Unit – 1: Interference and Polarization

Importance of Interference and Polarization in Engineering

Interference and polarization are fundamental concepts in engineering that play a crucial role in various fields, including electrical, optical, materials science, mechanical, aerospace, and biomedical engineering. Interference, the phenomenon where two or more waves overlap, is essential in optical communication systems, where it affects signal quality in fiber optic transmission. It also improves resolution in imaging systems, such as microscopy and telescopes, and enables spectroscopic analysis of materials. Moreover, interference is utilized in laser technology, radar systems, and audio signal processing. On the other hand, polarization, the orientation of electromagnetic waves, maintains signal integrity in fiber optics, analyzes material properties, enhances contrast and reduces glare in imaging systems, and distinguishes between surface features in remote sensing applications.

The understanding and manipulation of interference and polarization enable engineers to design efficient optical systems, develop advanced materials and coatings, improve signal quality and integrity, and enhance imaging and sensing capabilities. For instance, polarization is exploited in liquid crystal displays, polarized sunglasses, and radar systems, while interference is leveraged in optical coatings, laser interferometry, and optical coherence tomography. As technology advances, the importance of interference and polarization will only continue to grow, driving innovations in fields like metamaterials, miniaturized optical components, and high-speed polarization modulation. By grasping these concepts, engineers can unlock new possibilities in areas such as precision manufacturing, medical imaging, and telecommunications, ultimately shaping the future of various industries.

Subtopics in Unit – 1

Interference	**1.1. Introduction to Interference** 1.1.1. Principle of Superposition 1.1.2. Types of Interference 1.1.3. Coherent and Incoherent Light Sources 1.1.4. Methods for Obtaining Coherent Sources of Light **1.2. Equivalent Path and Equivalent Path Difference in Air** **1.3. Stoke's Law** **1.4. Snell's Law** **1.5. Interference in Thin Films** 1.5.1. Interference in Thin Films of Uniform Thickness for Reflected Light 1.5.2. Interference in Thin Films of Non-uniform Thickness (qualitative) **1.6. Applications of Interference** 1.6.1 Testing of Optical Flatness 1.6.2. Anti-reflection Film Coating
Polarization	**1.7. Introduction to Polarization** 1.7.1. Polarization of Light 1.7.2. Types of Polarization **1.8. Birefringence (Double Refraction)** 1.8.1. Huygens' Theory of Double Refraction 1.8.2. The Principle of Refractive Indices **1.9. Law of Malus** **1.10. Polaroids and its Working Principle** **1.11. Role of Malus in Stress Analysis (Photoelasticity)**

Interference

1.1. Introduction to Interference

Light interference is a phenomenon that shows the wave nature of light. It involves the superposition of two or more waves, resulting in a spatial redistribution of light intensity. According to the Superposition Principle, the resulting composite wave is the point-by-point algebraic sum of the individual waves.

1.1.1. Principle of Superposition

When two or more waves overlap, their displacements add algebraically at each point. This principle applies to all types of waves (mechanical, electromagnetic, etc.). The resulting wave is the sum of individual waves. No energy exchange takes place between waves; they pass through each other.

- ***Interference:*** It is a specific consequence of superposition. It occurs when two or more waves with similar frequencies and amplitudes overlap. Consequently, energy redistribution occurs, and the resulting wave pattern shows regions of constructive (enhanced) and destructive (reduced) interference patterns.
- Interference takes place when two waves are (Conditions for interference to take place):
    - a) Coherent
    - b) Monochromatic
    - c) Are of the same amplitude

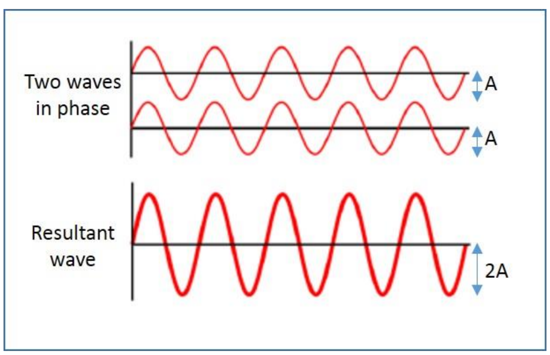

Figure 1.1. Illustration of Principle of Superposition. Two waves arriving in phase, amplifying each other.[1]

1.1.2. Types of Interference

a) Constructive Interference: The interference is constructive if the waves reinforce each other.

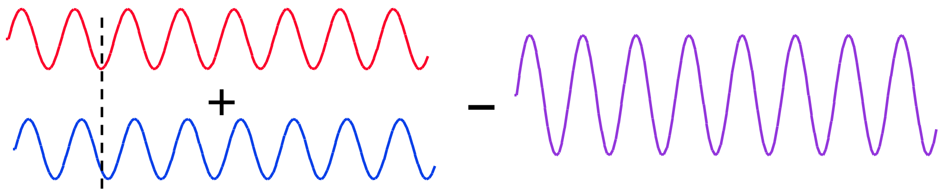

Figure 2.2. Constructive interference of two waves.[2]

- Constructive interference occurs when $\Delta x = 0$, or an integer multiple of the wavelength λ:

Path difference, $\Delta x = n\lambda$, ***$n = 0, \pm1, \pm2, \pm3, \ldots$ (Constructive Interference)***

Phase difference, $\delta = 2n\pi$, ***$n = \pm1, \pm2, \pm3, \ldots$***

b) Destructive Interference: The interference is destructive if the waves cancel each other.

