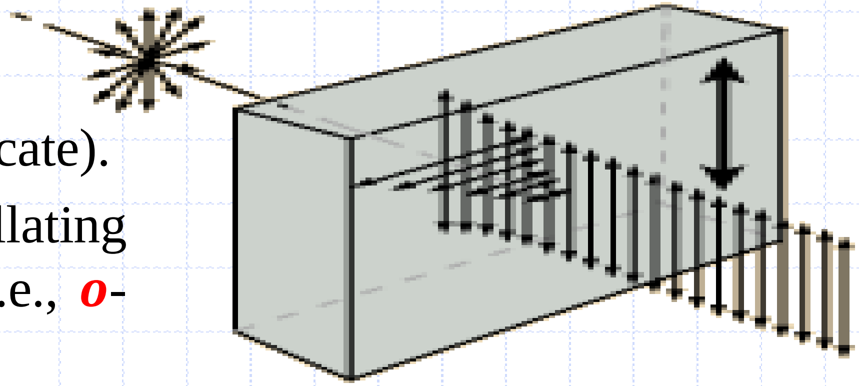




The Glan-Foucault prism

Polarization by Absorption: Dichroic materials

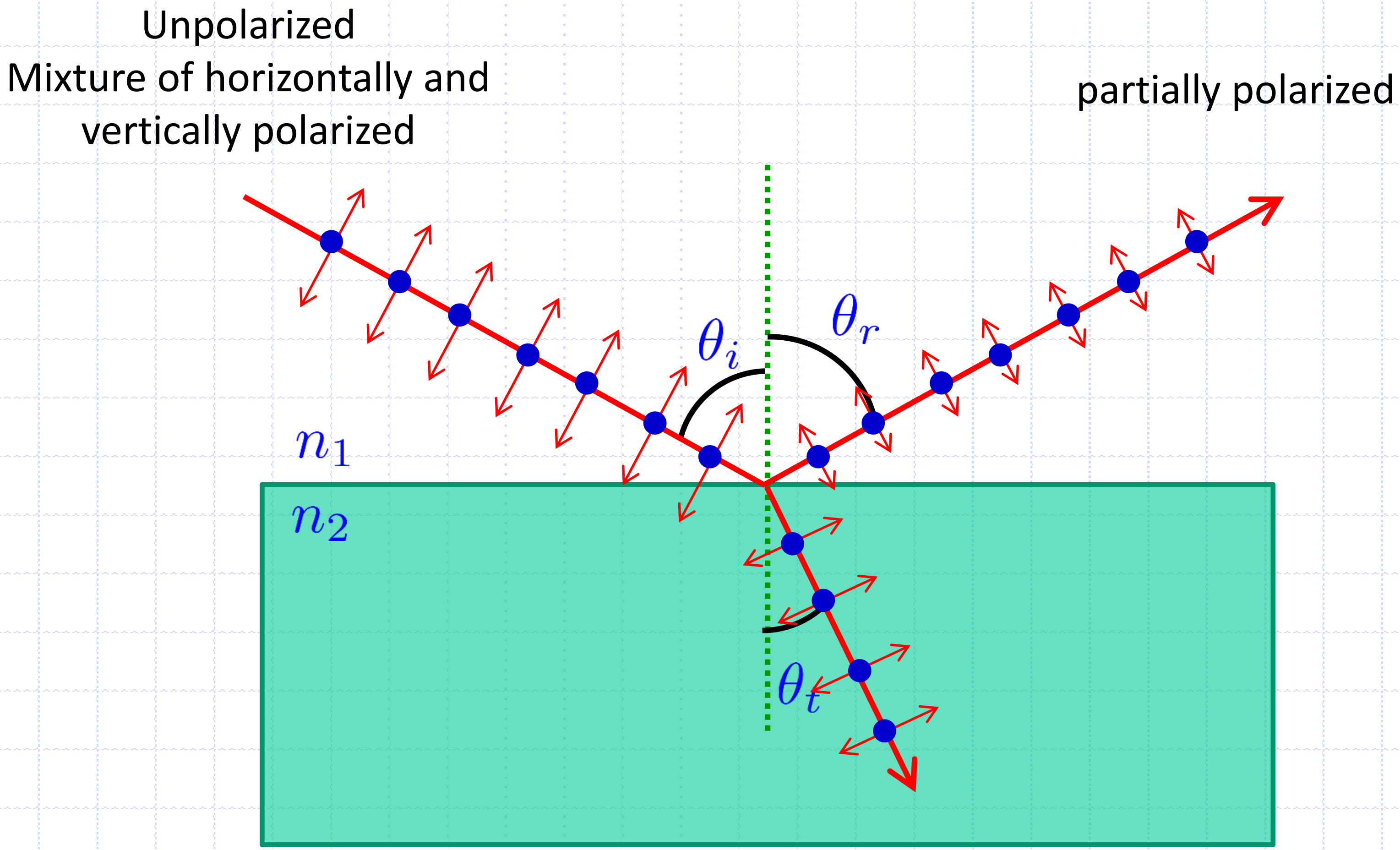
- **Diochroism:-** is a phenomenon in which optical absorption in a substance is dependent on the direction of propagation and the **state of polarization** of the light beam i.e. the direction E-field.
- A **dichroic crystal** is an optically **anisotropic** crystal in which either the ***e***-wave or the ***o***-wave is heavily attenuated (absorbed) by these materials.
  - This means that any light wave entering the material emerges with a **high degree of polarization** because the other is absorbed within the material.



- Example: tourmaline (aluminum borosilicate).

  They attenuate the fields not oscillating along the optical axis of the crystal (i.e., ***o***-wave is heavily absorbed).

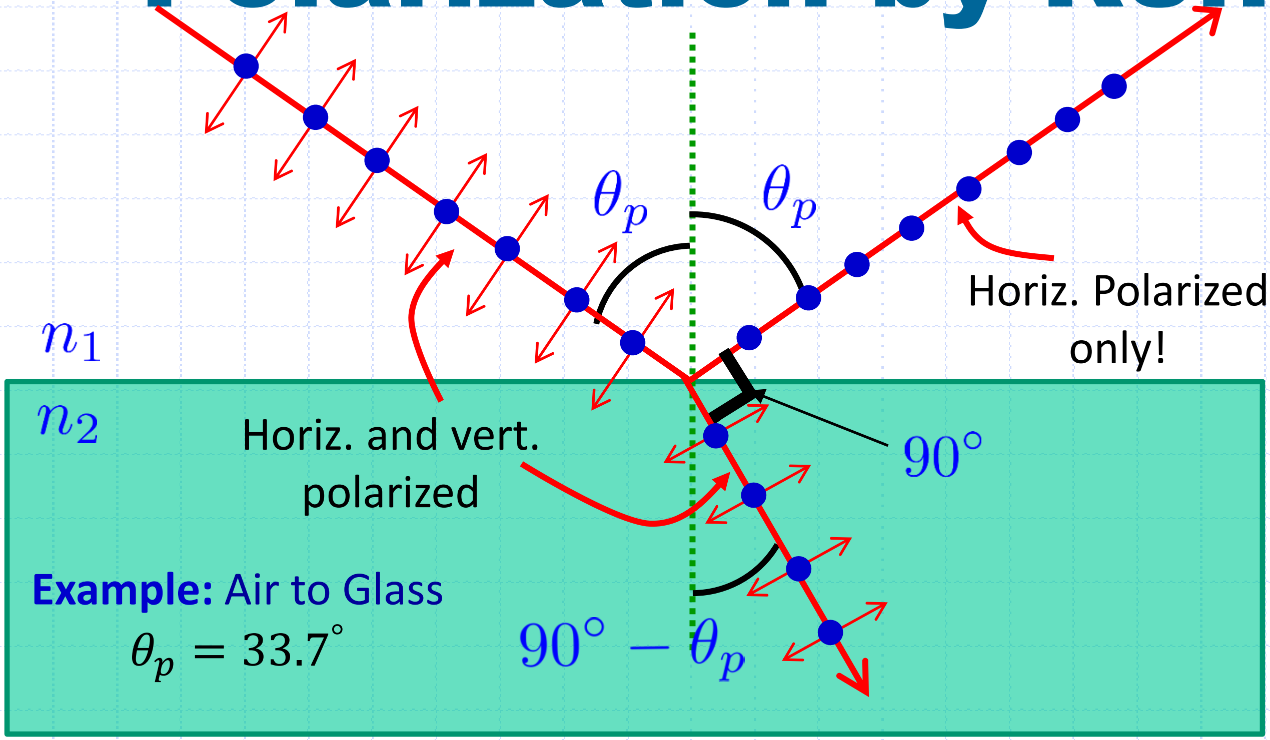
Polarization by Reflection



The reflected rays are partially polarized in the horizontal plane.

The transmitted rays are also partially polarized.

Polarization by Reflection



For a certain angle, the reflected light is completely polarized in the horizontal plane. This occurs when the angle between the reflected and refracted rays is 90°.

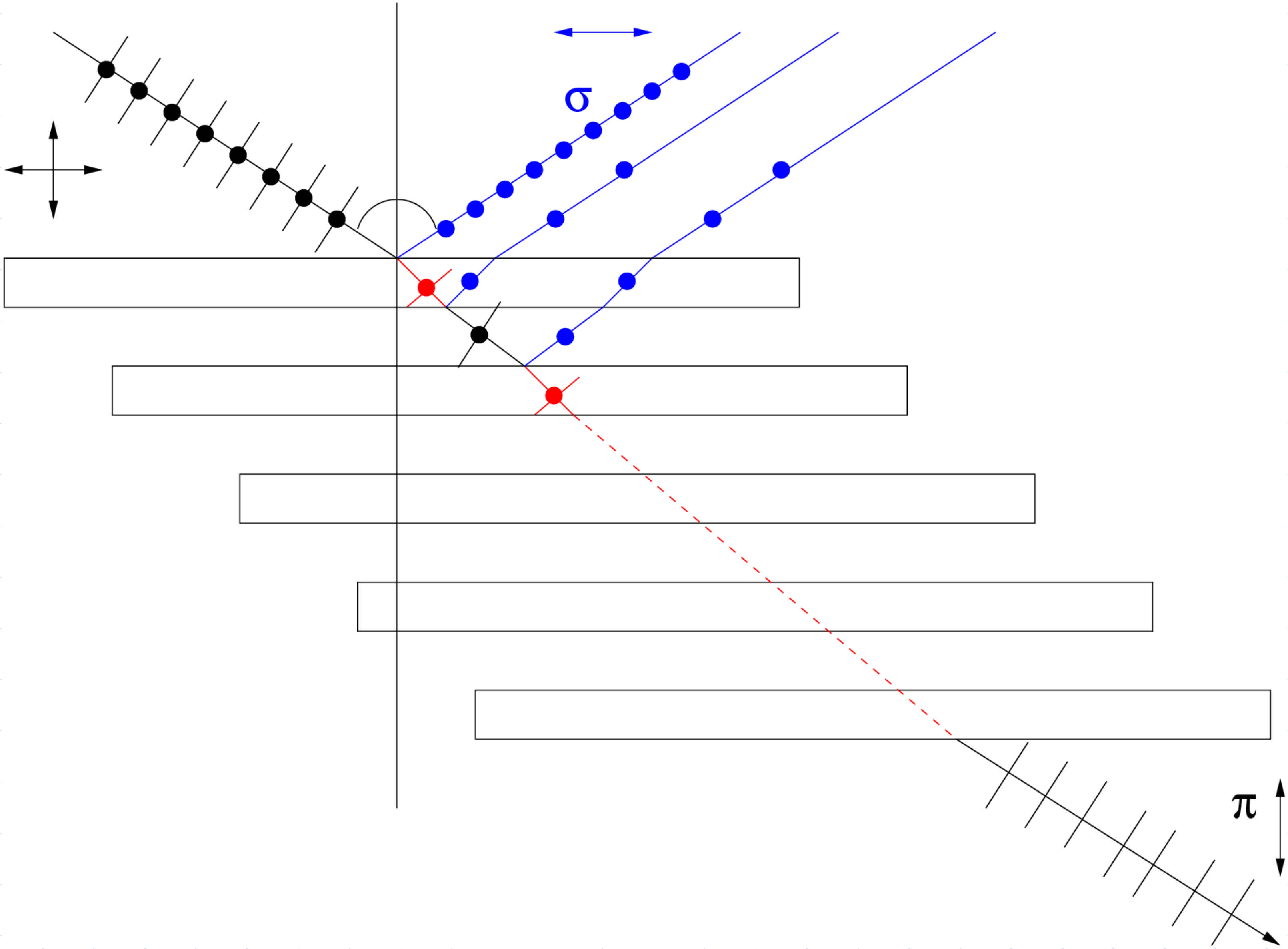
- The particular angle-of-incidence for which this situation occurs is designated by θ_p and referred to as the **polarization angle** or **Brewster's angle**, whereupon $\theta_p + \theta_t = 90^\circ$. From Snell's Law

