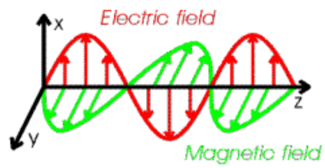
Polarization of Light

Introduction: From the properties of interference and diffraction we are led to conclude that light is a wave phenomenon, and we utilize these properties to measure the wavelength.

- These effects tell us nothing about the types of waves with which we are dealing whether they are longitudinal or transverse
- The phenomenon of polarization has helped to establish beyond doubt that light waves are transverse.

Light wave is transverse wave

- Light is an electromagnetic (EM) wave.
- It consists of vibrations of electric field and magnetic field.
- The electric field and magnetic field are perpendicular to each other and in phase.
- EM wave is a transverse wave.
- The speed of EM wave is 3 x 10^8 ms^{-1}.



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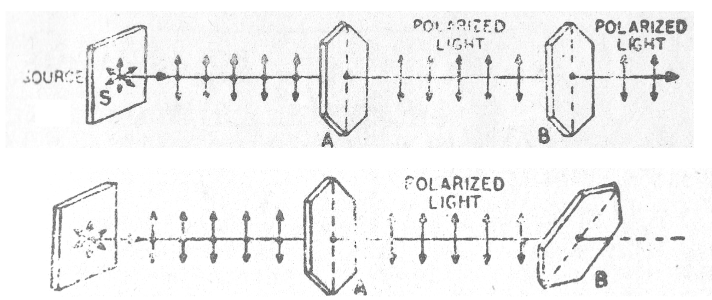
Proof of transverse wave: Suppose two tourmaline crystals A and B are placed with their axes *a* and *b* parallel as shown in Fig. below:



If a beam of light is incident on A, the light emerging from B is slightly darker. If B is rotated slowly about the line of vision with its plane parallel to A, the emergent light becomes darker and at one stage light will disappear completely. In the later case the axes *a* and *b* of the crystals are perpendicular. When B is rotated further the light reappears and becomes brightest when the axes *a* and *b* are parallel. This simple experiment leads to the conclusion that light waves are transverse wave; otherwise light emerging from B could never be extinguished by simple rotating the crystal.

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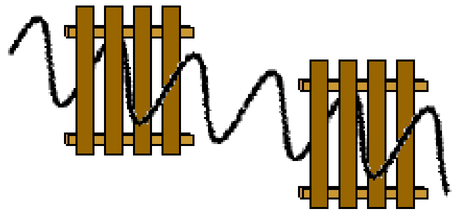
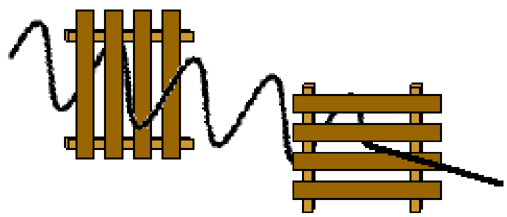
Polarization by Selective Absorption

The Picket Fence Analogy

Polarization of light by selective absorption is analogous to that shown in the diagrams.



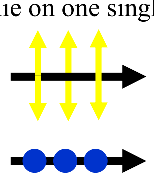
When the pickets of both fences are aligned in the vertical direction, a vertical vibration can make it through both fences.



When the pickets of the second fence are horizontal, vertical vibrations which make it through the first fence will be blocked.

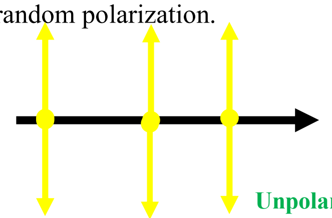
Polarized Light

Polarized Light
Vibrations lie on one single plane only.