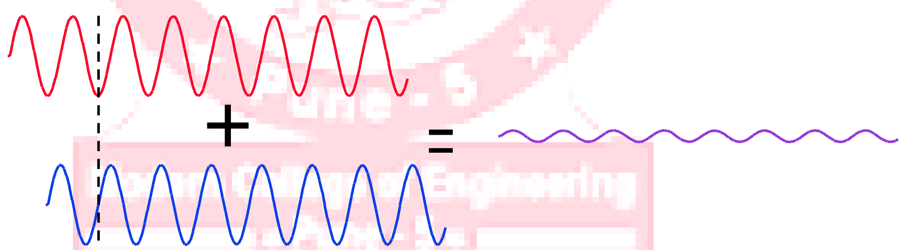

Figure 3.3. Destructive interference of two waves.[2]

- Destructive interference occurs when $\Delta x = 0$, or an integer multiple of the wavelength λ:

Path difference, $\Delta x = (2n+1)\lambda/2$, ***$n = 0, \pm1, \pm2, \pm3, \ldots$ (Destructive Interference)***

Phase difference, $\delta = (2n+1)\pi$, ***$n = \pm1, \pm2, \pm3, \ldots$***

1.1.3. **Coherent and Incoherent Sources of Light**

- ***Coherent light sources***: The light sources that emit waves with:

  1. Constant phase difference
  2. Same frequency
  3. Same polarization

  Examples:

  1. Lasers (e.g., helium-neon, semiconductor)
  2. Optical fibers with laser input
  3. Monochromatic LED sources
  4. Coherent LED arrays
  5. Synchrotron radiation

  Characteristics:

  1. High directional intensity
  2. Narrow spectral bandwidth
  3. Long coherence length

- ***Incoherent light sources***: Incoherent light sources emit waves with:

  1. Random phase difference
  2. Varied frequencies
  3. Random polarization

  Examples:

  1. Incandescent bulbs (e.g., tungsten filament)
  2. Fluorescent lamps
  3. Light-emitting diodes (LEDs) without coherence control

4. Natural light (sunlight, moonlight)

5. Glow discharge lamps

Characteristics:

1. Low directional intensity
2. Broad spectral bandwidth
3. Short coherence length

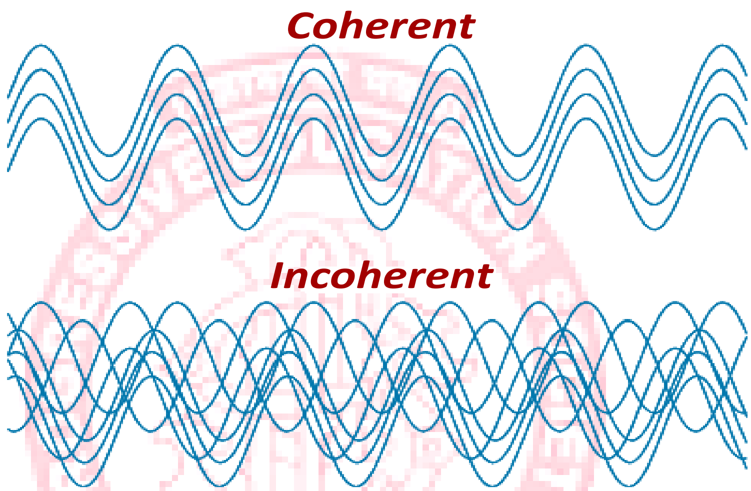

Figure 4.4. Illustration of phase relationship in coherent and incoherent waves.[3]

1.1.4. Methods for Obtaining Two Coherent Waves of Equal Amplitudes

a) **Division of Wavefront:** A technique that splits a wavefront into two separate parts, allowing them to propagate along different paths before they recombine to form an interference pattern. This approach is frequently used to generate coherent light sources. One of the many ways to divide a wavefront is by using Young's double-slit method.

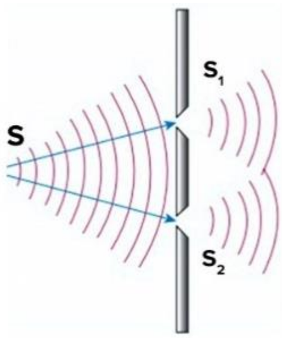

Figure 5.5. Wavefront division using Young's double-slit method.[4]

a) **Division of Amplitude:** A technique that splits the amplitude of an incident beam into two or more parts, resulting in the production of coherent beams of light. Multiple refractions and transmissions take place in the process.

- Thin-film interference: When a wave is reflected from two surfaces of a thin film, this is also considered division of amplitude.
- The split components travel different paths and then reunite, causing interference. For example, light incident on a thin film can produce an interference pattern.

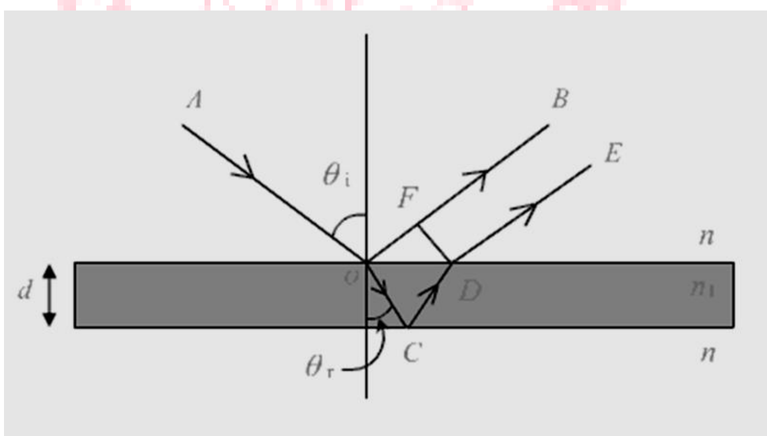

Figure 6.6. Illustration of amplitude division.[5]

1.2. Optical Path (Equivalent Path) and Optical (Equivalent) Path Difference in Air

- If two waves starting from a single source travel equal distances before meeting at a point, then the path difference is 0. This is true only if the waves travel in the same medium.

Optical path

The path a light ray takes as it propagates through an optical medium. The optical path length is the distance light travels in a vacuum in the same time it takes to travel a distance in a medium. The optical path length is calculated by multiplying the refractive index by the distance covered.

Optical path difference

The phase shift that occurs when light from two coherent sources passes through mediums with different refractive indices. The optical path difference is calculated by multiplying the difference in refractive index by the thickness. The optical path difference can be large even if the object is thin.

- Consider a wave traveling a distance λ in the air (μ=1) and another wave traveling the same distance λ in another medium of refractive index μ.

