WAVE OPTICS

POLARISATION

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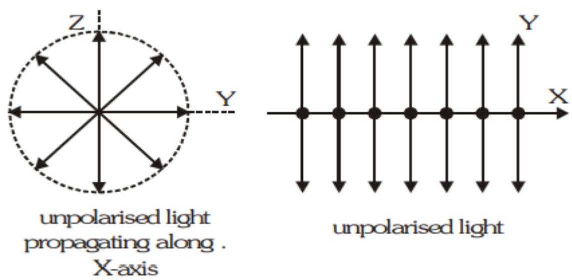
Experiments concerning interference and diffraction have provided compelling evidence that light exhibits wave-like characteristics. However, these observations alone do not elucidate the specific nature of this wave motion, that is, whether light waves manifest as longitudinal or transverse waves. It is through the phenomenon of polarization that we have garnered conclusive proof, firmly establishing that light waves indeed exhibit the attributes of transverse waves.

UNPOLARISED LIGHT

A typical beam of light comprises a multitude of individual waves, each originating from the atoms within the light source. In this context, each atom generates a wave with its own unique orientation of the electric vector $\vec{E}$. Consequently, the various directions in which the electric vector $\vec{E}$ can oscillate are all equally likely and probable.



The collective electromagnetic wave that emerges is a composite of the individual waves generated by the myriad atomic sources, and it is identified as polarized light. In the context of ordinary or polarized light, the oscillations of the electric vector transpire symmetrically in all conceivable directions within a plane that is perpendicular to the light's propagation direction.

POLARISATION

The process of constraining the oscillation of light, specifically the electric vector, to a particular orientation perpendicular to the direction of the wave's propagation, is recognized as the polarization of light. In polarized light, the electric vector's vibrations manifest within a plane that is orthogonal to the direction of light's propagation, and these vibrations are limited to a singular direction within that plane, as opposed to symmetrically spanning all possible directions. Consequently, following the process of polarization, the vibrations adopt an asymmetric pattern about the direction of light's propagation.

POLARISER

Tourmaline crystal

When light is transmitted through a tourmaline crystal cut in a manner parallel to its optic axis, the light's oscillations are constrained to a singular direction within a plane that is orthogonal to the path of light propagation. The light emerging from the crystal under these conditions is referred to as "plane-polarized light." This phenomenon was instrumental in the development of the Nicol prism, a device designed to manipulate polarized light.

Prism

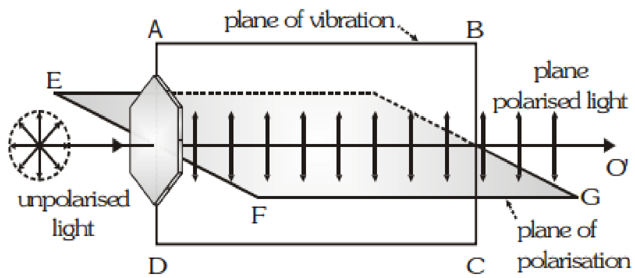
The Nicol prism stands as an optical instrument employed to create and identify plane-polarized light. This ingenious device, attributed to the inventor William Nicol in the year 1828, plays a pivotal role in manipulating polarized light for various scientific and industrial applications.

Polaroid

A Polaroid refers to a slender commercial sheet, typically fashioned in the shape of a circular disc. It leverages the principle of selective absorption to generate a concentrated stream of plane-polarized light. This property makes Polaroid's valuable tools for various applications where polarized light is required.

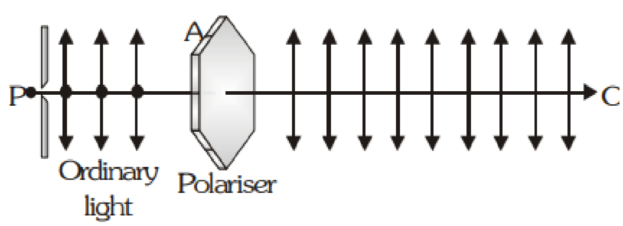
PLANE OF POLARISATION AND PLANE OF VIBRATION

The plane encompassing the oscillations of the light vector and the direction of its propagation is designated as the "plane of vibration." Perpendicular to this plane of vibration, there exists another plane where no oscillations of light occur, and this plane is referred to as the "plane of polarization."