$$n_1 \sin\theta_p = n_2 \sin(90^\circ - \theta_p)$$

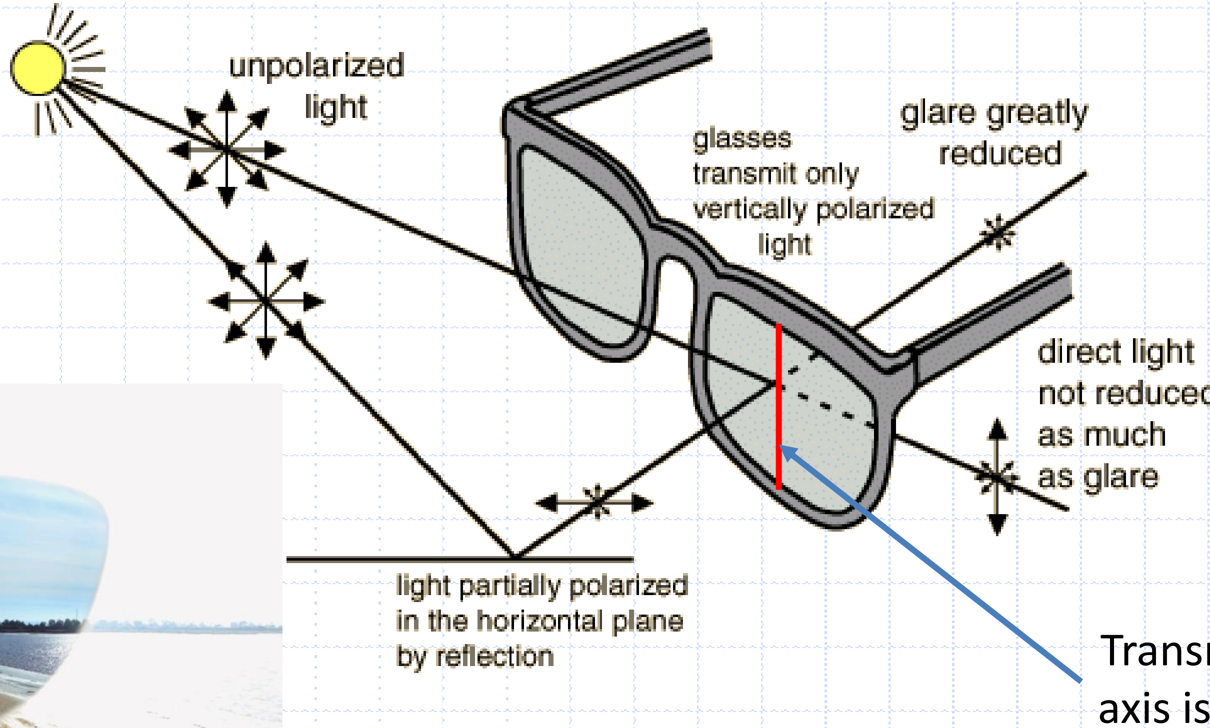
$$n_1 \sin\theta_p = n_2 \cos\theta_p$$

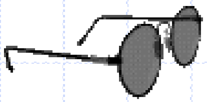
$$\Rightarrow \quad \tan\theta_p = n_2/n_1$$

Polarization by Reflection



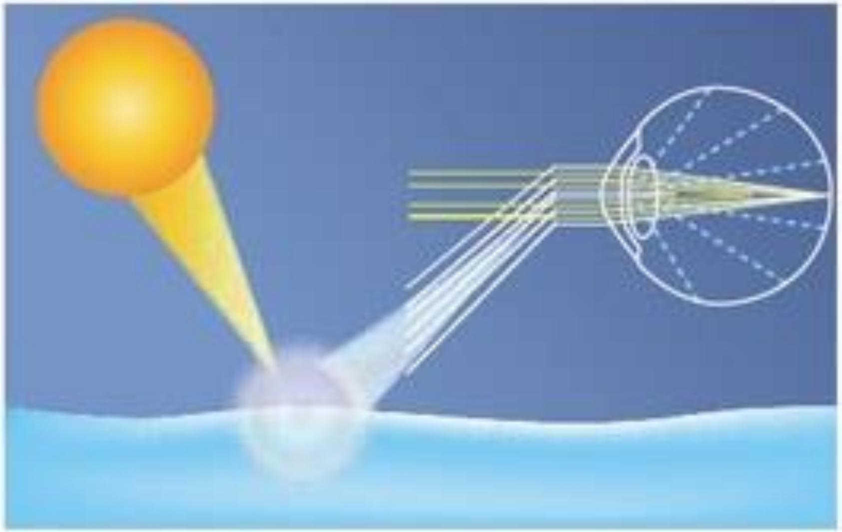
Applications of Polarization



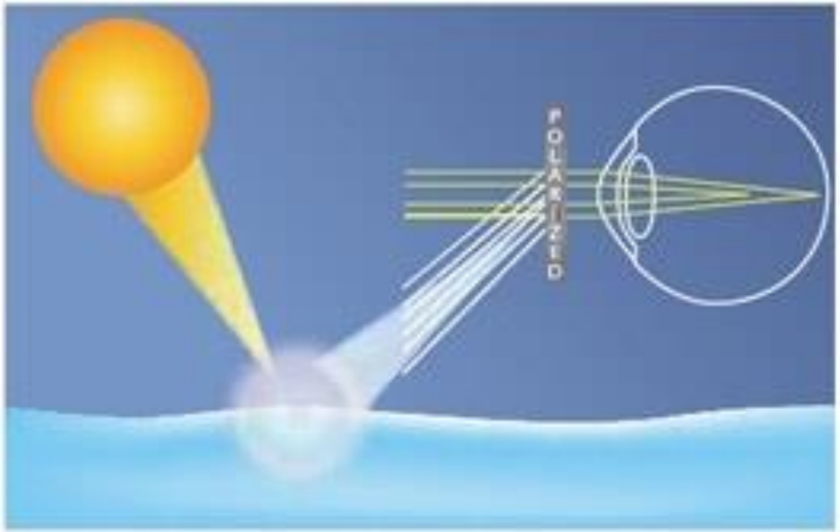


Anti-glare windows

Applications of Polarization



Without polarized lenses

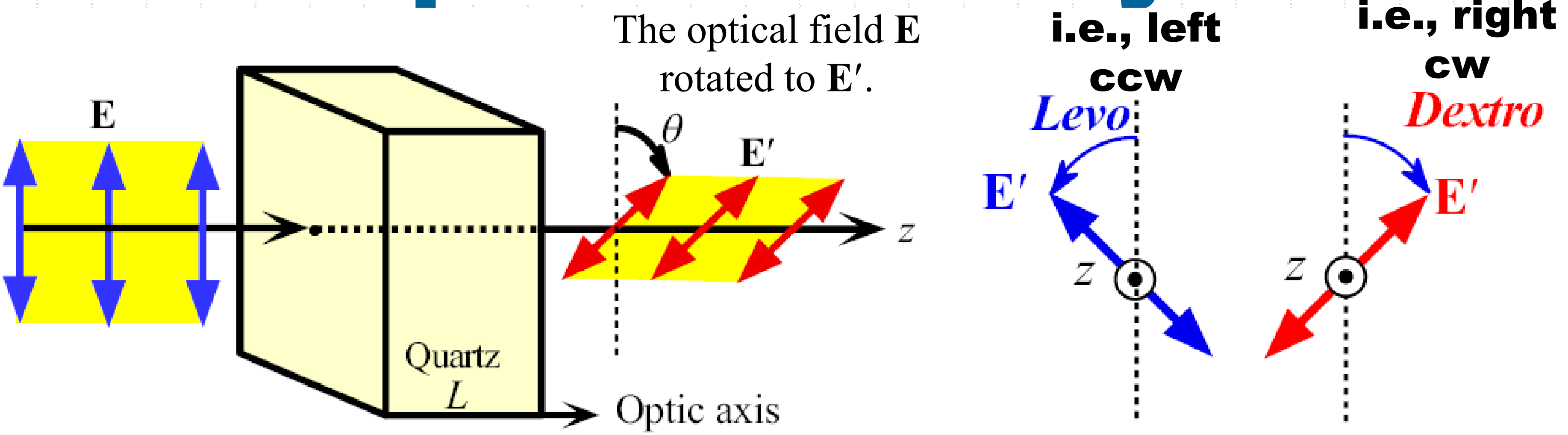


With polarized lenses

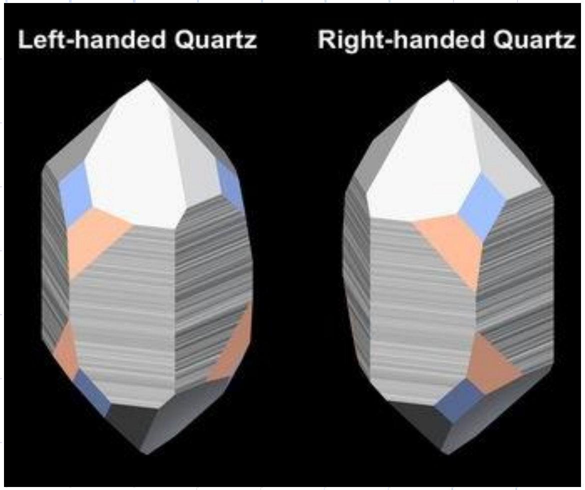
Applications of Polarization

Polarization and Stress Tests

Optical Activity



- **Optical activity:-** rotation of the polarization plane of a linearly polarized light when travelling through certain materials, e.g., **quartz**.
  - It occurs due to the **helical twisting** of the molecular or atomic arrangements in the crystal.
  - The velocity of a circularly polarized wave depends on whether the optical field rotates CW or CCW.
  - It is an interesting fact that some substances will rotate the plane of polarization CW and others in an CCW.



Optical Activity

- Angle of rotation after traversing the crystal length *L* :

$$\boldsymbol{\theta = \frac{k_L - k_R}{2} L = \frac{\pi}{\lambda}(n_L - n_R)L}$$

or

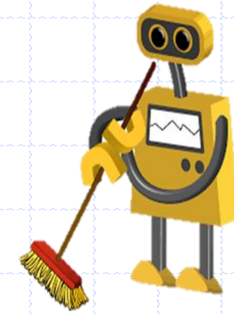
$$\boldsymbol{\theta = \frac{\pi}{\lambda}\left(\frac{c}{v_L} - \frac{c}{v_R}\right)L}$$

- Rotation direction:
  - $k_R > k_L$ ($v_R < v_L$), counterclockwise, *levo-rotatory* (*l*-rotatory);
  - $k_R < k_L (v_R > v_L)$, clockwise, dextro-rotatory (*d*-rotatory).
- **Specific rotary power** (θ/L): the extent of rotation per unit of distance traveled in the optically active substance.

$$\frac{\theta}{L} = \frac{\pi}{\lambda}(n_L - n_R)$$

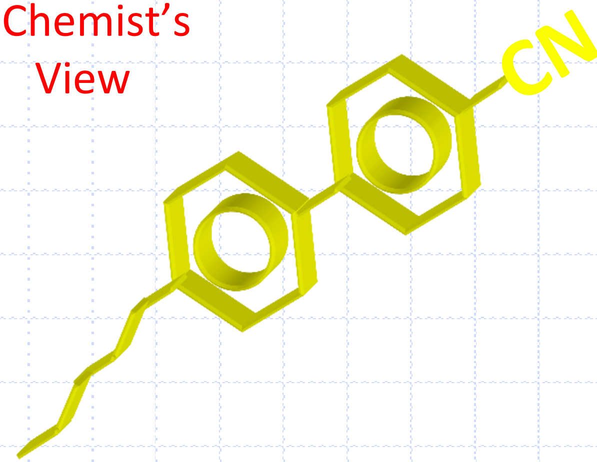
  - θ/L in quartz is 49°/m @ 400 nm but 17°/m @ 650 nm (wavelength dependent).

Liquid Crystals

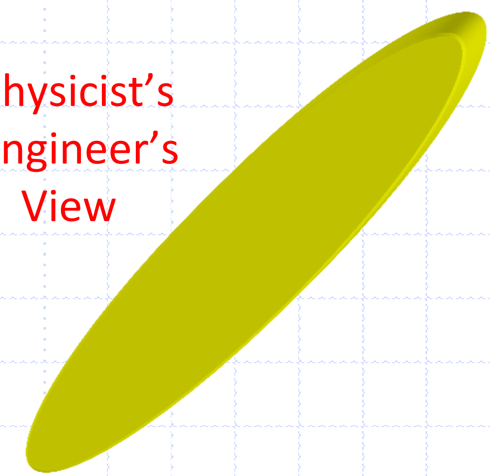


Many flat-panel televisions and computer displays are liquid crystal displays (LCDs) in which liquid crystals cause changes in the polarization of a passing beam of light.