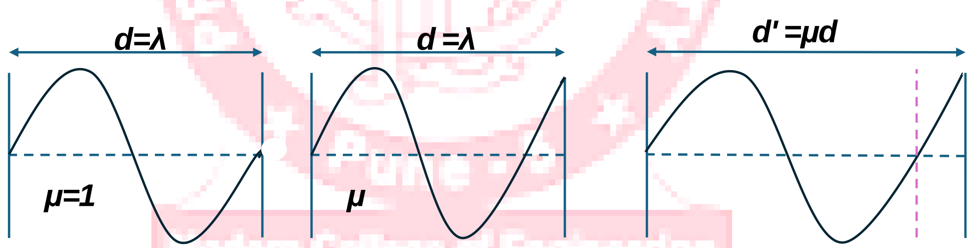

Figure 7.7. Equivalent path travelled by the wave in a changing medium.[6]

$$\mu = \frac{velocity\ of\ light\ in\ air}{velocity\ of\ light\ in\ medium} = \frac{c}{v}$$

$$\mu = \frac{\lambda\, v}{\lambda'\, v}$$

$$\mu = \frac{\lambda}{\lambda'}$$

$$\lambda = \mu\, \lambda'$$

$$\lambda' < \lambda$$

- As the wavelengths are different, the two waves will not be exactly in phase and their interference will not be completely constructive.
- To find the path difference between two waves when the wave changes the medium, we calculate the optical path.
- To find the nature of interference in such cases, the distance traveled by the wave in the medium is multiplied by μ to obtain the optical path length in air.

$$d' = \mu d$$

- As, $\lambda = \mu \lambda'$, multiplying d in the medium by μ stretches the wavelength in the medium to match the wavelength in the air.

1.3. Phase Change due to reflection (Stoke's Law)

a) When light is reflected from a denser medium, a phase change of π corresponds to the path difference of λ/2 for the reflected light.

b) There is no phase change if it is reflected from a rarer to a denser medium.

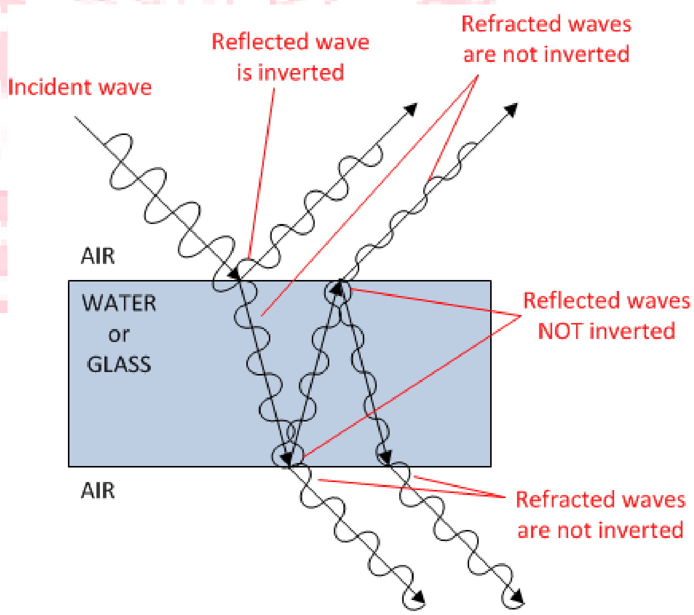

Figure 8.8. Illustration of Stoke's law.[7]

General Method for Analyzing Interference of Two Waves

1. Find the equivalent distance travelled by the two waves.
2. Find the optical path difference.
3. Add $\pm\lambda/2$ to the optical path difference if only one of the two rays suffers phase change due to reflection. This is called net optical path difference.
4. Net optical path difference = $n\lambda$ (Constructive Interference)

   = $(2n-1)\lambda/2$ (Destructive Interference)

1.4. Snell's Law

Snell's Law is a fundamental principle in optics that describes how light bends or refracts when passing from one medium to another with a different optical density.

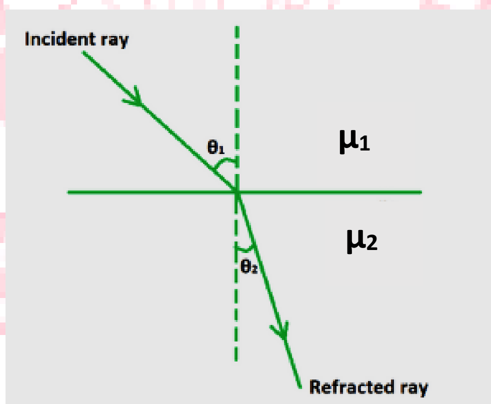

Figure 9.9. Illustration of Snell's law.[8]

$$\mu_1 \sin(\theta_1) = \mu_2 \sin(\theta_2)$$

μ_1: Refractive index of the incident medium

θ_1: Angle of incidence (the angle at which light enters the second medium)

μ_2: Refractive index of the refracting medium

θ_2: Angle of refraction (the angle at which light bends in the second medium)

1.5. Thin Film Interference

- Thin film interference is an interesting optical phenomenon that we regularly observe in day-to-day life.
- Thin film interference occurs when light waves reflect off the surfaces of a thin film, causing interference patterns due to the differences in optical path length.

Principle:

a) Light hits the thin film, dividing it into two waves: one reflected from the top surface, and one reflected from the bottom surface.

b) The two waves travel different distances, creating a path length difference. The light wave reflecting off the bottom surface travels a slightly longer path because it has to pass through the film and back. This path difference will lead to constructive and destructive interference resulting in patterns.

c) The waves recombine, producing interference patterns due to constructive and destructive interference.

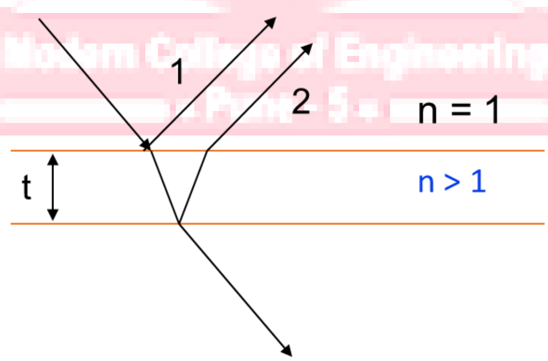

Figure 10.10. Illustration of interference in a thin film of thickness, 't'.