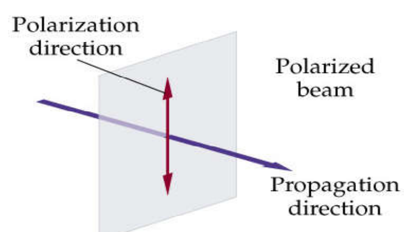


Polarized

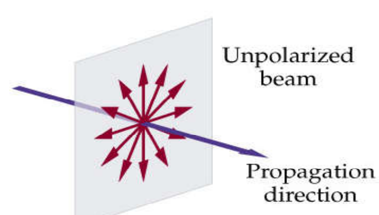
Unpolarized Light
Superposition of many beams, in the same direction of propagation, but each with random polarization.



Unpolarized



(a)



(b)

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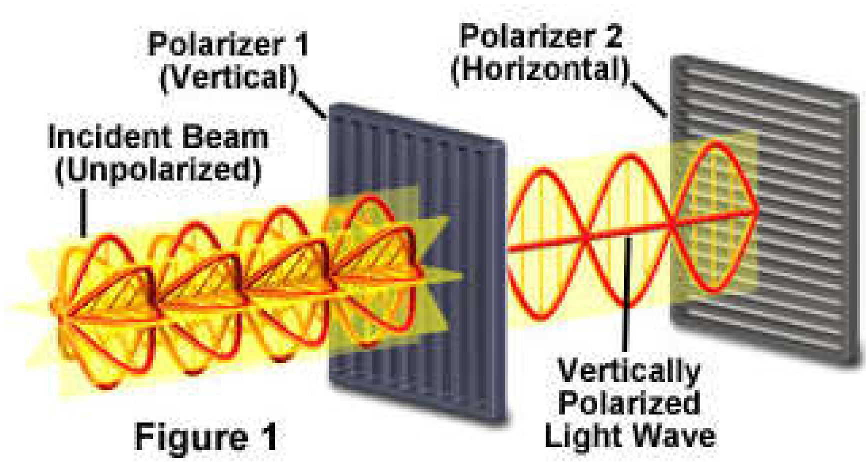
Polarization of Light



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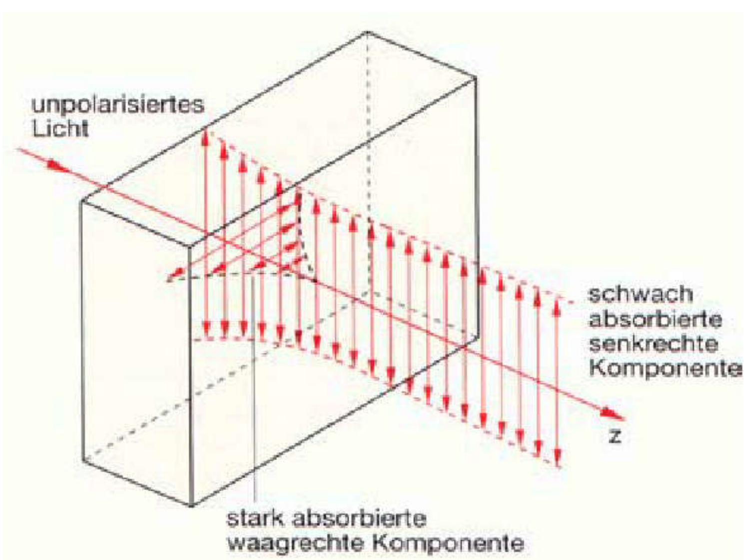

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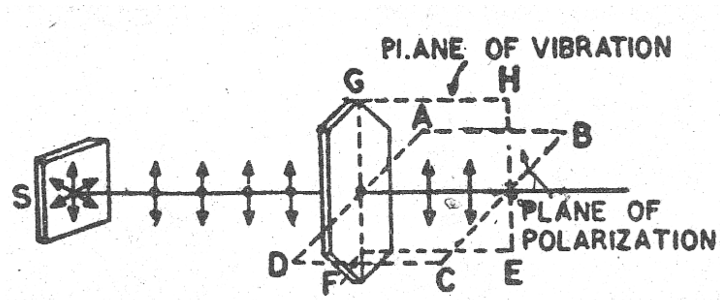
Polarization

By allowing a natural beam of light to pass through a tourmaline crystal if the arbitrary vibrations of the light waves can be confined only to a single direction, in the plane perpendicular to the direction of propagation of light, the light is said to be **plane polarized** and the phenomenon is known as *polarization of light*.