Chemist's View

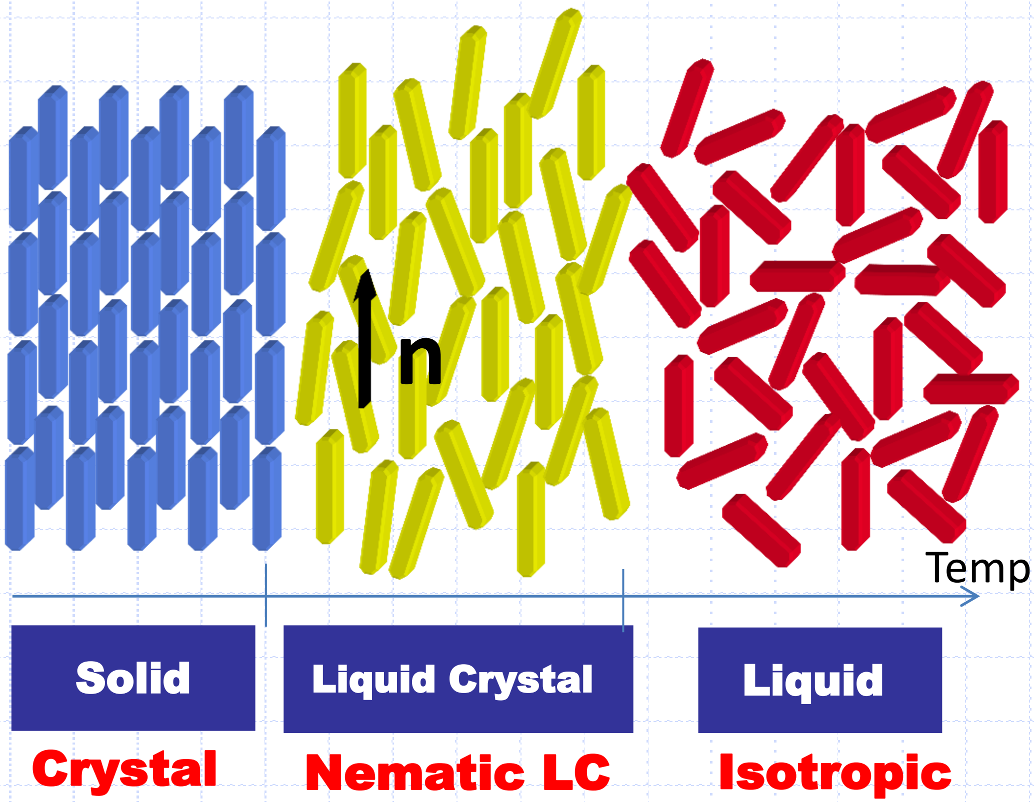


Physicist's
Engineer's
View



What are Liquid Crystals?

- **Liquid crystals (LCs):-** materials exhibiting properties that are between those of a liquid phase (e.g., they can flow like a liquid) and those of a crystalline solid phase (possess crystalline domains that lead to anisotropic optical properties).
  - Have a rod-like molecular structure, called **mesogens**.
  - Shape Anisotropy



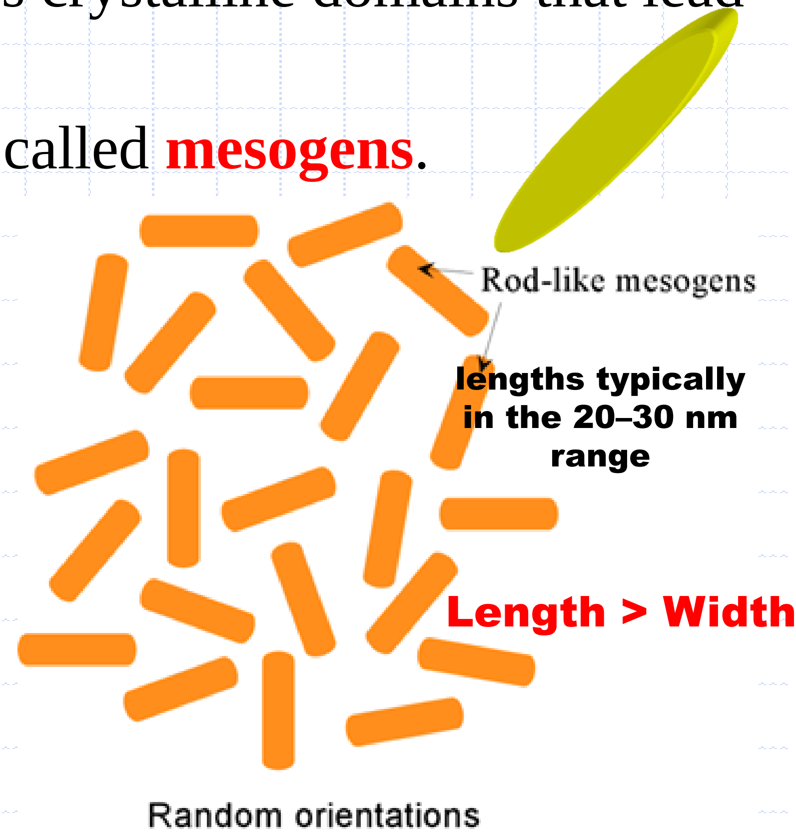
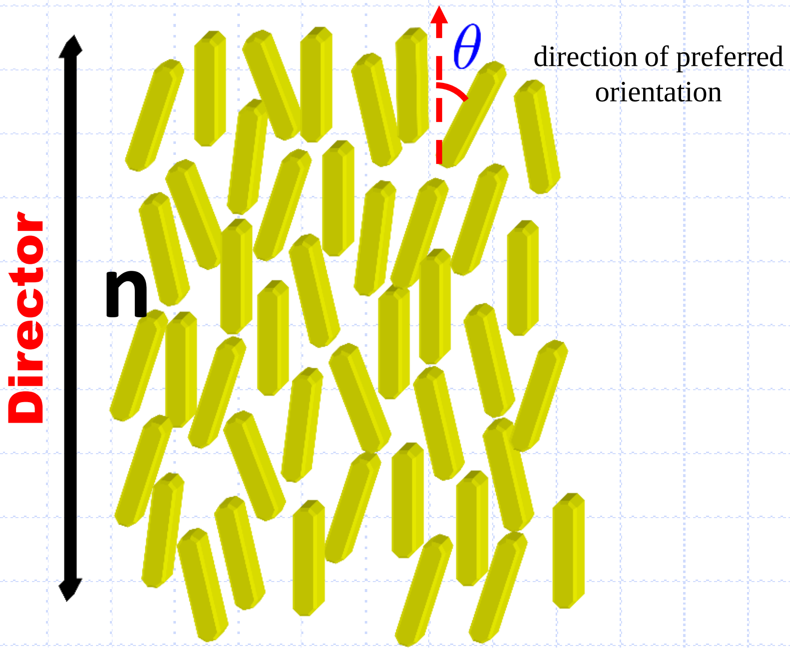


Illustration of orientational disorder in a liquid with rod-like mesogens. No order, and rods are randomly oriented.

Liquid Crystals

- A distinct characteristic of the LC state is the tendency of the mesogens to point along a common axis called the **director**, a preferred common axis in the LC that results in an orientationally ordered state.

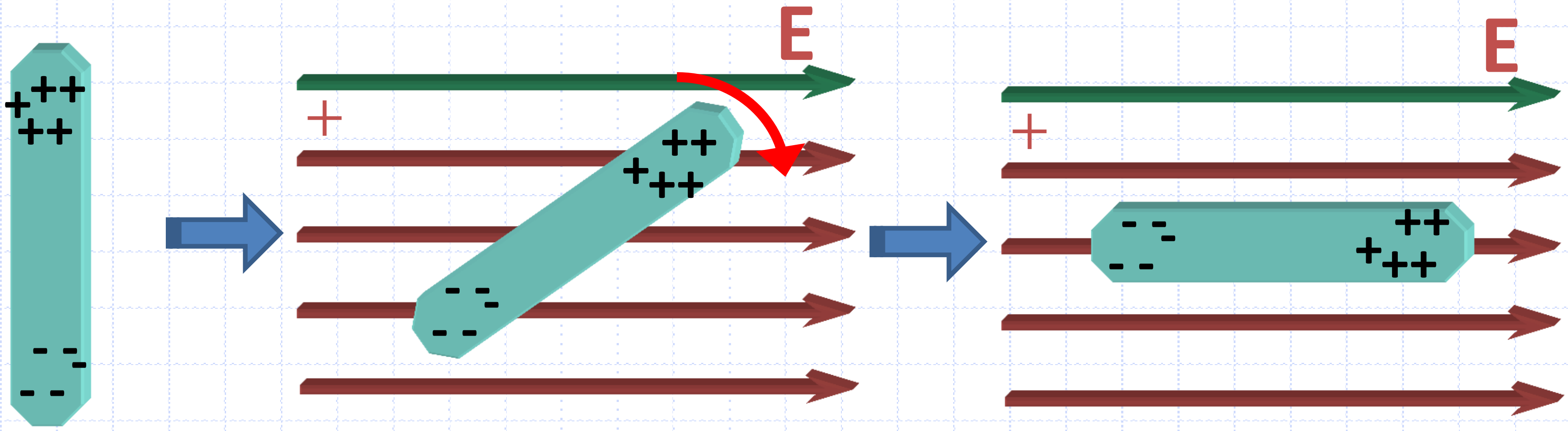


Nematic phase with a degree of orientational disorder

- **Nematic phase**: characterized by mesogens that have no positional order, but tend to point along the same direction, *i.e.*, *along director*.

Effect of Electric Field

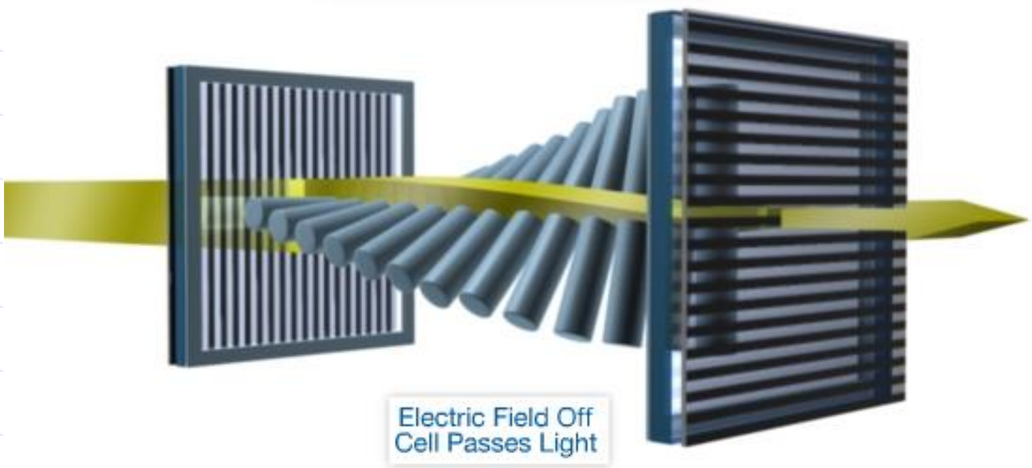
- Many LC molecules possess permanent electric dipole.
- A distinct advantage is that the molecular orientation and hence the optical properties can be controlled by an **applied field**.
- Under an electric field, the molecules tend to rotate until the positive and negative ends line up with the electric field.



Electric field OFF

Electric field ON

Twisted Nematic (TN) Display



Change in Plane of Polarization

The simplest LC display: twisted nematic mode with **On** and **OFF** states only.

Make use of the **change in brightness** of the device (Black vs. White).

The glass surfaces have been treated so that the LC molecules prefer to align parallel to the surface.