Applications:

1. Optical coatings (anti-reflective, reflective)

2. Thin-film solar cells

3. LED displays

4. Optical filters

5. Bio-sensing and medical diagnostics

Examples:

1. Oil slicks on water

2. Soap bubbles

3. Thin-film coatings on eyeglasses

4. Color-shifting paint

1.5.1. Interference in Thin Film of Uniform Thickness

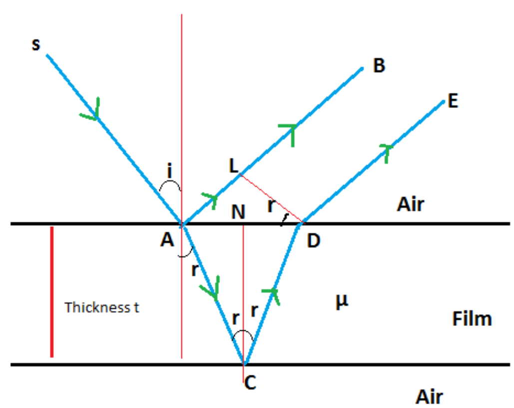

Figure 11.11. Illustration of interference in a thin film of uniform thickness, 't'.

- Consider a ray of light SA incident on a thin film of thickness **t** and refractive index "μ". At point "A" the ray gets partially reflected as "AB" and refracted as "AC". Again, at point "C" the ray gets partially reflected as "CD" and gets transmitted as "DE".

- To study the phenomenon of interference in a thin film of refractive index μ, assume a ray of monochromatic light ray SA of wavelength λ is incident on the upper surface of the film of uniform thickness "t" and refractive index μ.
- The ray SA is partly reflected along AB and partly refracted along AC at an angle r. This refracted ray will be reflected at C at the lower surface of the film and finally emerge along DE.
- From the figure, the path difference between rays AB and DE is

$$\Delta = path\ (AC + CD) in\ the\ film - AL\ in\ the\ air$$

$$\Delta = \mu(AC + CD) - AL \text{ ---------- } (1)$$

In triangle ACN, we have $\cos r = \frac{CN}{AC}$

$$AC = \frac{CN}{COSr} = \frac{t}{cosr} \text{ ----- } (2)$$

Where angle ACN =r and CN=t, the thickness of the film.

Similarly in another right-angled triangle CND we have

$$\cos r = \frac{CN}{CD}$$

$$CD = \frac{CN}{COSr} = \frac{t}{cosr} \text{ ---------- } (3)$$

Where angle NCD=r

In right angled triangle ADL, $\sin \mathrm{i} = \frac{AL}{AD}$

AL=AD Sin i

AL= (AN+ND) Sin (i)

Where angle ADL= i

Again, in triangle CAN and CND;

$\tan(\mathrm{r}) = \frac{AN}{NC}$ and $\tan(\mathrm{r}) = \frac{ND}{NC}$ and

Which means AN=NC tan r, ND= NC tan r

Therefore AN=(t)tan r , ND= (t)tan r

Put values of AN and ND in equation ---------------(4)

Therefore AL= ((t)tan r +(t)tan r Sin i

=(2t) tan r.x sin i

$$AL=2t\frac{Sin\,r}{Cos\,r}xsin\,i$$

$$= 2t\frac{Sin\,r}{Cos\,r}x\frac{Sin\,i}{Sin\,r}xsin\,r$$

$$AL=2\mu t\,(\frac{Sin^2\,r}{Cos\,r})\ \text{[From Snell's law } \frac{Sin\,i}{Sin\,r} = \mu \quad \text{-------- (5)}$$

Now substituting the value of AL, AC, and CD from equations 1,3,5 in equation (1) we get path difference as

$$\Delta = \mu\left(\frac{t}{cos\,r} + \frac{t}{cosr}\right) - 2\mu t(\frac{Sin^2\,r}{Cos\,r})$$

$$\Delta = \frac{2\mu t}{cosr} - 2\mu t[\frac{Sin^2\,r}{Cos\,r}]$$

$$\frac{2\mu t[1 - Sin^2\,r]}{cosr}$$

$$\frac{2\mu t[Cos^2\,r\,]}{cosr}$$

$$\Delta = 2\mu t cosr$$

- As the ray AB is reflected from a denser medium to a rarer medium there occurs an additional path difference of $\pm\frac{\lambda}{2}$
- We have to note that at point "B" the reflection is from the rarer medium. Therefore, an additional path difference of λ/2 is introduced.

- At C the reflection is from a denser medium therefore no path difference is introduced at point C.

Condition for Constructive Interference in Reflected System

$$\Delta = 2\mu t cosr = n\lambda \mp \frac{\lambda}{2} = (2n \mp 1)\,\frac{\lambda}{2},\ \text{n = 0, ±1, ±2, ±3, …}$$

Condition for Destructive Interference in reflected system

$$\Delta = 2\mu t cosr = (2n \mp 1)\,\frac{\lambda}{2} \mp \frac{\lambda}{2}$$

$$2\mu t cosr = n\lambda,\ \text{n = 0, ±1, ±2, ±3, …}$$

1.5.2. Wedge-Shaped Thin Films: Thin Film of Variable Thickness

- Films with zero thickness at one end and with progressively increasing thickness to the other end are called wedge-shaped films. The wedge-shaped film is bound by two plane surfaces, inclined at an angle α.
- The angle of the wedge, α is very small in the order of fraction of a degree.
- Path difference between the two reflected rays:

$$\Delta = 2\mu t cos(r + \alpha) \pm \frac{\lambda}{2}$$

Condition for Constructive Interference in Reflected System

$$\Delta = 2\mu t cos(r + \alpha) = n\lambda \mp \frac{\lambda}{2} = (2n \mp 1)\,\frac{\lambda}{2},\quad \text{n = 0, ±1, ±2, ±3, …}$$

Condition for Destructive Interference in reflected system

$$\Delta = 2\mu t cos(r + \alpha) = (2n \mp 1)\,\frac{\lambda}{2} \mp \frac{\lambda}{2}$$

$$2\mu t\cos(r+\alpha) = n\lambda, \quad n = 0, \pm1, \pm2, \pm3, \ldots$$

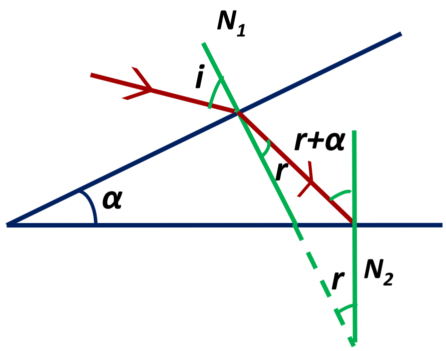

Figure 12.12. Illustration of interference in a thin film of non-uniform thickness.