The plane of polarization is that plane in which no vibrations occur (ABCD). The vibrations occur at right angle to plane of polarization and the plane in which vibrations occur is known as plane of vibration (EFGH).

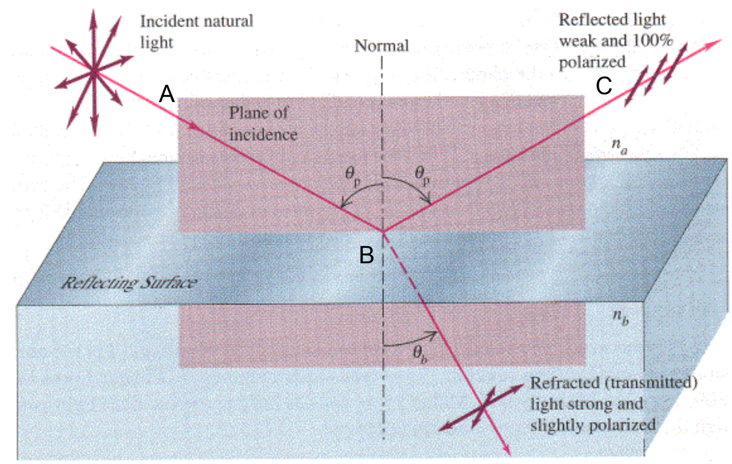


Methods of producing plane polarized light

Plane polarized light can be produced by the following way:

(i) By reflection
(ii) By Polaroid
(iii) By transmission through a pile of plates
(iv) By double refraction
(v) By scattering
(vi) By Dichroic crystals.

Polarization by reflection



Polarization of light by reflection from the surface of glass was discovered by ***Etienne Louis Malus, military engineer and captain in the army of Napoleon,*** in 1808. He found that polarized light can be obtained when ordinary light is reflected by a plane sheet of glass.

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Consider the light is incident along the path AB on the glass surface. Light will be reflected along BC. In the path of BC, place a tourmaline crystal and rotate it slowly. It will be observed that the light will be totally extinguished only at one particular crystal of incidence. This angle of incidence θp is about 57^0 for glass surface and is known as ***polarizing angle***.

The production of polarized light by glass can be explained as follows:

Vibration of the incident light can be resolved into two components parallel to the glass surface and is perpendicular to the glass surface. Light due to the component parallel to the glass surface is reflected, whereas light due to component perpendicular to the glass surface is transmitted.

Thus the light reflected by glass is plane polarized and can be detected by a tourmaline crystal.

Because of the “inconvenient geometry” – the polarized wave does not travel along the same direction as the incident wave -- polarization by reflection is not very often used in practical devices, even though it is perhaps the least expensive method!

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Brewster's Law

In 1811, Brewster found that ordinary light is completely polarized in the plane of incidence when it gets itself reflected from a transparent medium at a particular angle known as the angle of polarization.

"It was found that the tangent of the angle of polarization is numerically equal to the refractive index of the medium. Moreover, the reflected and refracted rays are perpendicular to each other."

Suppose, the unpolarized light is incident at an angle equal to the polarizing angle on the glass surface. It is reflected along BC and refracted along BD.

According to Brewster's law

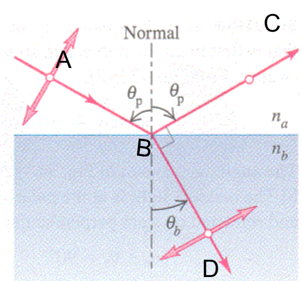
$$\mu = \tan\theta_P$$

$$or,\ \mu = \frac{\sin\theta_P}{\cos\theta_P}$$

According to Snell's law

$$or,\ \mu = \frac{\sin\theta_P}{\sin\theta_b}$$

This is the condition for the reflected wave to be 100% polarized. The incident angle satisfying this condition is called the Brewster Angle.