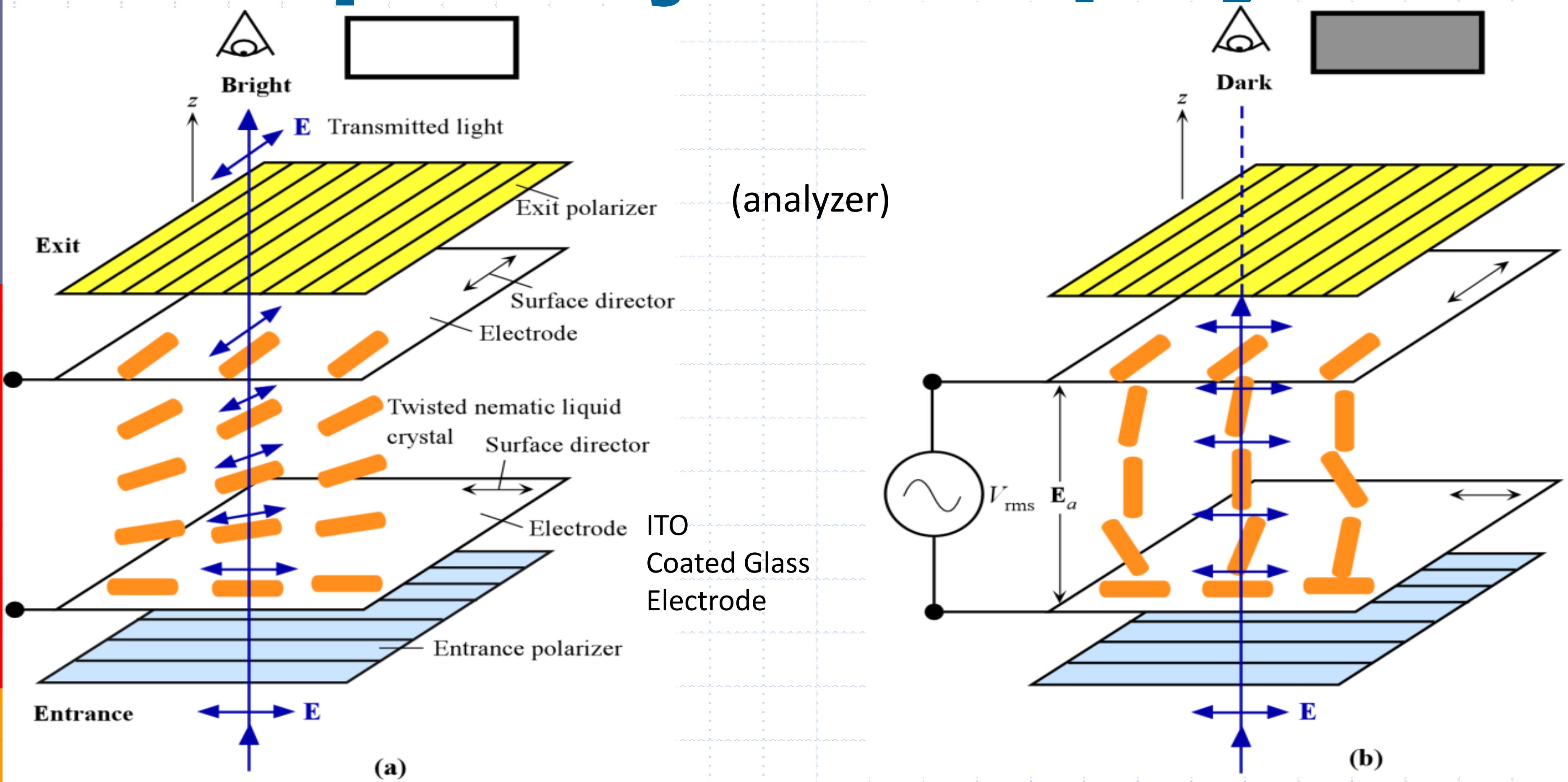
The two alignments layer for the LC material are orthogonal.

The director of the nematic LC molecules is forced to twisted through an angle of 90° within the cell.

The light entering the polarizer panel rotates by the twist in the LC and allowing it to **pass through** the second polarizer

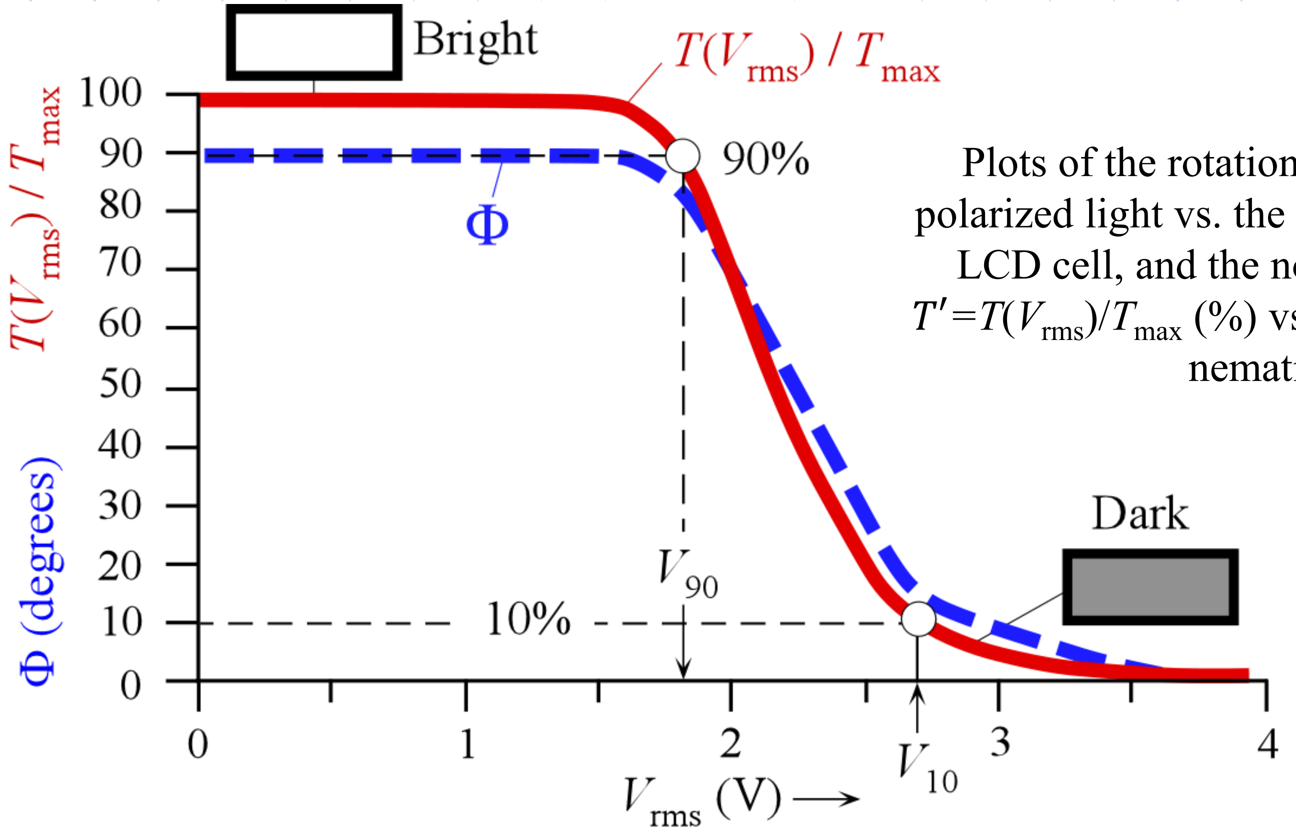
(i.e. the polarization direction of light rotates 90° by the LC molecules)

Liquid Crystal Displays



Transmission based LCD. (a) In the **absence of a field**, the LC has the **twisted nematic phase** and the light passing through it has its polarization rotated by 90°. The light is transmitted through both polarizers. The viewer sees a bright image. (b) When a voltage, and hence a field $\mathbf{E}_a$, is applied, the molecules in the LC align with the field $\mathbf{E}_a$ and are **unable to rotate** the polarization of the light passing through it; light therefore cannot pass through the exit polarizer. The light is extinguished, and the viewer see dark image.

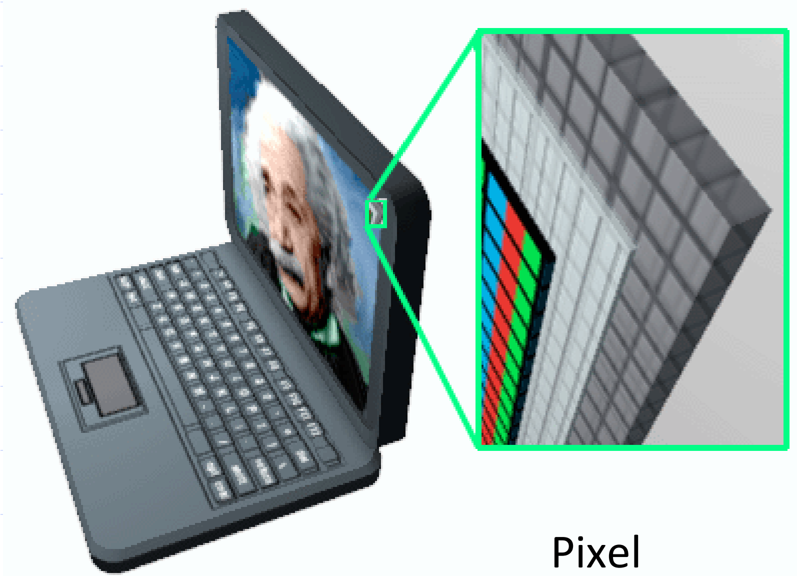
Liquid Crystal Displays

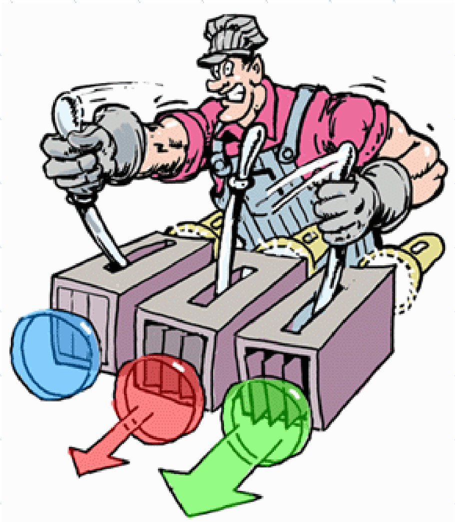


Plots of the rotation angle Φ of the linearly polarized light vs. the rms voltage V_{rms} across an LCD cell, and the normalized transmittance $T'=T(V_{rms})/T_{max}$ (%) vs. V_{rms} for a typical twisted nematic LC cell.

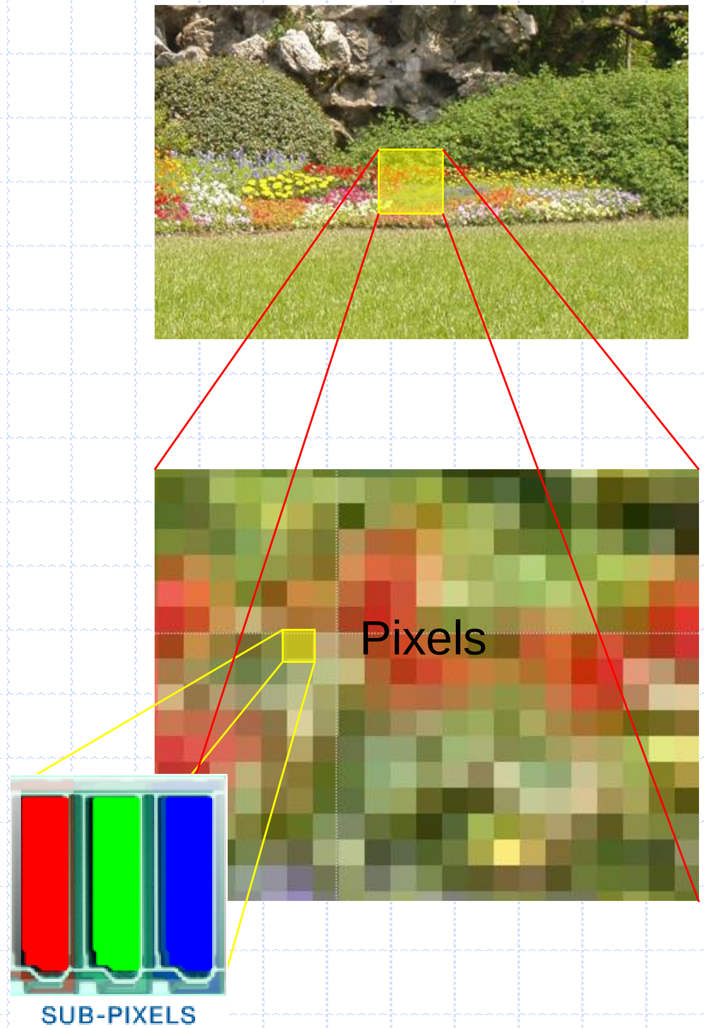
- A **threshold voltage** is required to start untwisting the alignment of the mesogens.
- **A threshold voltage, V_{90}**: usually taken as the rms voltage corresponding to 90% normalized transmission T'.
- **A saturation voltage**, V_{10}: the rms voltage at which T' has dropped to 10%.