1.6. Applications of Interference

1.6.1. Measurement of Optical Flatness

- One of the most important and useful applications of interference phenomenon is to determine the optical flatness of any glass surface used for optical applications.
- If the two surfaces OA and OB are perfectly plane, the air film gradually varies in thickness from O to A.
- The fringes are of equal thickness because each fringe is the locus of the points at which the thickness of the film has a constant value.

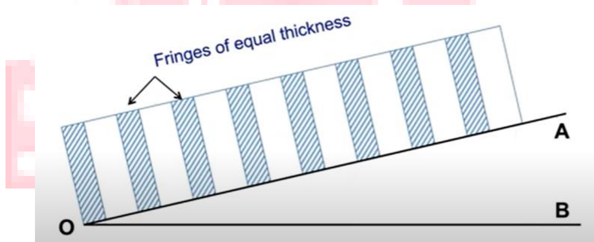

Figure 13.13. Testing of flatness of an optical surface.

- If the fringes are not of equal thickness, it means the surfaces are not plane.
- The standard method is to take an optically plane surface OA and the surface to be tested OB. The fringes are observed in the field of view and if they are of equal thickness, the surface OB is plane. If not, the surface OB is not plane.

- The surface OB is polished, and the process is repeated. When the fringes observed are of equal width, it means that the surface OB is plane.

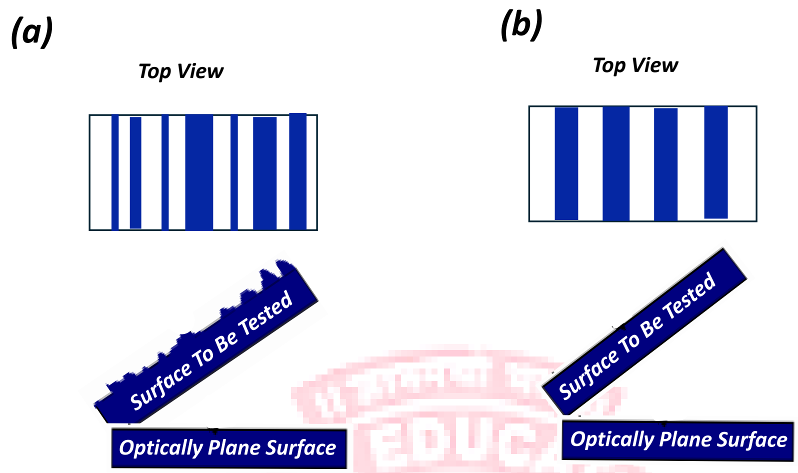

Figure 14.14. Difference between the fringes obtained from the optical testing of (a) optically rough and (b) plane surfaces, respectively.

1.6.2. Anti-reflection coating:

- An anti-reflective or anti-reflection coating is a type of optical applied to the surface of lenses and other optical elements to reduce reflection.
- In a typical imaging system this improves the efficiency since less light is lost due to reflection.
- In complex systems, such as — telescopes and microscopes, the reduction in reflections also improves the contrast of the image by eliminating stray light.
- The primary benefit is the illumination of the reflection itself such as a coating on eyeglass lenses that makes the eyes more visible to others.
- Anti-reflection coatings are used in Cameras, projectors, lens, to prevent unwanted reflections from the light surfaces. In these cases, the image formed by the lens is less bright if the loss of light due to reflection is more. To minimize this loss an anti-reflection coating will be used.
- In this process, the thickness "t" is chosen in such a way that it provides distractive interference between the beam reflected from the surface coating and that reflected from the lens.

Derivation:

- Measurement of the thickness of the coating to give perfect anti-reflection.
- Anti-reflective coating reduces the intensity of the reflected light by destructive interference and hence, enhances transmission.
- This is achieved by depositing a thin film of transparent material having μ<glass on a glass surface of λ'/4, λ': mean wavelength of light in the film.
- The most popular transparent material for anti-reflection coating is MgF_2 with a refractive index of 1.38. We need destructive rays in interference for antireflection to happen.

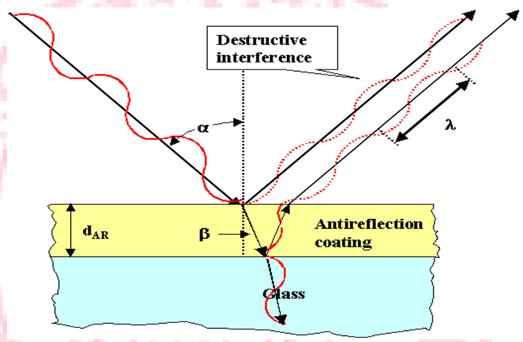

Figure 15.15. Illustration of phenomenon of destructive interference and anti-reflective coating.

- Therefore:

  Path difference, $2\mu t\cos r = (2n\mp1)\frac{\lambda}{2}$ -------- [1]

- As both rays travel from denser to rarer medium [From glass (μ =1.5) to MgF_2 (μ =1.38) and from MgF_2 (μ =1.38) to air (μ =1)], here in this equation we need not have to consider the additional path difference of $\pm\frac{\lambda}{2}$ which is considered while solving the path difference equation of uniform thin film.
- Considering path difference for the first destructive wave

$$2\mu t\cos r = (2n-1)\frac{\lambda}{2}$$

- For normal incidence angle of refraction, r =0, i.e., r=0 and consider first order i.e., n=1

$$2\mu t\cos r = (2-1)\frac{\lambda}{2} \text{ -------- [1]}$$

2µtcos0= (2-1)$\frac{\lambda}{2}$

2µt=$\frac{\lambda}{2}$

- Therefore, the thickness of the anti-reflection coating we need to have to get a perfect anti-reflection is

$$\boxed{t=\frac{\lambda}{4\mu}}$$

For near-normal incidence:

$$\Delta x = \mu\left(2\frac{\lambda'}{4}\right) = \frac{\mu\lambda'}{2}$$

As,

$$\mu = \frac{\lambda}{\lambda'}$$

$$\lambda = \mu\lambda'$$

Therefore, $\Delta x = \frac{\lambda}{\lambda\prime} * 2\frac{\lambda'}{4}$, therefore, $\Delta x = \frac{\lambda}{2}$

- There is a phase change of π for both the rays, as they are reflected from the denser medium.
- Hence, no net phase change due to reflection will take place and the path difference remains λ/2. This causes destructive interference.