Therefore,
$$\mu = \frac{\sin\theta_P}{\sin\theta_b} = \frac{\sin\theta_P}{\cos\theta_P}$$
$$or,\ \sin\theta_b = \cos\theta_P$$
$$Or,\ \cos\left(\frac{\pi}{2} - \theta_b\right) = \cos\theta_P$$
$$or,\ \theta_P + \theta_b = \frac{\pi}{2}$$

$$Thus\ \angle CBD = \frac{\pi}{2}$$

Thus reflected and refracted rays are at right angles to each other.

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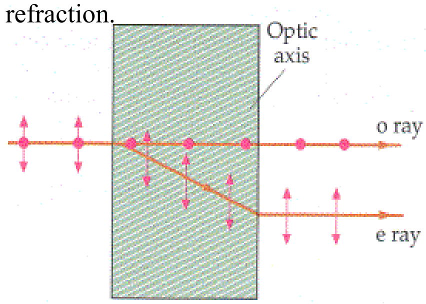
Polarization by the effect of double refraction or *birefringence*

Some crystals have the peculiar property, called birefringence: Polarization can be achieved with crystalline materials which have a different index of refraction in different planes. Such materials are said to be birefringent or doubly refracting. It was found that when a ray of light is refracted by a crystal of calcite it gives two refracted rays. This phenomenon is called double refraction.



A light ray incident on a birefringent material is split into two beams, called the ordinary (o ray) and extraordinary ray (e ray), that have mutually perpendicular polarizations.

(Calcite is chemically $CaCO_3$). Calcite occurs in nature in a great variety of crystal forms (in the rhombohedral class of the hexagonal system) but it breaks readily into simple cleavage rhombohedron of the from as shown in figure. Each face of the crystal is a parallelogram whose angles are 78° and 102 ° (more accurately 78°5/ ansd 101°55/).

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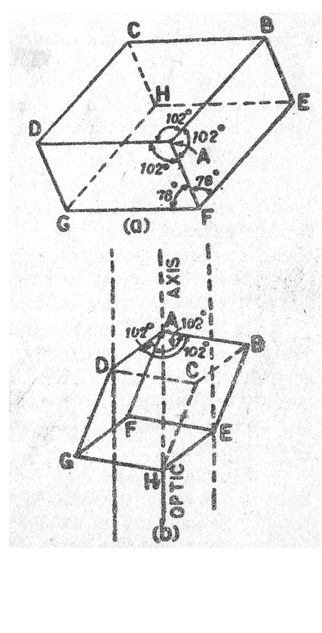

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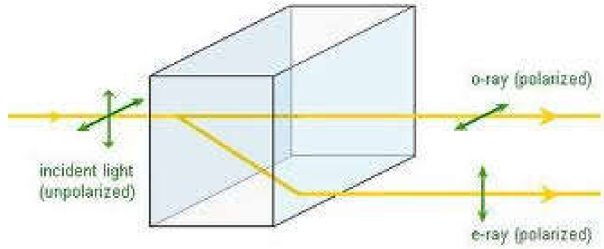
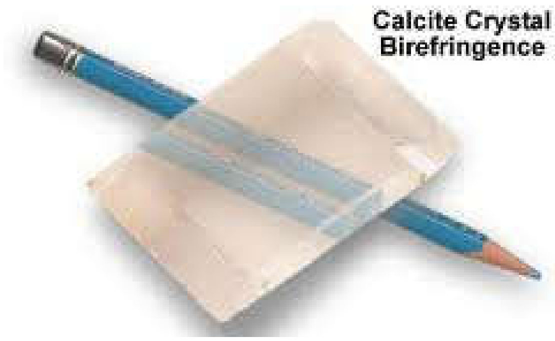


Calcite (a crystalline form of $CaCO_3$) is transparent, completely colorless, and exhibits unusually strong birefringence properties.