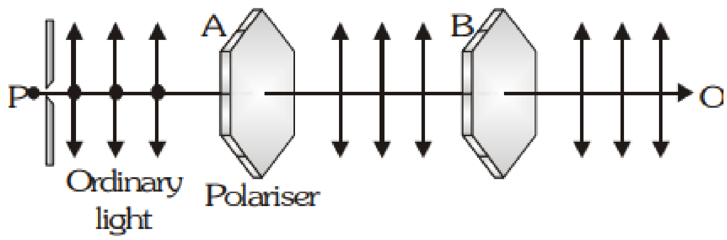
EXPERIMENTAL DEMONSTRATION OF POLARISATION OF LIGHT

Obtain two tourmaline crystals that have been precisely cut to align with their crystallographic axis, which is often referred to as the optic axis.

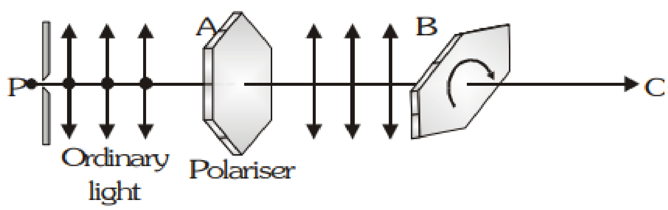


Begin by positioning the crystal denoted as A at a right angle to the direction of a colored light beam. In this configuration, the emerging light will exhibit a faint coloration. When you proceed to rotate crystal A around its central axis, you will observe no alterations in either the brightness or the hue of the transmitted light.

Subsequently, introduce another crystal, denoted as B, into the path of the emerging light so that its axis aligns parallel to the axis of crystal A. In this setup, the light beam now traverses both crystals, resulting in the transmitted light displaying a discernible coloration.



Next, proceed to pivot crystal B around the axis labeled as PO. You will observe that the intensity of the light emerging from the crystals diminishes. When the axes of both crystals are situated in a configuration where they are perpendicular to each other, no light passes through crystal B, resulting in the absence of light exiting from it.



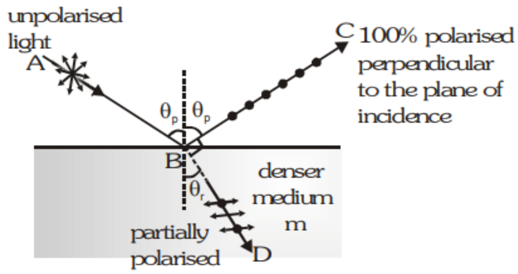
Continuing the experiment, when you further rotate crystal B, you'll notice that light re-emerges, and its intensity reaches its maximum point once the axes of the two crystals become parallel again. This specific outcome is achieved through an additional 90° rotation of crystal B. This experimental demonstration serves as a confirmation of the transverse nature of light waves, where the vibrations within light waves are oriented perpendicular to the direction of wave propagation.

In this context, the initial crystal, denoted as A, functions to polarize the light, earning it the title of "polarizer." Meanwhile, the second crystal, B, is responsible for assessing whether the light is polarized or not, hence it is referred to as an "analyzer."

METHODS OF OBTAINING PLANE POLARISED LIGHT

Polarization by reflection

The most straightforward technique for generating plane-polarized light is through the process of reflection. This particular method was first identified by Malus in the year 1808. When a beam of ordinary light is directed towards a surface and subsequently reflected, the resulting reflected light becomes partially polarized. The extent of polarization in the reflected light is most pronounced when the incident light approaches the surface at a specific angle, commonly referred to as the "polarizing angle" or "Brewster's angle."



Polarizing angle

The polarizing angle is defined as the angle of incidence at which the reflected light becomes fully plane-polarized.

Brewster's Law

When unpolarized light meets an interface separating a rarer medium from a denser one, characterized by a refractive index μ, at a specific angle of incidence denoted as θ_P, such that $\mu = \tan\theta_P$, the light reflected from the rarer medium becomes entirely plane-polarized. Additionally, the reflected and refracted rays are oriented at right angles to each other. This fundamental relationship is recognized as Brewster's law, which succinctly states that the tangent of the polarizing angle of incidence within a transparent medium equals its refractive index: $\mu = \tan\theta_P$.