Digital Images and Pixels





Blue Red Green (RGB)



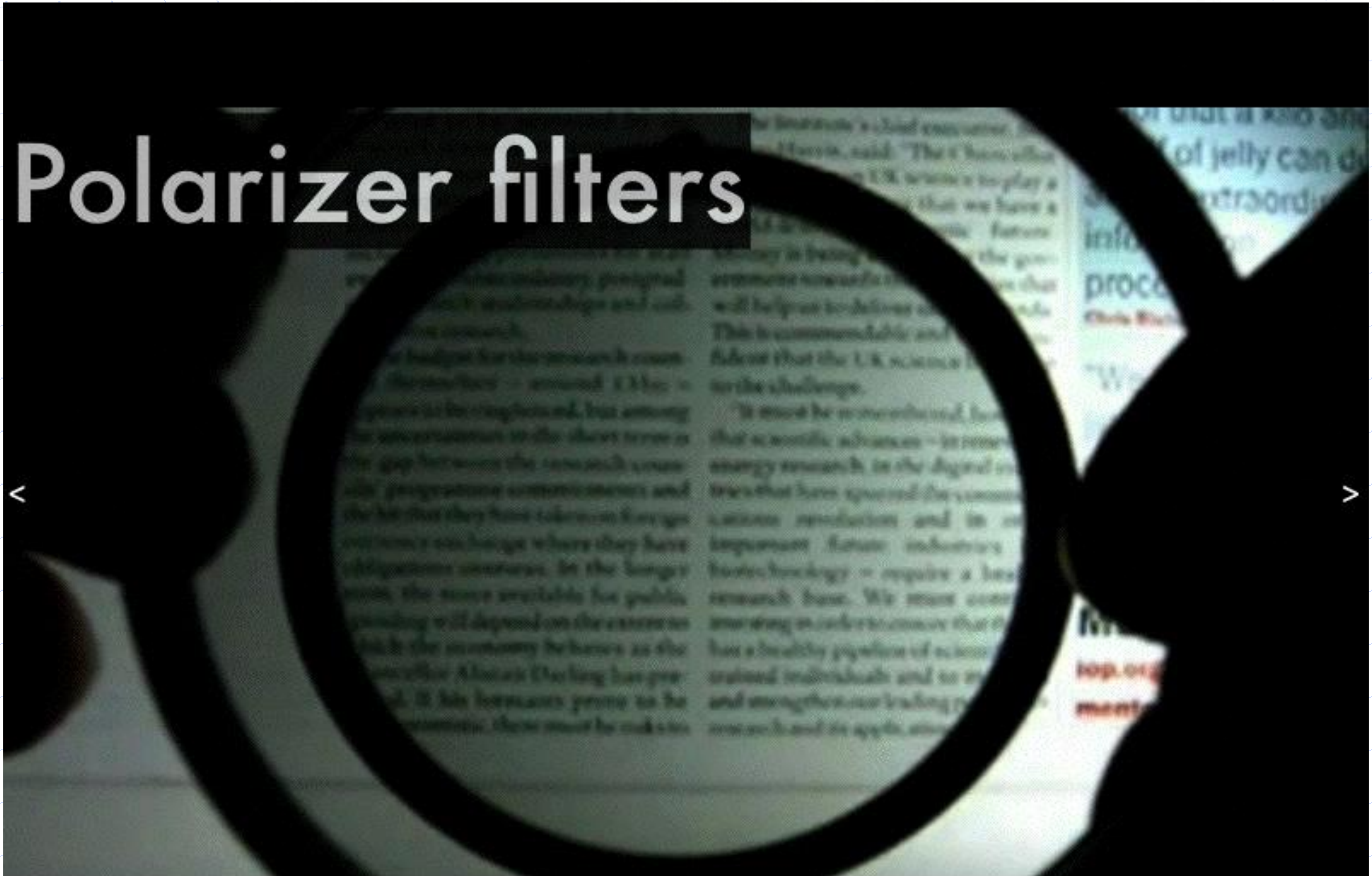
LCDs use polarized light and a LC to orient the polarization of the light passing through

The light from an LCD display is linearly polarized.
Two polarizers have been placed at right angles. One allows the transmission of light, whereas the other, whose polarization axis is at right angles, extinguishes the light.

Photo by S. Kasap

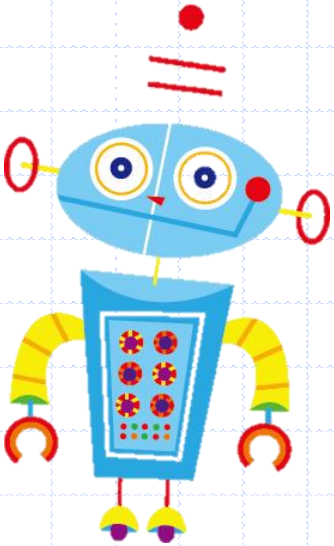
LCDs emit linearly polarized light

(typically at 45° to the vertical)



"Polarization of Light and Microwaves (Quantum Physics)"
(Source: teralabUK/Robert Hunt)
http://www.youtube.com/watch?v=ZudziPffS9E

Electro-Optic Effects



Electro-Optic Effects

- **Electro-optic effects:** refer to changes in the refractive index, *n*, of a material induced by the application of **an external electric field**, which therefore "***modulates***" the optical properties.
  - The applied field is not the electric field of any light wave, but a **separate** external field.
  - The presence of such a field **distorts** the electron motions in the atoms or molecules of the substance, or **distorts** the crystal structure, resulting in changes in the optical properties.

Field induced refractive index

$$n' = n(E) = n + a_1 E + a_2 E^2 + \ldots$$

from Taylor expansion

new refractive index (n')

Linear electro-optic effect ($a_1 E$)
The Pockels effect

$$\Delta n = a_1 E$$

2nd order electro-optic effect ($a_2 E^2$)
The Kerr effect

$$\Delta n = a_2 E^2 = (\lambda K) E^2$$

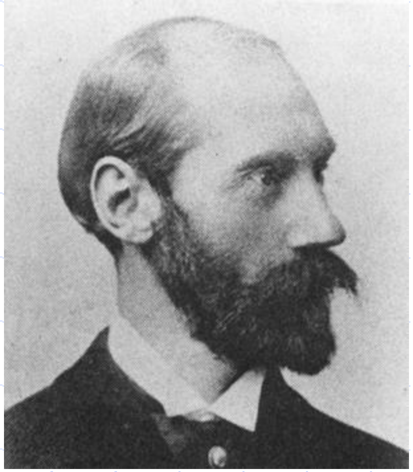
K is called the Kerr coefficient

Electro-Optic Effects

$$n' = n + a_1 E + a_2 E^2 + \ldots$$

Linear electro-optic effect.
The Pockels effect

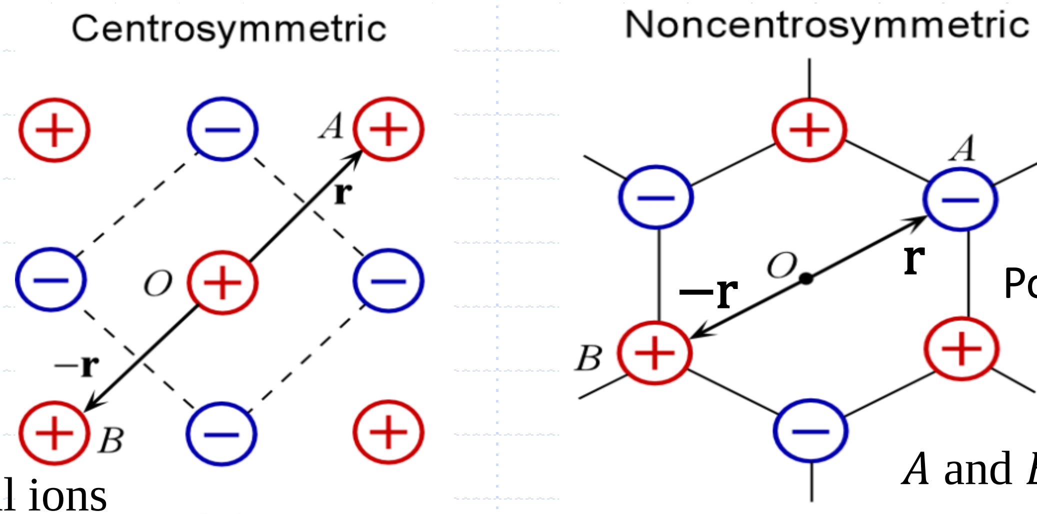
$$\Delta n = a_1 E$$



- If we apply a field **E** in one direction and then reverse the field and apply $-\mathbf{E}$, $\Rightarrow$ Δn should change sign.
  - If the refractive index increases for **E**, it must decrease for -**E**.
  - Reversing the field should not lead to an identical effect (the same Δn). The structure has to respond differently to **E** and -**E**; there must therefore be **some asymmetry** in the structure to distinguish between **E** and -**E**.
- In a **noncrystalline material**, Δn for **E** would be the same as Δn for -**E** as all directions are equivalent in terms of dielectric properties. $\Rightarrow$ $\boldsymbol{a_1 = 0}$ for all noncrystalline materials (such as glasses and liquids).

Pockels Effect

$a_1 = 0$
No pockels effect



A and B are identical ions

(a)

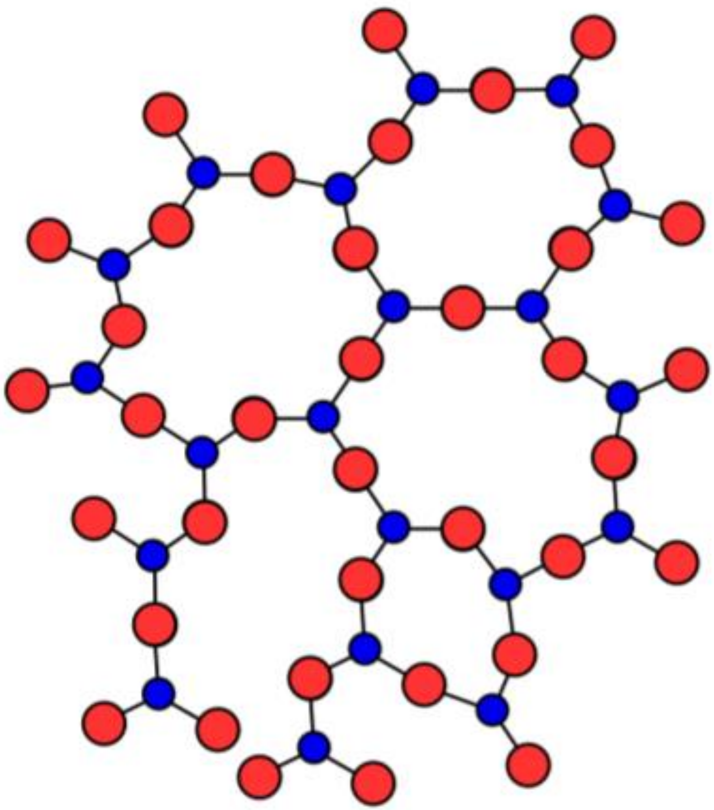
$a_1 \neq 0$
Posses pockels effect

A and B are different ions

(b)

- If the crystal structure has a center of symmetry, i.e., **centrosymmetric crystal,** as shown in Fig. (a), then reversing the field direction has an identical effect ($a_1 = 0$).
- Fig. (b) shows a **noncentrosymmetric** hexagonal crystal. If we draw a vector **r** from *O* to *A*, and then invert this, we would find a different ion *B* at **-r**; *A* and *B* are different ions.
- All materials exhibit the Kerr effect
- Only crystals that are **noncentrosymmetric** exhibit the Pockels effect .
  - For example a NaCl crystal (centrosymmetric) exhibits no Pockels effect but a GaAs crystal (noncentrosymmetric) does

Glasses and liquids exhibit no Pockels effect

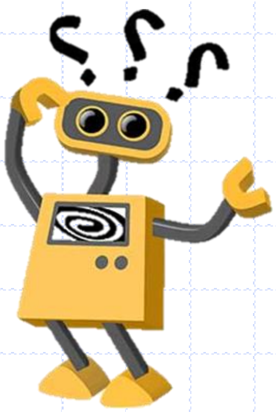


$$\Delta n = a_1 E$$

$$a_1 = 0$$

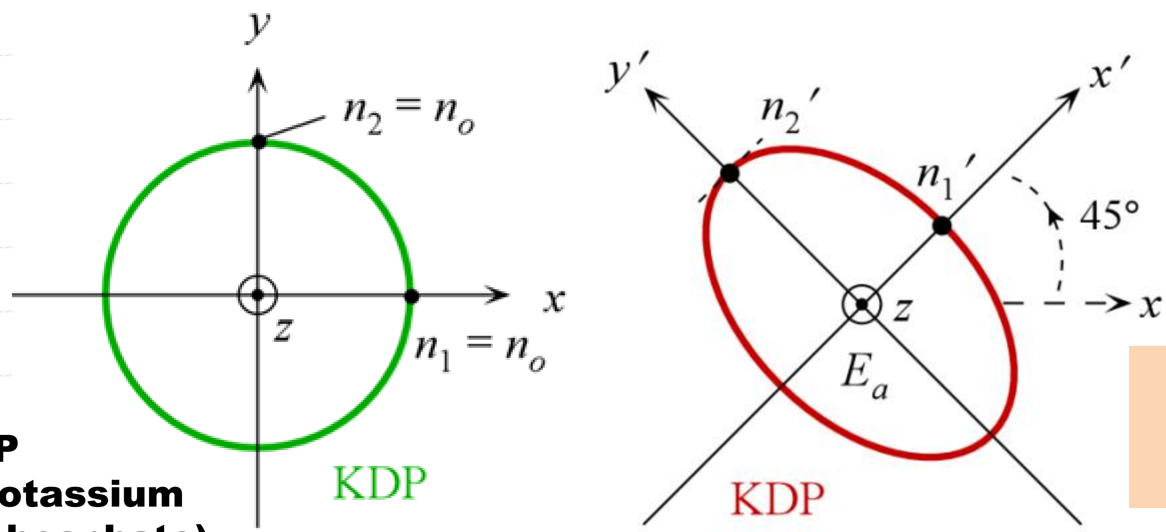
for all noncrystalline materials

e.g. glasses and liquids



Note: There may be <u>exceptions</u> if asymmetry is induced in the glass structure that destroys the structural isotropy