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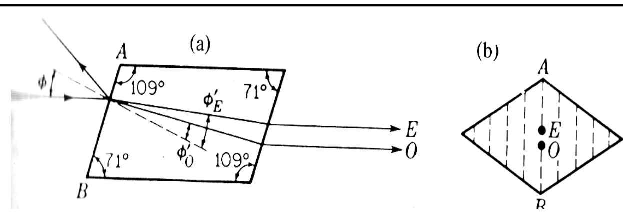

Quartz is another crystal, which exhibit double refraction. Chemically, quartz is pure silica (SiO_2).

When a beam of ordinary unpolarized light is incident on a calcite or quartz crystal, there will be, in addition to the reflected beam, two refracted beams in place of the usual single one observed for example in glass. This phenomenon for calcite is called **double refraction or birefringence.** Upon measuring the angle of refraction $\phi'(i.e.\ \phi'_0, \phi'_E)$ for different angles of incidence ϕ, it can be found that Snell's law of refraction $(\frac{\sin\phi}{\sin\phi'} = \mu)$ hold's for one ray but not for the other. The ray for which the law holds is called the ***ordinary ray*** and the other is called the ***extraordinary ray***.

It is found that both rays are plane polarized. The vibrations of the ordinary rays are perpendicular to the principle section of the crystal while the vibrations of the extraordinary rays are in the plane of the principle section of the crystal.

(A plane which contains the optic axis and perpendicular to the opposite faces of the crystal is called the principle section of the crystal)

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becomes plane polarized. When this plane polarized light incident on a second tourmaline crystal, it will pass through if the optic axis of the second crystal is parallel to the first crystal. The first crystal is referred to as the ***polarizer***. While the second crystal is known as the ***analyzer*** as it helps to detect polarized light. When the optic axes of both the polarizer and the analyzer are parallel to each other the intensity of the emergent polarized light is maximum let this maximum intensity be $I_{0.}$ As the analyzer is gradually rotated, the intensity of the transmitted light goes on decreasing until it becomes zero, when the optic axes of the two crystals are at right angles to each other. If the rotation of the analyzer is continued then light gradually re-appears until original intensity of the emergent light is restored. When the analyzer has turned through 180^0 with respect to the polarizer i.e. the two axes again becomes parallel to another. Consider the case when the analyzer has been rotated through and angle

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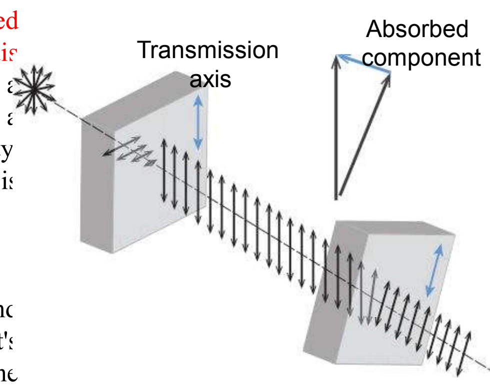
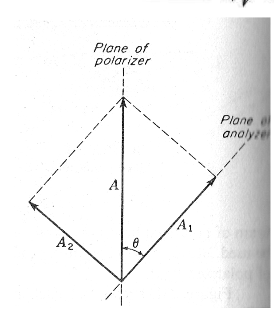
Malus' law, discovered experimentally by Etienne-Louis Malus in 1809, says that when a perfect polarizer is placed in a polarized beam of light, the intensity *I*, of the light that passes through is given by

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

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



Consider the case when the analyzer has been rotated through and angle θ from its position of maximum intensity. The amplitude A of the plane polarized light incident on the analyzer can be resolved into two components perpendicular to each other.



The component A cosθ is transmitted while the component Asinθ is eliminated in the analyzer.
The intensity I of the transmitted light at this position is given by

$$I \propto A^2 \cos^2\theta$$
$$I_0 \propto A^2$$
$$Therefore,\ I = I_0 \ \cos^2\theta$$

This is known as Malus cosine law according to which the intensity at the polarized light emerging from the analyzer is proportional to the square of the cosine of the angle between polarizer and analyzer.