Polarization

1.7. Introduction to Polarization

1.7.1. Polarization of Light

- Polarization is the phenomenon of producing polarized light from unpolarized light.
- Polarized light is light where the electric field oscillates in one specific direction, either vertically, horizontally, diagonally, or in any other particular direction.

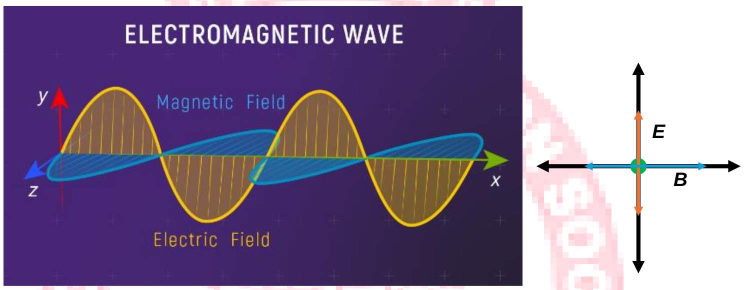

Figure 16.16. Pictorial representation of electric and magnetic field vectors of an EM wave.[9]

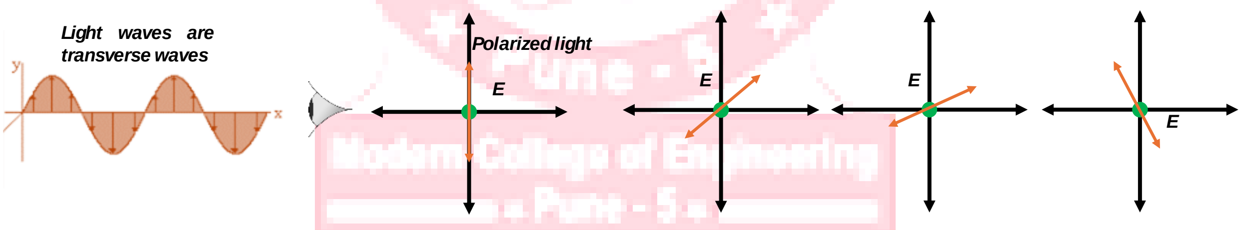

Figure 17.17. Representation of possible orientations of electric field vector direction after light passes through the polarizer .[9]

- How can we polarize a light? Using polarizers (e.g., polaroid filters), birefringent materials, optical fibers, liquid crystals

1.7.2. Types of Polarization

a) ***Unpolarized light***, also known as randomly polarized light, is a type of electromagnetic radiation where the electric field vector oscillates randomly in all directions perpendicular to the direction of propagation.

Characteristics:

1. Random electric field orientation
2. No preferred polarization direction
3. Equal intensity in all polarization directions
4. Unpredictable phase relationships between different polarization components

Properties:

1. Uniformly distributed polarization states
2. No net polarization
3. No change in polarization upon rotation

Examples:

1. Natural sunlight
2. Incandescent bulb emission
3. Fluorescent light
4. Thermal radiation

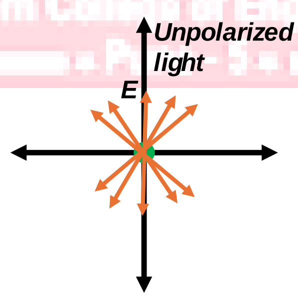

Figure 18.18. Representation of an unpolarized light.

b) ***Plane or linearly polarized light***, a type of electromagnetic radiation or light, where the electric field vector oscillates in a single plane, maintaining a fixed orientation perpendicular to the direction of propagation.

Characteristics:

1. Electric field vector oscillates in one plane
2. Fixed polarization direction
3. Constant amplitude and phase
4. Linear polarization state

Properties:

1. Polarization direction remains constant
2. The electric field vector aligns with the polarization axis
3. No rotation of the polarization axis

Types:

1. Horizontal polarization
2. Vertical polarization
3. Linear polarization at an angle (e.g., 45°, 135°)

Linearly polarized light is crucial in:

1. Optical communication systems
2. Polarimetry
3. Spectroscopy
4. Imaging and microscopy

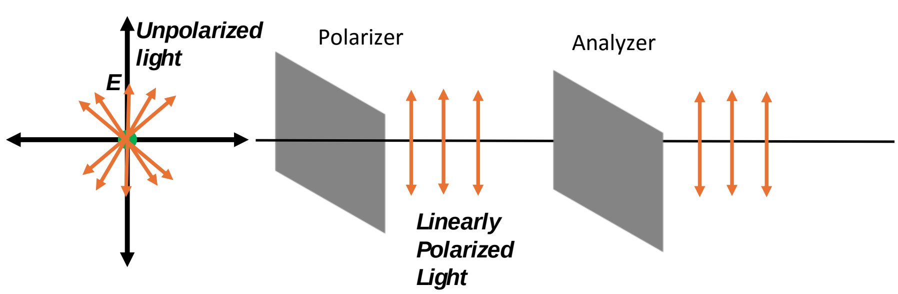

Figure 19.19. Representation of the effect of polarizer and its orientation on the polarization of light. Angle between the polarizer and analyzer is zero.

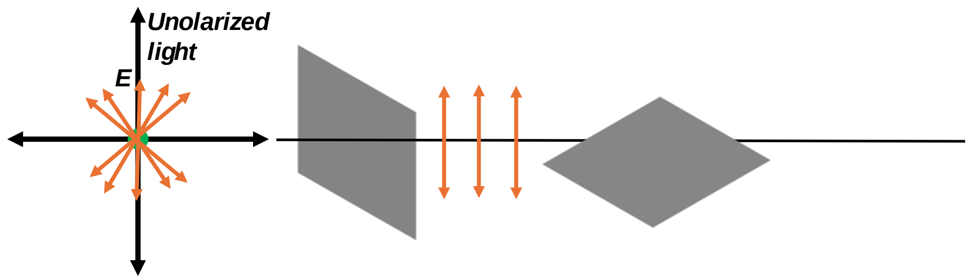

Figure 20.20. The effect of polarizer and its orientation on the polarization of light. Angle between the polarizer and analyzer is 90°.

- ***Plane of vibration:*** The plane in which the electric field vector of plane-polarized light vibrates.
- ***Plane of Polarization:*** A plane perpendicular to the plane of vibration.