Pockels Effect and the Indicatrix



● out of paper

applied field E_a along the z-axis

KDP (KH_2PO_4—potassium dihydrogen phosphate)

(a) **(b)**

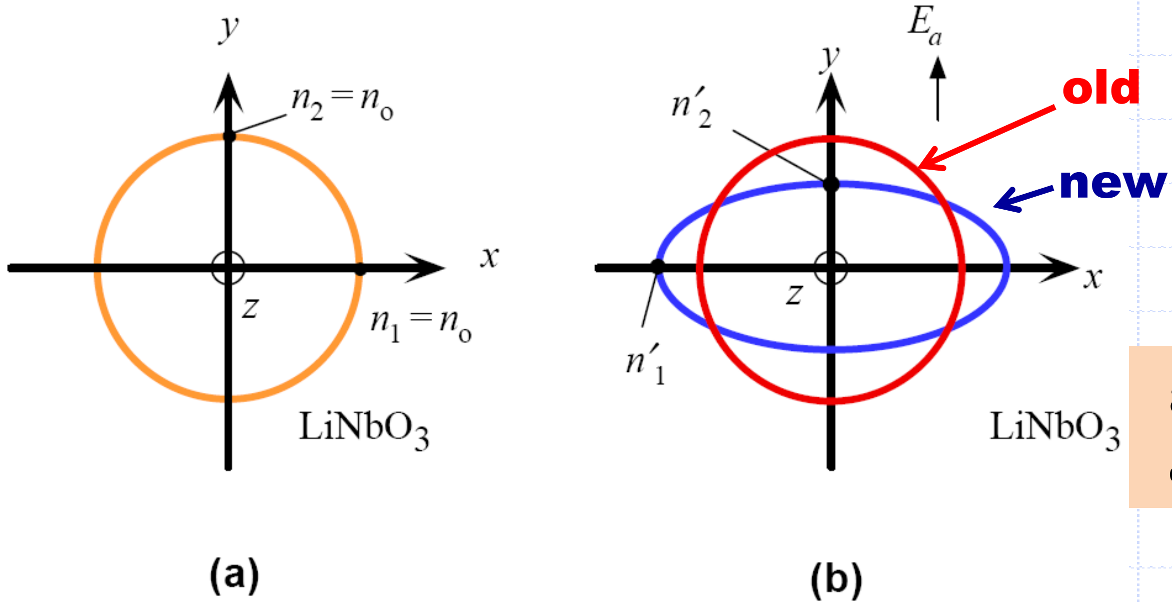
(a) Cross section of the optical indicatrix for an optically isotropic crystal with no applied field, $n_1 = n_2 = n_o$.

(b) The applied external field E_a along the z-axis (by suitably applying a voltage across a crystal) modifies the **optical indicatrix**.

- In a KDP crystal, it rotates the principal axes by 45° to x' and y' and n_1 and n_2 change to n_1' and n_2'.

- In Pockels effect, the field will modify the optical indicatrix. The exact effect <u>depends on</u> the crystal structure.

Pockels Effect and the Indicatrix



applied field E_a along the z-axis

(a) Cross section of the optical indicatrix with no applied field, $n_1 = n_2 = n_o$.
(b) Applied field along y-axis in $LiNbO_2$ modifies the indicatrix and changes n_1 and n_2 to n'_1 and n'_2.

In the case of $LiNbO_3$, an **optoelectronically important uniaxial crystal**, a field E_a along the y-direction does not significantly rotate the principal axes but rather changes the principal refractive indices n_1 and n_2 (both equal to n_o) to n_1' and n_2'.

The applied field *induces a* ***birefringence*** for light traveling along the z-axis.

Pockels Effect and the Indicatrix

Before the field E_a is applied, the refractive indices n_1 and n_2 are both equal to n_o.

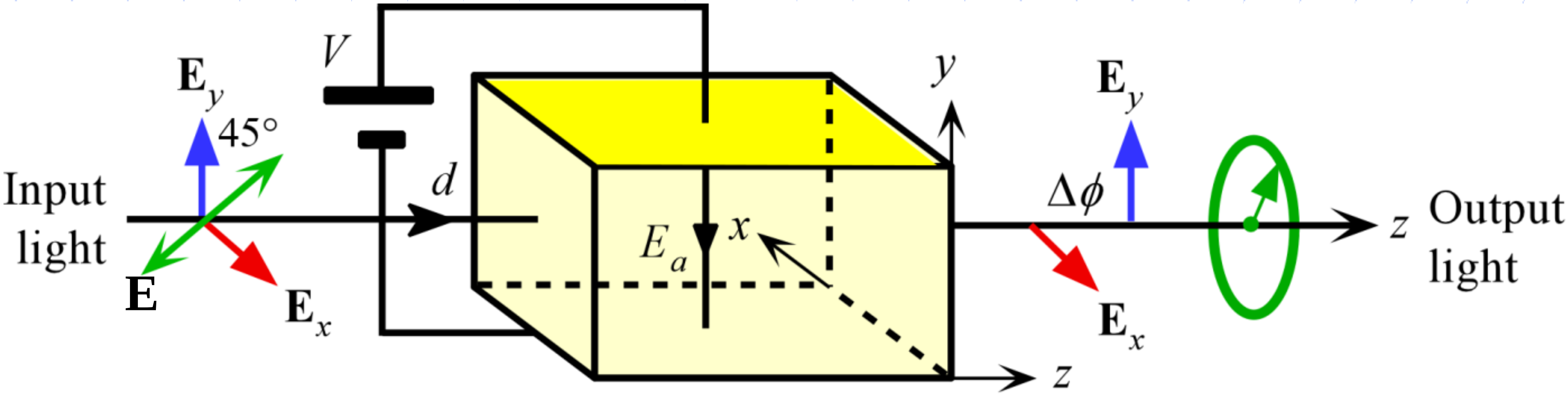
The Pockels effect then gives the new refractive indices n'_1 and n'_2 in the presence of E_a as

$$n'_1 \approx n_1 + \frac{1}{2} n_1^3 r_{22} E_a \quad \text{and} \quad n'_2 \approx n_2 - \frac{1}{2} n_2^3 r_{22} E_a$$

Applied field

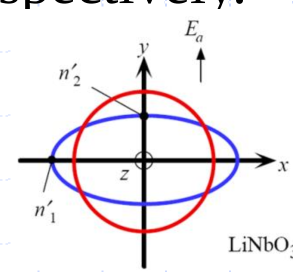
where r_{22} is a constant, called a **Pockels coefficient**, that depends on the crystal structure and the material.

Transverse Pockels Cell



- The applied electric field, $E_a = V/d$, is applied parallel to the ***y*-direction**, normal to the direction of light propagation along z.
- Suppose that the incident beam is **linearly polarized** (shown as **E**), say at 45° to the y-axis.
- The incident light can be represented in terms of polarizations E_x and E_y along the x- and y-axes, respectively.
  - E_x and E_y, experience refractive indices n_1' and n_2', respectively.
- E_x traverses the distance L and its phase changes by ϕ_1,

$$\phi_1 = \frac{2\pi n_1'}{\lambda} L = \frac{2\pi L}{\lambda}\left(n_o + \frac{1}{2} n_o^3 r_{22} \frac{V}{d}\right)$$



Transverse Pockels Cell

- The phase change ϕ_2 of the component E_y traversing the distance L

$$\phi_2 = \frac{2\pi n_2'}{\lambda} L = \frac{2\pi L}{\lambda}\left(n_o - \frac{1}{2} n_o^3 r_{22} \frac{V}{d}\right)$$

- The phase change $\Delta\phi$ between the two field components is

$$\Delta\phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V$$

  - The applied voltage V thus inserts an adjustable phase difference $\Delta\phi$ between the two field components.

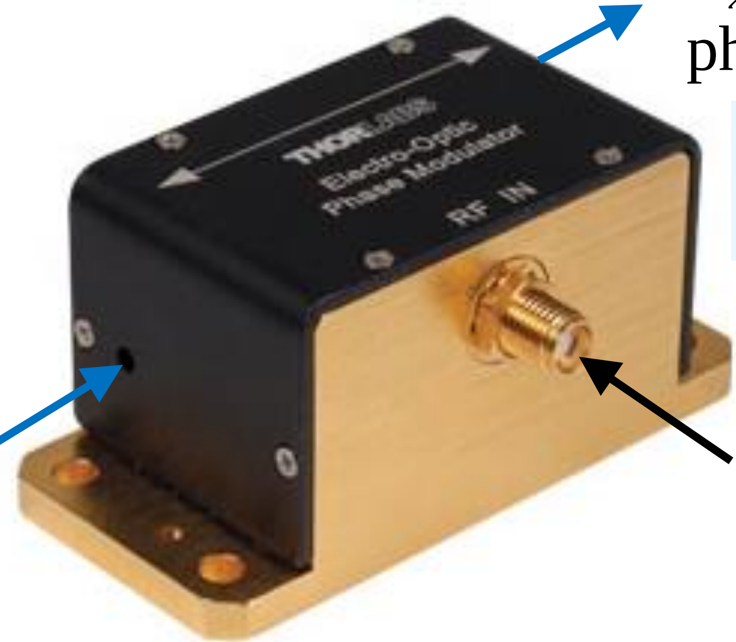
- The polarization state of output wave can therefore be controlled by the applied voltage and the Pockels cell is a **polarization modulator**.

- We can change the medium from a quarter-wave to a half-wave plate by simply adjusting V.
  - The voltage $V = V_{\lambda/2} = V_\pi$, the **half-wave voltage**, corresponds to $\Delta\phi = \pi$ and generates a half-wave plate.

Pockels Phase Modulator

Light out
$\mathbf{E}_x$, $\mathbf{E}_y$ with imposed phase difference $\Delta\phi$

$$\Delta\phi = \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V$$



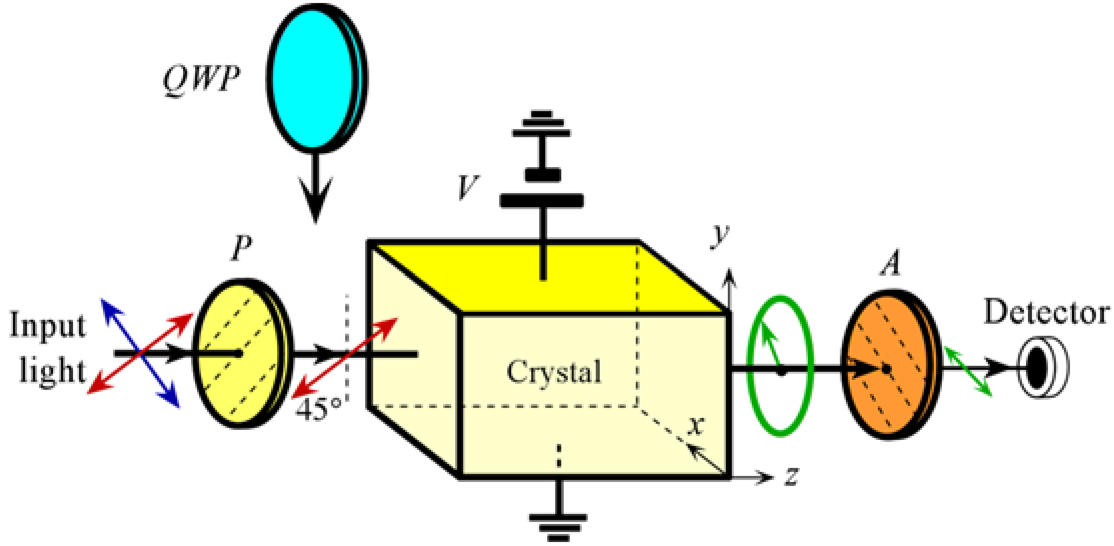
Light in
$\mathbf{E}_x$, $\mathbf{E}_y$

Modulating voltage V

Electro-optic phase modulator using $LiNbO_3$. The socket is the RF modulation input.