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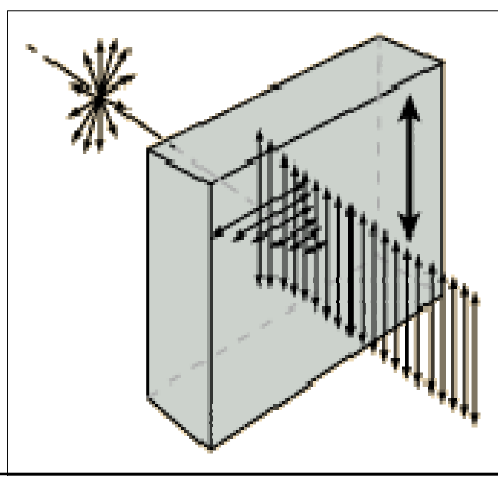
Polarization by Dichroism

A dichroic material has different absorption properties for perpendicular incident planes. An example of a dichroic material is the tourmaline that is a class of borone silicate. The tourmaline has a unique optic axis, and any electronic field normal to it is strongly absorbed.



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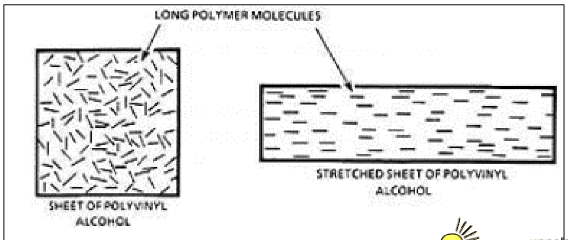
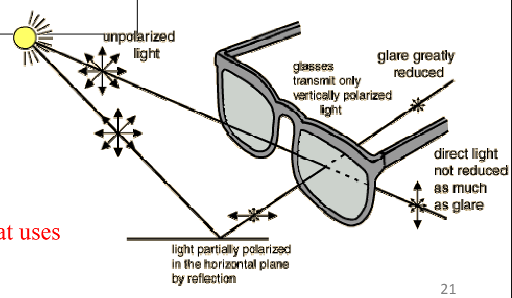
Polaroids (Dichroism)

In 1928 Edwin H. Land undergraduate at Harvard College invented the Polaroid J-sheet. It consists of many microscopic Crystals of iodoquinine sulphate embeded in a transparent Nitrocellulose polymer film.

Edwin H. Land 1909-1991





The sunglasses use polaroid material that uses dichroism to achieve absorption..

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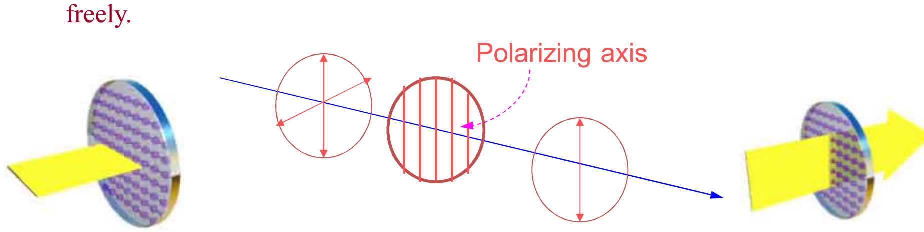
- A Polaroid filter transmits 80% or more of the intensity of a wave that is polarized parallel to a certain axis in the material, called the *polarizing axis*.
- Polaroid is made from long chain molecules oriented with their axis perpendicular to the polarizing axis; these molecules preferentially absorb light that is polarized along their length.
- An electric field *E* that oscillates parallel to the long molecules can set electrons into motion along the molecules, thus doing work on them and transferring energy. Hence, *E* gets absorbed.
- An electric field *E* perpendicular to the long molecules does not have this possibility of doing work and transferring its energy, and so passes through freely.



- When we speak of the axis of a Polaroid, we mean the direction which *E* is passed, so a polarizing axis is perpendicular to the long molecules.