In the context of polarization by reflection, the following observations hold:

1. When the angle of incidence (i) is equal to the polarizing angle (θ_P), the refracted light is only partially polarized.

2. When the angle of incidence equals the polarizing angle ($i = \theta_P$), both the reflected and refracted rays are oriented at right angles to each other.

3. When the angle of incidence is either less than ($i < \theta_P$) or greater than ($i > \theta_P$) the polarizing angle, both the reflected and refracted light exhibit partial polarization to some degree.

According to snell's law

$$\mu = \frac{\sin\theta_p}{\sin\theta_r} \quad \text{............ (i)}$$

But according to Brewster's law

$$\mu = \tan\theta_p = \frac{\sin\theta_p}{\cos\theta_r} \quad \text{............ (ii)}$$

From equation (i) and (ii)

$$\frac{\sin\theta_p}{\sin\theta_r} = \frac{\sin\theta_p}{\cos\theta_p} \Rightarrow \sin\theta_r = \cos\theta_p$$

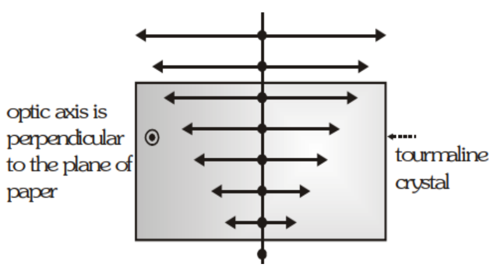
$$\sin\theta_r = \sin(90° - \theta_p) \Rightarrow \theta_r = 90° - \theta_p \text{ or } \theta_p + \theta_r = 90$$

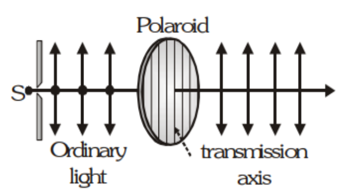
Thus, reflected and refracted rays are mutually perpendicular

By Refraction

In this technique, a stack of glass plates is created by assembling approximately 20 to 30 microscope slides, and light is directed towards them at an incident angle of 57°, which is the polarizing angle as determined by Brewster's law. According to this law, the light reflected from this setup will be plane-polarized, with vibrations occurring perpendicular to the plane of incidence. Simultaneously, the light that passes through the plates will be partially polarized.

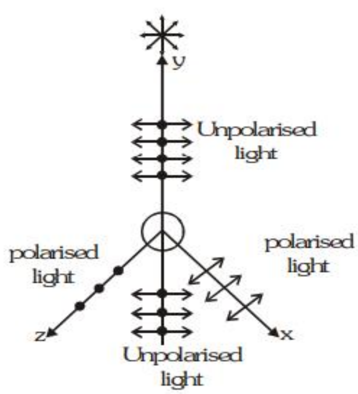
Given that approximately 15% of the light, with vibrations perpendicular to the plane of the glass plates, is reflected in each reflection, after passing through multiple plates, the emerging light will transform into plane-polarized light, with its vibrations occurring within the plane of the glass plates.



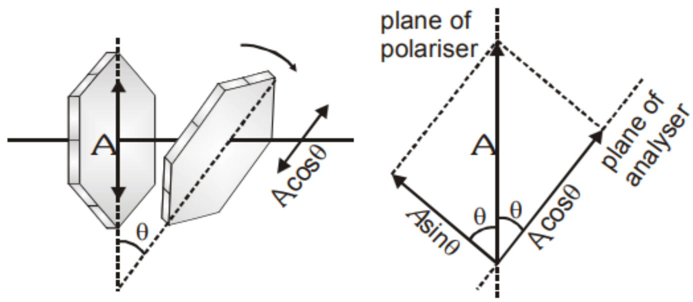


By scattering

When light strikes tiny particles like dust or air molecules, which are considerably smaller in size compared to the wavelength of light, it gets absorbed by the electrons within these particles and is subsequently re-emitted in various directions. This phenomenon is commonly referred to as scattering. Notably, the light that scatters in a direction perpendicular to the incident light is consistently plane-polarized.



The Law of Malus, when applied to a fully plane-polarized light beam interacting with an analyzer, dictates that the intensity of the resulting emergent light is directly proportional to the square of the cosine of the angle formed between the planes of transmission of the analyzer and the polarizer. In mathematical terms, this relationship can be expressed as $I \propto \cos^2(\theta)$, which can be further denoted as $I = I_0 \cos^2(\theta)$, where I0 represents the initial intensity of the light.