Courtesy of Thorlabs

A Tranverse Pockels Cell Intensity Modulator



- An **intensity modulator** can be built from the polarization modulator by inserting a polarizer *P* and an analyzer *A* before and after the phase modulator such that they are cross-polarized, i.e., *P* and *A* have their **TAs** at 90° to each other.
- The TA of *P* is at **45°** to the y-axis (hence *A* also has its TA at **-45°** to *y*) so that the light entering the crystal has equal E_x and E_y components.
- When $\boldsymbol{V = 0}$, the two components travel with the same refractive index, and polarization output from the crystal is the same as its input.
  - There is no light detected at the detector as *A* and *P* are at right angles ($\theta = 90°$ in Malus's law).

A Tranverse Pockels Cell Intensity Modulator

- An applied voltage inserts a phase difference $\Delta\phi$ between the two electric field components.
- Light leaving the crystal → elliptical polarized
- The total field **E** at the analyzer is

$$\mathbf{E} = -\hat{\mathbf{x}}\frac{E_o}{\sqrt{2}}\cos(\omega t) + \hat{\mathbf{y}}\frac{E_o}{\sqrt{2}}\cos(\omega t + \Delta\phi)$$

Pockels effect modifies this

- use a trigonometric identity

$$E = E_o \sin(\tfrac{1}{2}\Delta\phi)\sin(\omega t + \tfrac{1}{2}\Delta\phi)$$

the amplitude of the wave incident on the crystal face

$$\Delta\phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V$$

$$I = I_o \sin^2(\tfrac{1}{2}\Delta\phi)$$

I_o is the light intensity under full transmission

$$I = I_o \sin^2\left(\frac{\pi}{2}\cdot\frac{V}{V_{\lambda/2}}\right)$$

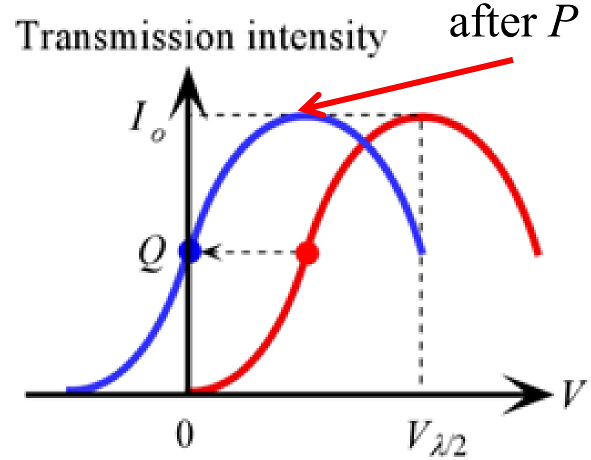
An applied voltage of $V_{\lambda/2}$ is needed to allow full transmission.

A Tranverse Pockels Cell Intensity Modulator

Transmission intensity vs. applied voltage characteristics. If a quarter-wave plate (QWP) is inserted after P, the characteristic is shifted to the blue curve.

$$I = I_o \sin^2\left(\frac{\pi}{2} \cdot \frac{V}{V_{\lambda/2}}\right)$$

In case a QWP is inserted after P



- In **digital electronics**, we would switch a light pulse on and off so that the nonlinear dependence of transmission intensity on V would not be a problem.
- To obtain a **linear modulation** between the intensity I and V we need to bias this structure about the apparent "linear region" of the curve at half-height.
  - This is done by inserting a quarter-wave plate (QWP) after the polarizer P.
  - The insertion of QWP means that $\Delta\phi$ is already shifted by $\pi/4$ before any applied voltage.
  - The applied voltage then, depending on the sign, increases or decreases $\Delta\phi$.

Example: Pockels Cell Modulator

What should be the aspect ratio *d/L* for the transverse $LiNbO_3$ phase modulator that will operate at a free-space wavelength of 1.3 μm and will provide a phase shift $\Delta\phi$ of π (half wavelength) between the two field components propagating through the crystal for an applied voltage of 12 V? At $\lambda = 1.3$ μm, $LiNbO_3$ has $n_o \approx 2.21$, $r_{22} \approx 5\times10^{-12}$ m/V.

Solution

Use $\Delta\phi = \pi$ for the phase difference between the field components $\mathbf{E}_x$ and $\mathbf{E}_y$,

$$\Delta\phi = \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V_{\lambda/2} = \pi$$

$$\frac{d}{L} = \frac{1}{\Delta\phi} \cdot \frac{2\pi}{\lambda} n_o^3 r_{22} V_{\lambda/2} \approx \frac{1}{\pi} \cdot \frac{2\pi}{(1.3\times10^{-6})} (2.21)^3 (5\times10^{-12})(12)$$

$$d/L \approx 1\times10^{-3}$$

This particular transverse phase modulator has the field applied along the *y*-direction and light traveling along the *z*-direction (optic axis). If we were to use the transverse arrangement in which the field is applied along the *z*-axis, and the light travels along the *y*-axis, the relevant Pockels coefficients would be greater, and the corresponding aspect ratio *d/L* would be ~10^{-2}. We cannot arbitrarily set *d/L* to any ratio we like for the simple reason that when *d* becomes too small, the light will suffer diffraction effects that will prevent it from passing through the device. *d/L* ratios $10^{-3} - 10^{-2}$ in practice can be implemented by fabricating an integrated optical device.

Kerr Effect

$$n' = n + a_1 E + a_2 E^2 + \ldots$$

Kerr effect term

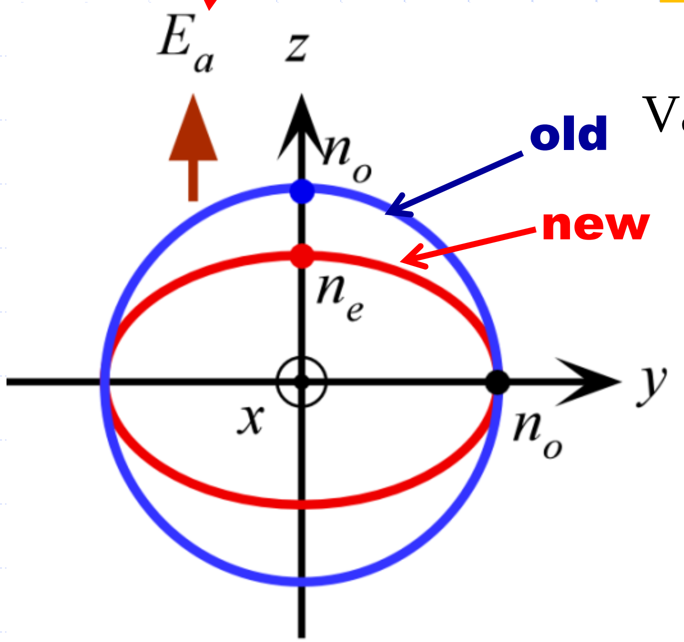
$$\Delta n = \lambda K E_a^2$$

Vacuum wavelength

Kerr coefficient

Applied field

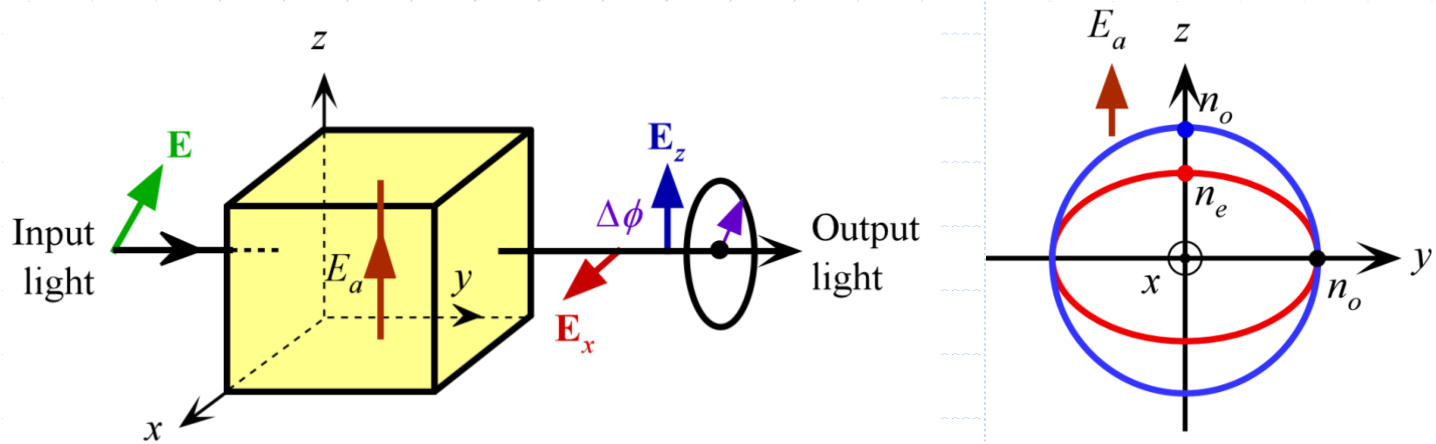
z-axis of a Cartesian coordinate system is along the applied field



An applied electric field, via the Kerr effect, induces birefringences in an optically isotropic material

Suppose that we apply a strong electric field to an optically isotropic material such as glass (or liquid). The change in the refractive index will be only due to the Kerr effect, a second-order effect.

Kerr Cell Phase Modulator.



- The figure shows the phase modulator that uses Kerr effect, whereupon the applied field E_a along z **induces a refractive index n_e** parallel to the z-axes, whereas that along the x-axis will still be n_o.
- The light components E_x and E_z then travel along the material with different velocities and emerge with a phase difference $\Delta\phi$ resulting in an elliptically polarized light.
- The change in the refractive index for polarization parallel to the applied field

$$\Delta n = \lambda K E_a^2$$

  - where K is the Kerr coefficient.

used to find the induced phase difference $\Delta\phi$

Electro-Optic Properties

Pockels (r) and Kerr (K) coefficients in a few selected materials
Values in parentheses for r values are at very high frequencies

Material	Crystal	Indices	Pockels Coefficients ´ 10^{-12} m/V	K m/V^2	Comment
$LiNbO_3$	Uniaxial	$n_o = 2.286$ $n_e = 2.200$	$r_{13} = 9.6$ (8.6); $r_{33} = 309$ (30.8) $r_{22} = 6.8$ (3.4); $r_{51} = 32.6$ (28)		$\lambda \approx 633$ nm
KDP (KH_2PO_4)	Uniaxial	$n_o = 1.512$ $n_e = 1.470$	$r_{41} = 8.8$; $r_{63} = 10.3$		$\lambda \approx 546$ nm
KD*P (KD_2PO_4)	Uniaxial	$n_o = 1.508$ $n_e = 1.468$	$r_{41} = 8.8$; $r_{63} = 26.8$		$\lambda \approx 546$ nm
GaAs	Isotropic	$n_o = 3.6$	$r_{41} = 1.43$		$\lambda \approx 1.15$ μm
Glass	Isotropic	$n_o \approx 1.5$	0	3×10^{-15}	
Nitrobenzene	Isotropic	$n_o \approx 1.5$	0	3×10^{-12}	

Kerr Effect Example

Example: Kerr Effect Modulator

Suppose that we have a glass rectangular block of thickness (d) 100 μm and length (L) 20 mm and we wish to use the Kerr effect to implement a phase modulator in a fashion depicted in Figure 6.26. The input light has been polarized parallel to the applied field E_a direction, along the z-axis. What is the applied voltage that induces a phase change of π (half-wavelength)?

Solution

The phase change $\Delta\phi$ for the optical field E_z is

$$\Delta\phi = \frac{2\pi\Delta n}{\lambda}L = \frac{2\pi(\lambda K E_a^2)}{\lambda}L = \frac{2\pi L K V^2}{d^2}$$

For $\Delta\phi = \pi$, $V = V_{\lambda/2}$,

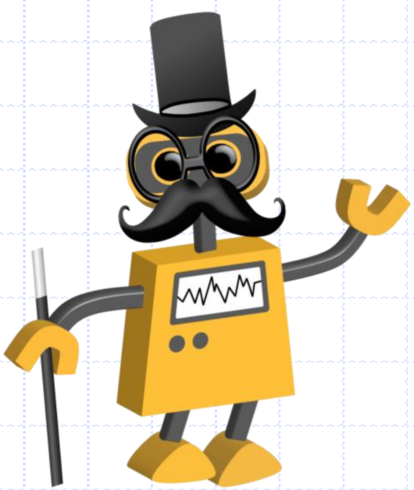
$$V_{\lambda/2} = \frac{d}{\sqrt{2LK}} = \frac{(100\times10^{-6})}{\sqrt{2(20\times10^{-3})(3\times10^{-15})}} = 9.1\text{kV}$$

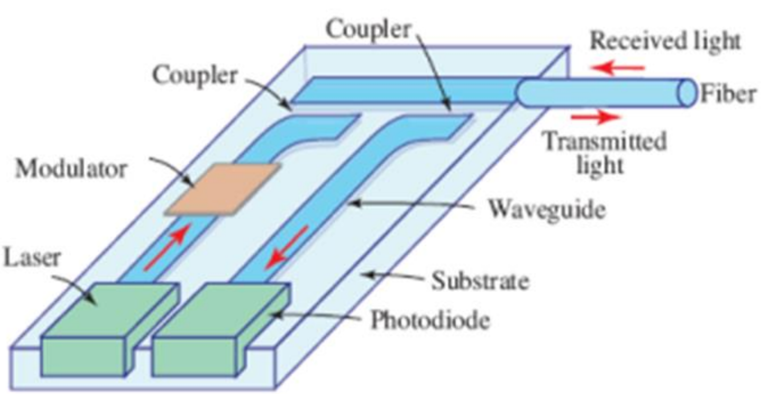
Although the Kerr effect is fast, it comes at a costly price. Notice that K depends on the wavelength and so does $V_{\lambda/2}$.