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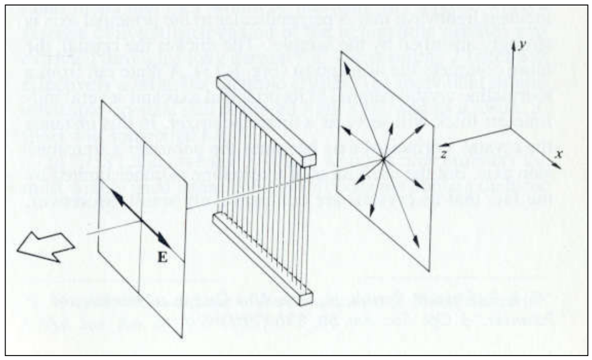
Wire-Grid Polarizer (Dichroism)

Grid of parallel conducting wires with a spacing comparable to the wavelength of the electromagnetic wave. The Electric Field vector parallel to the wires is attenuated because of the currents induced in the wires.



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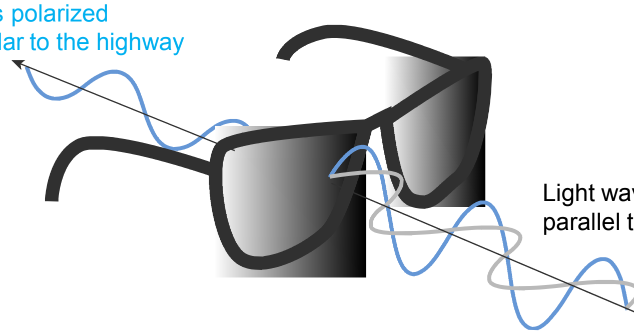
Polarized Sunglasses



- Polarized lenses have the added benefit of filtering out reflected light, or glare, off surfaces such as water or pavement
- Ideal for boating, fishing, driving or any other activity associated with intense glare. Reduce glare off the roads while driving .
- Reduces eyestrain and fatigue, while increasing contrast and visual acuity

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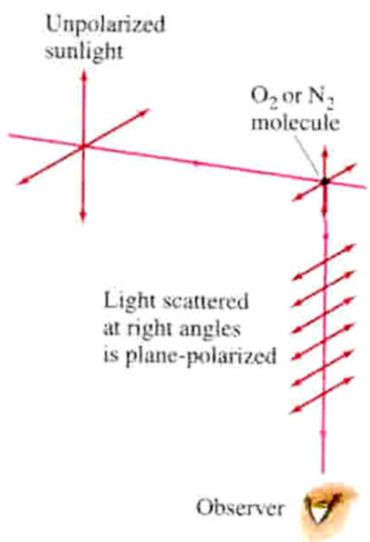
Scattering of Sunlight



When unpolarised sunlight impinges on the molecules, the electric field of the EM wave sets the electric charges within the molecules into motion. The EM wave is **absorbed**.

The molecules then quickly **re-emit light in all directions** since oscillating electric charges produce EM waves.

Because of the **transverse nature** of light, the electric field of the re-emitted waves should be in the plane that includes the line of oscillation, the **scattered light is completely plane polarized** with its electric vector in the direction shown.

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NICOL PRISM

It is an Optical device used for producing analyzing plane polarized light. It was invented by William Nicol in 1828. The Nicol prism is made in such a way that it removes one of the two refracted rays by total internal reflection.

Construction

First a calcite crystal about three times as long as it is wide is taken and the ends cut down from 71° in the principal section to a more acute angle of 68°. The crystal is then cut apart along the plane $A^/D^/$ perpendicular to both the principle section and the end faces. The two cut surfaces are round and polished optically flat and then cemented together with Canada balsam. Canada balsam is used because it is clear transparent substance with an index of refraction about midway between the index of the O and E rays.