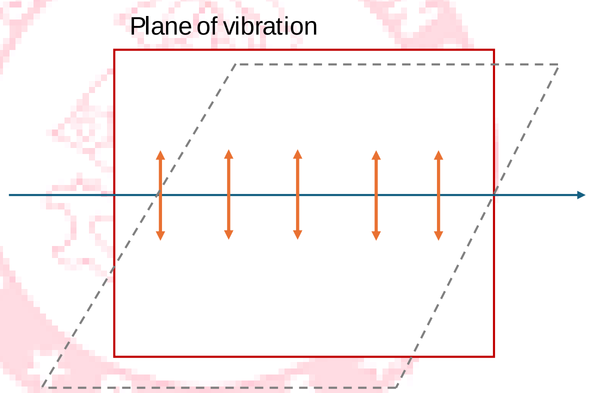

Figure 21.21.Planes of vibration and polarization.

c) ***Partially polarized light***: Partially polarized light refers to light that has an intermediate state of polarization between completely polarized and unpolarized. A mixture of both polarized and unpolarized components, meaning that the electric field still has some directional preference but is not perfectly aligned.

- Sources of partially polarized light can include reflections from surfaces like water, glass, or certain types of scattering in the atmosphere, such as when sunlight passes through the atmosphere and interacts with particles.

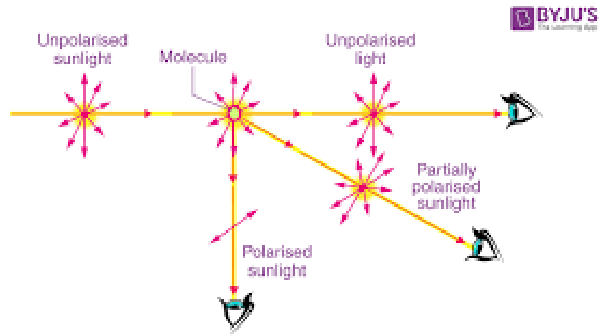

Figure 22.22. Partially polarized light.[10]

d) ***Circularly polarized light:*** The electric field rotates in a circular motion as the light wave travels. The tip of the electric field vector traces a helix along the direction of propagation. Circular polarization can be either:

- ***Right-Hand Circular Polarization****:* The electric field rotates clockwise when viewed in the direction of propagation.
- ***Left-Hand Circular Polarization***: The electric field rotates counterclockwise when viewed in the direction of propagation.
- Circular polarization can result from the combination of two perpendicular linearly polarized waves with a 90° phase difference.

e) ***Elliptically polarized light:*** The electric field traces an ellipse as the wave propagates. This is a more general form of polarization that includes both linear and circular polarization as special cases. Elliptical polarization occurs when two perpendicular linearly polarized components have both different amplitudes and a phase difference other than 90°.

- Most naturally occurring polarized light is elliptically polarized.

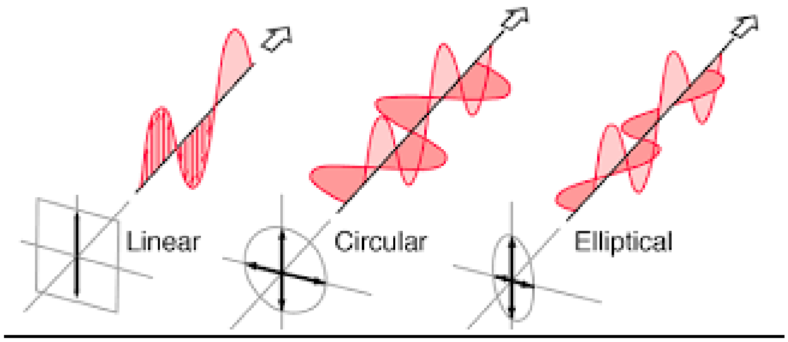

Figure 23.23. Pictorial representation of the difference between linearly, circularly and elliptically polarized light.[11]

1.8. Birefringence (Double Refraction)

- An optical property in which a single ray of un-polarized light entering an anisotropic medium is split into two rays, each traveling in a different direction.
- One ray (called the extraordinary ray) is bent, or refracted, at an angle as it travels through the medium; the other ray (called the ordinary ray) passes through the medium unchanged.
- The appearance of two beams is due to a phenomenon, called double refraction.

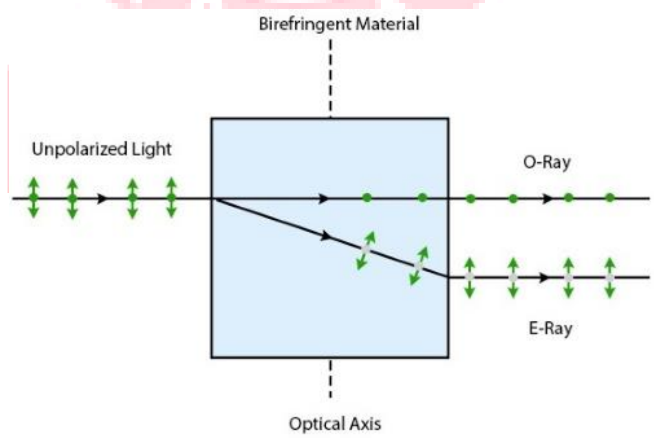

Figure 24.24. Illustration of birefringence phenomenon.

1.8.1. Huygens' Theory of Double Refraction

- Explains how unpolarized light splits into two rays when it passes through a uniaxial anisotropic material, like calcite.
- The theory is named after Dutch physicist Christiaan Huygens.
- Huygens explained the theory of double refraction based on the following assumptions.
    1. Every point in a double refracting medium is the source of two types of wavefronts: Ordinary wavefront (o-ray) and extraordinary wave (e-ray) front.
    2. The ordinary wave travels with the same speed v_0 in all directions and the crystal has the same μ_0. Therefore, o-wavefront is spherical.
    3. The extraordinary waves travel with different velocities in different directions. So, μ_e varies with direction as $\mu_e = c/v_e$. Therefore, e-waves are elliptical.
    4. O-waves and e-waves travel at the same speed along the optic axis. They touch each other at two points in the optic axis.
- In some crystals velocity of the ordinary wave is greater than the velocity of the extraordinary wave in all directions other than the optic axis and such crystals are called ***positive crystals.***
  Ex: Quartz, Ice
- In some crystals velocity of extraordinary waves is greater than the velocity of ordinary waves in all directions other than the optic axis and such crystals are called ***negative crystals.***
  Ex: Calcite.