(i) If $\theta = 0°$ then $I = I_0$ maximum value (Parallel arrangement)

(ii) If $\theta = 90°$ then $I = 0$ minimum value (Crossed arrangement)

In the scenario where plane-polarized light, characterized by an intensity denoted as I0 (or equivalently KA^2), is directed onto a polaroid, and its oscillations, characterized by an amplitude A, form an angle θ with the polaroid's transmission axis, the component of vibrations parallel to the transmission axis will be A cosθ, and the component perpendicular to it will be A sinθ.

The Polaroid selectively permits the passage of vibrations that align parallel to its transmission axis, which means that it only allows vibrations that have a parallel orientation to pass through.

A cosθ,

$I_0 \propto A^2$

So, the intensity of emergent light $I = K(A\cos\theta)^2 = KA^2\cos^2\theta$

When unpolarized light is transformed into plane-polarized light, its intensity is effectively reduced to half of its original value. If light with an intensity represented as I_1, which emanates from an initial polaroid known as the polarizer, is directed onto a second polaroid referred to as the analyzer, the intensity of the light emerging from the second polaroid, denoted as I_2, is determined by the equation $I_2 = I_1 \cos^2 2(\theta)$, where θ signifies the angle between the transmission axes of the two polaroids.

Optical Activity

When plane-polarized light traverses specific materials, it undergoes a rotation in the plane of its polarization about the direction of light propagation by a particular angle. This phenomenon is referred to as optical rotation.

The substances capable of inducing this rotation in the plane of polarization are known as optical active substances. Examples include sugar solutions, sugar crystals, and sodium chlorate, among others.

The measurement of a substance's optical activity is conducted using a polarimeter and is expressed in terms of its specific rotation. Specific rotation is defined as the angle of rotation produced by a solution with a length of 10 centimeters (1 decimeter) and a concentration of 1 gram per cubic centimeter, for a given wavelength of light at a specified temperature.

Specific rotation $[a]_{t^\circ c}^{\lambda} = \frac{\theta}{L \times C}$ θ = rotation in length L at concentration

Types of optically active substances

A. Dextrose Rotatory Substances

Substances that cause the plane of polarization to rotate in a clockwise direction are categorized as dextrose rotatory or right-handed substances.

B. Levo Rotatory Substances

These are substances that induce a counterclockwise rotation in the plane of polarization and are referred to as levo rotatory or left-handed substances.

The degree of optical rotation is contingent upon factors such as the thickness and density of the crystal (or concentration in the case of solutions), the temperature, and the wavelength of the incident light. Additionally, the rotation is inversely proportional to the square of the light's wavelength.

APPLICATIONS AND USES OF POLARISATION

- The refractive index of a dark, transparent substance can be determined by establishing the polarizing angle and applying Brewster's Law, where $\mu = \tan\theta_P$.

- Liquid crystal displays (LCDs) employed in calculators and watches generate numbers and letters through the polarization of light, providing an efficient means of displaying information.

- In CD players, a polarized laser beam serves as the "needle" for extracting sound from a compact disc, contributing to high-quality audio playback.

- Polarization finds application in the recording and playback of three-dimensional images, enabling the creation of immersive visual experiences.

- Optical stress analysis, known as photo elasticity, utilizes polarized light to assess and understand stress distribution in materials.

- Polarization is harnessed to investigate asymmetries in molecules and crystals, often employed in the study of optical activity, offering valuable insights into the properties of these substances.

Example.

What is the specific angle of incidence at which light, upon reflection from a medium like water characterized by a refractive index (μ) of 1.3, will become entirely plane-polarized?

Solution.

$\mu = 1.3$,

From Brewster's law $\tan \theta_p = \mu = 1.3 \Rightarrow \theta = \tan^{-1} 1.3 = 53°$

Example.

If a light beam is directed onto the interface between air and glass at the polarizing angle, which measures 56.3 degrees, what would be the corresponding angle of refraction within the glass material?

Solution.

$i_P + r_P = 90°$ $\quad\quad \therefore r_P = 90° - i_P = 90° - 56.3° = 33.7$