For sodium light Index of O ray, $\mu_0 = 1.65836$

Index of Canada balsam $\mu_B = 1.55$, Index of E ray $\mu_E = 1.48641$

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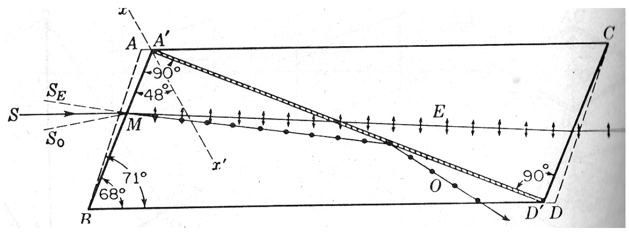

Optically the balsam is denser than the calcite for the E-ray and lens dense for O-ray. Therefore, when the O-ray passes from a portion of the crystal into the layer at Canada balsam it passes from denser to rarer medium. If the angle of incidence is greater than the critical angle, the ray is totally internally reflected and is not transmitted. The E-ray is not affected and is there fore transmitted through the prism.

The Nicol Prism is an extremely efficient polarizer, but very expensive. Therefore, it is used only in apparatus in which high precision is crucial.

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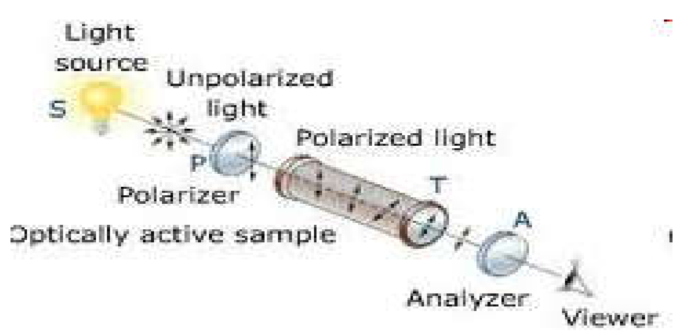
Optically active media

Some materials and compounds have the ability of "twisting" the polarization direction of polarized light passing through them. We call them "optically active".



Some materials rotate the plane of vibration to the right and they are called dextro-rotatory or right-handed. The substance that rotate the plane of vibration to the left are known as laevo-rotatory or left-handed.

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Specific rotation

Liquids containing an optically active substance e.g. sugar solution, camphor in alcohol etc, rotate the plane of the polarized light. The angle through which the plane polarized light is rotated depends upon.

(i) The thickness of the medium,
(ii) Concentration of the solution,
(iii)Wavelength of light, and (iv) temperature

The specific rotation is defined as the rotation produced by a decimeter (10cm) long column of the liquid containing 1g of the active substance in 1 cm^3 of the solution.

Then $S_\lambda^t = \dfrac{10\theta}{lc}$ where, l = length of the solution, θ angle of rotation, c = concentration of the solution.

Problem: Calculate specific rotation if the plane of polarization is turned through 26.4°, traversing 20 cm length of 20% sugar solution.

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Problems

2. The refractive index for plastic is 1.25. Calculate the angle of refraction for a ray of light incident at polarizing angle.

Solution; According to Brewster's law

$$\mu = \tan\theta$$
$$or, \theta = \tan^{-1}(1.25) = 51.4^0$$
$$Now \quad \theta + \gamma = 90^0$$
$$\gamma = 38.6^0$$

3. How will you orient the Polarizer and the analyzer, 80 that a beam at natural light is reduced to (i) 0.125 (ii)0.25 (iii) 0.5 and (iv) 0.75 of its original intensity?

From Malus Law

$$I = I_0 \cos^2\theta.$$
$$or \quad \frac{I}{I_0} = \cos^2\theta$$

$$\cos^2\theta = \frac{I}{I_0} = 0.125 \quad or \ \cos\theta = \sqrt{0.125} = 0.35$$
$$\theta = \cos^{-1}(0.35) = 69^0 18'$$

$(ii)\ \theta = 60^\circ$, $(iii)\ \theta = 45^\circ$, $(iv)\theta = 30^\circ$

4, The critical angle for certain wavelength of light in the case of a piece of glass 40^0. Find the polarizing angle the glass.

$$\mu = \frac{1}{\sin\theta_c} = \frac{1}{\sin 40^0} = 1.556$$

$$\mu = \tan\theta_p$$
$$\theta_p = \tan^{-1}(\mu) = 57.3^0$$

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