Integrated Optical Modulators

Integrated optics refers to the integration of various optical devices and components on a single common substrate, for example lithium niobate, just as in integrated electronics all the necessary devices for a given function are integrated in the same semiconductor crystal substrate (chip).

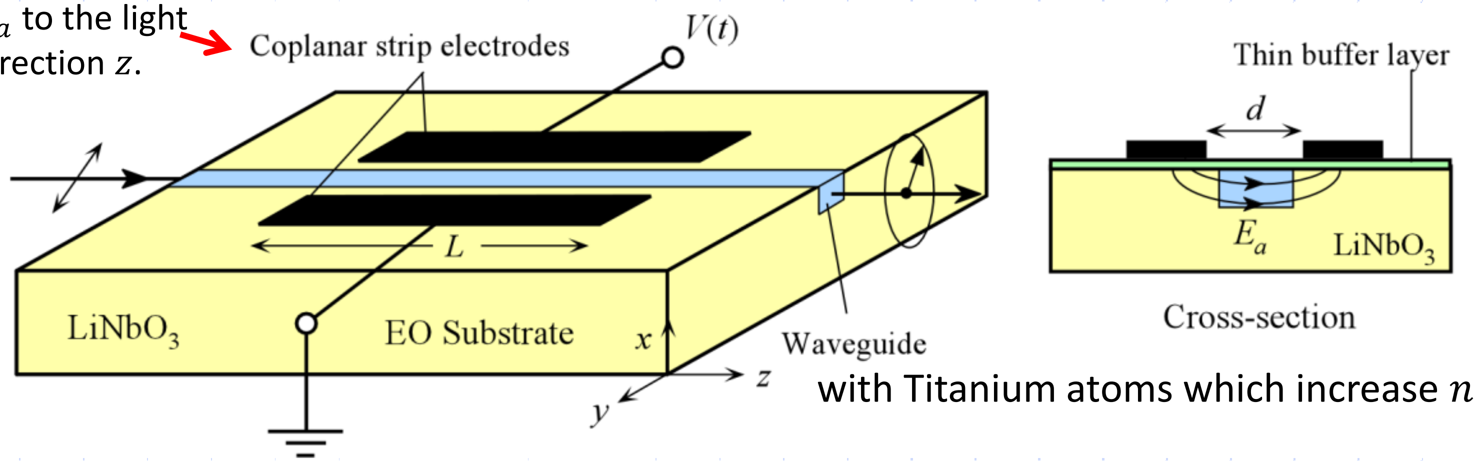
There is a distinct advantage to implementing various optically communicated devices, for example laser diodes, waveguides, splitters, modulators, and photodetectors on the same substrate, as it leads to **miniaturization** and also to an overall **enhancement** in performance and **usability**.





Phase and Polarization Modulation

enable the application of a transverse field E_a to the light propagation direction z.



with Titanium atoms which increase n

The electro-optic effect takes place over the spatial overlap region between the applied field and the optical fields.

The **spatial overlap efficiency** is represented by a coefficient Γ

The **phase shift** is $\Delta\phi$ and depends on the voltage V through the **Pockels effect**

$$\Delta\phi = \Gamma \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V$$

- Induced phase change: $\Delta\phi$
- Length of electrodes: L
- Applied voltage: V
- Electrode separation: d
- Pockels coefficient Different for different crystal orientations: r_{22}
- Spatial overlap efficiency = 0.5 – 0.7: Γ

Integrated Optical Modulators

$$\Delta\phi = \Gamma \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V$$

$\Delta\phi$ depends on the product $V \times L$

When $\Delta\phi = \pi$, then $V \times L = V_{\lambda/2} L$

Consider an x-cut $LiNbO_3$ modulator (as in the previous figure) with $d \approx 10\ \mu m$,

operating at $\lambda = 1.5\ \mu m$

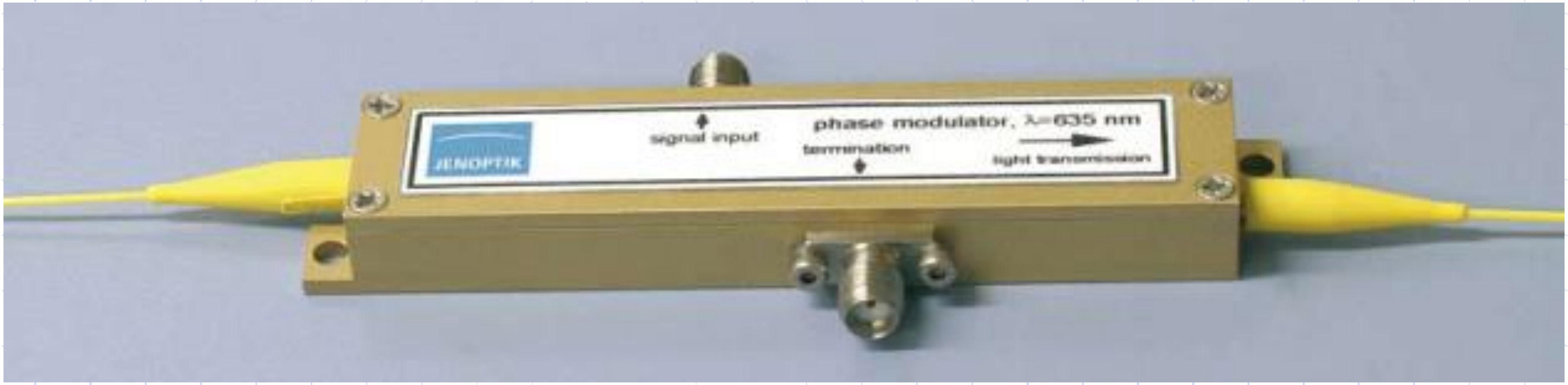
This will have $V_{\lambda/2} L \approx 35$ V·cm

A modulator with $L = 2$ cm has $V_{\lambda/2} = 17.5$ V

By comparison, for a z-cut $LiNbO_3$ plate, that is for light propagation along the y-direction and E_a along z, the relevant Pockels coefficients (r_{13} and r_{33}) are much greater than r_{22} so that

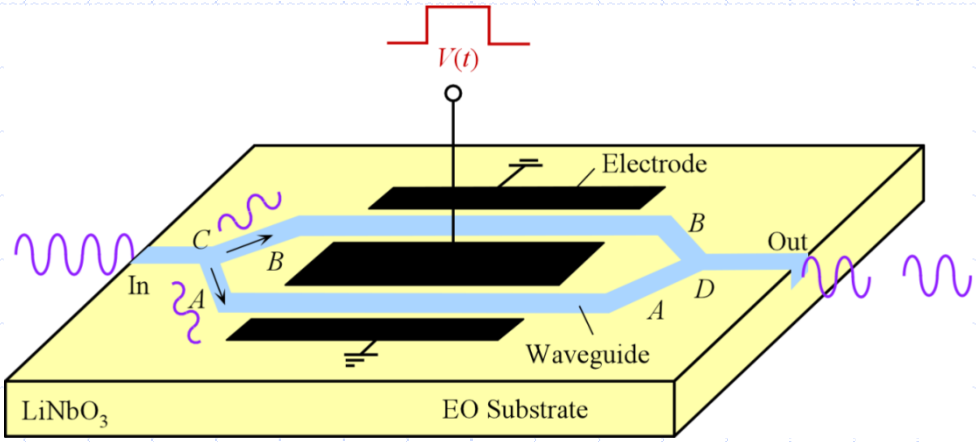
$V_{\lambda/2} L \approx 5$ V·cm

A $LiNbO_3$ Phase Modulator



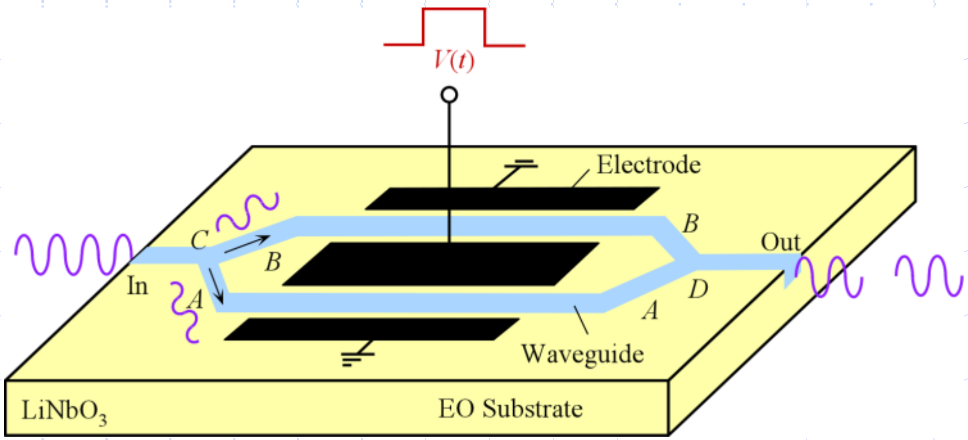
A $LiNbO_3$ based phase modulator for use from the visible spectrum to telecom wavelngths, with modulation speeds up to 5 GHz. This particular model has $V_{\lambda/2}$ = 10 V at 1550 nm. (© JENOPTIK Optical System GmbH.)

Integrated Mach-Zehnder Modulators



- Induced **phase shift** by applied voltage can be converted to an **amplitude variation** by using an **interferometer**, a device that interferes two waves of the same frequency but different phase.
- The structure acts as an interferometer because the two waves traveling through the arms *A* and *B* interfere at the output port *D*, and the **output amplitude** depends on the **phase difference** (optical path difference) between the *A* and *B*-branches.
- Two back-to-back identical phase modulators enable the phase changes in *A* and *B* to be modulated.
- The applied field in branch *A* is in the opposite direction to that in branch *B*.
  - The refractive index changes are therefore opposite, which means the phase changes in arms *A* and *B* are also opposite.

Integrated Mach-Zehnder Modulators



Approximate analysis

Input C breaks into A and B

A and B experience opposite phase changes arising from the Pockels effect

A and B interfere at D. Assume they have the same amplitude A

But, they have opposite phases

$$E_{out} \propto A\cos(\omega t + \phi) + A\cos(\omega t - \phi) = 2A\cos(\phi)\ \cos(\omega t)$$

Amplitude

Output power $P_{out} \propto E_{out}^2$

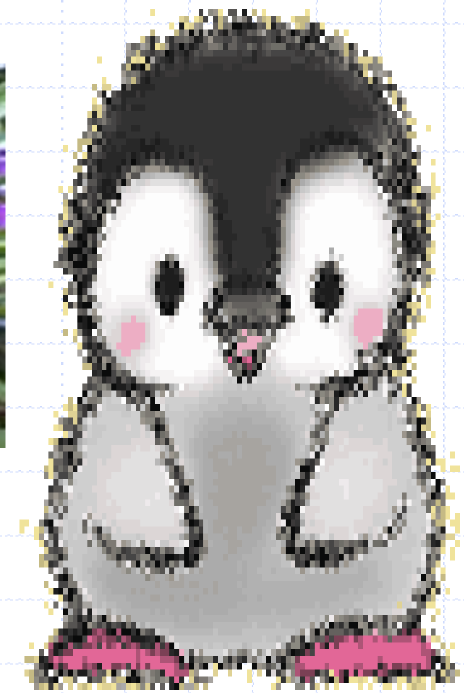
$$\frac{P_{out}(\phi)}{P_{out}(0)} = \cos^2 \phi$$

maximum when $\phi = 0$

A $LiNbO_3$ Mach-Zehnder Modulator

A $LiNbO_3$ based Mach-Zehnder amplitude modulator for use from the visible spectrum to telecom wavelengths, with modulation frequencies up to 5 GHz. This particular model has $V_{\lambda/2}$ = 5 V at 1550 nm. (© JENOPTIK Optical System GmbH.)

Thank you



Have a nice day.