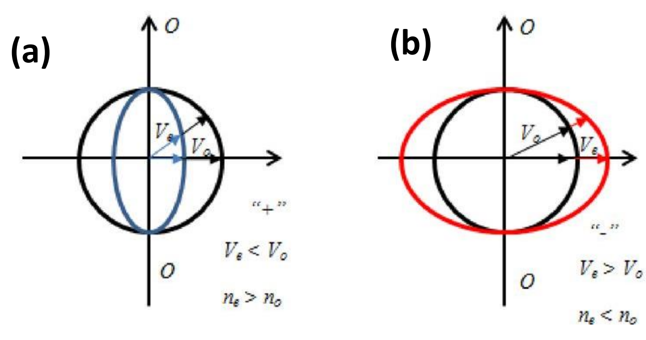

Figure 25.25. (a) A positive crystal, (b) a negative crystal.

1.8.2. Principle of Refractive Indices

- The principle of refractive indices is based on the way light changes direction when it passes from one medium into another. A refractive index (n or μ) is a measure of how much the speed of light is reduced inside a medium compared to its speed in a vacuum.
- ***Refractive index:*** The refractive index is a measure of how fast light travels through different mediums. It's inversely proportional to the wavelength of light and the speed of light in the medium.

$$\mu = \frac{c}{v}$$

* μ is the refractive index of the medium,
* c is the speed of light in a vacuum (~3×10^{8} m/s),
* v is the speed of light in the medium.

1.9. Law of Malus

- This law describes how the intensity of polarized light changes as it passes through an analyzer, and is fundamental to understanding polarization phenomena.
- When unpolarized light passes through a polarizer and then an analyzer, the transmitted intensity (I) relative to the polarizer's transmitted intensity (I_0) is proportional to the square of the cosine of the angle (θ) between the polarizer and analyzer axes, i.e., $I/I_0=\cos^2(\theta)$

  Where,

  I: intensity transmitted by analyzer

  I_0: intensity transmitted by polarizer

  θ: angle between axes of polarizer and analyzer.

Proof:

- Consider the axis of the analyzer to be at an angle θ with the axis of the polarizer.
- The amplitude of light (E_0) transmitted by the polarizer is parallel to the axis of the polarizer and hence will make angle θ with the axis of the analyzer. E_0 can resolved into two mutually perpendicular components.

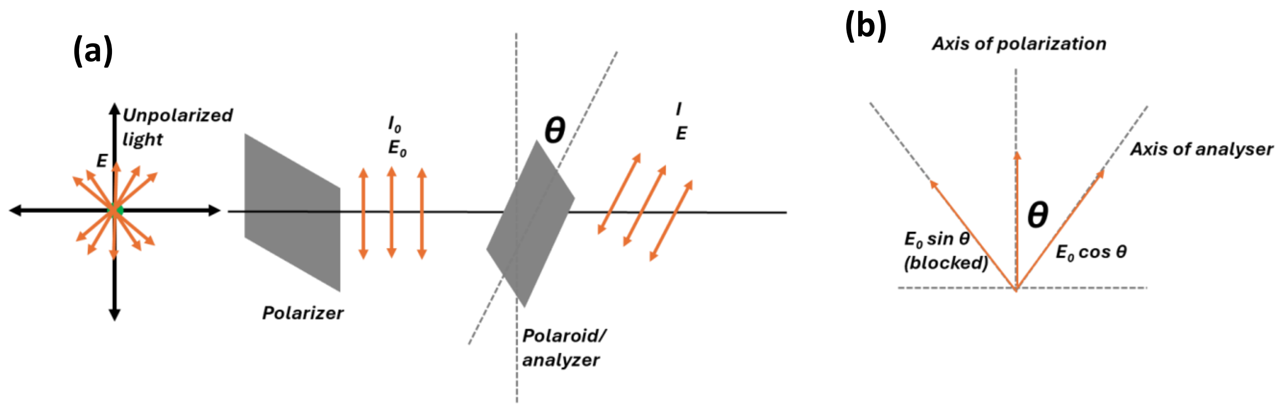

Figure 26.26. Illustration of Malus Law.

  - * $E_0 \cos(\theta)$ parallel to the axis of the analyzer, which is allowed to pass through.
  - * $E_0 \sin(\theta)$ perpendicular to the axis of the analyzer, which is blocked.

- Therefore, amplitude E of light transmitted by the analyzer is:

$$E=E_0 \cos\theta$$

$$E^2=E_0^2\cos^2\theta$$

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

$$I/I_0 =\cos^2\theta$$

- The above equation gives two values of θ for a given ratio of I/I_0. One value is θ, and the other is (180-θ).

1.10. Polaroids and Working Principle

- Polarizing sheets used to produce plane-polarized light.
- There are two methods to construct polaroids.

Method 1:

  - They are made from dichroic crystals, such as quinine iodosulphate.
  - A paste is formed by mixing these tiny crystals in nitrocellulose, which is then pressed through a series of fine, parallel slits.

- This process produces a thin sheet where the crystals are aligned with their axes parallel to each other.
- The sheet is then placed between two glass or plastic plates to complete the structure.

Method 2:

- They are created by stretching a sheet of polyvinyl alcohol (PVA), which aligns the molecules in the direction of the tension, causing the material to become birefringent.
- The stretched sheet is then treated with iodine, imparting dichroic properties. These are referred to as ***H-polaroids***.
- When the stretched PVA films are heated with hydrochloric acid (HCl), the film darkens and exhibits dichroic behavior, forming what are called ***K-polaroids***.

<u>Working Principle of Polaroids (Polarization by Selective Absorption)</u>

- The working principle of **polaroids** is based on the selective absorption and transmission of light waves. Polaroids are optical filters made from materials that allow only light waves vibrating in a specific direction (plane) to pass through while blocking light waves vibrating in other directions. This process is called **polarization**.
- Certain birefringent (double-refracting) crystals possess the ability to absorb one of the two refracted light waves—either the ordinary wave (O-wave) or the extraordinary wave (E-wave)—more than the other. This selective absorption characteristic is called **dichroism**. For instance, the crystal **tourmaline** absorbs the O-waves much more effectively than the E-waves.
- By carefully adjusting the thickness of such crystals, it is possible to absorb the O-waves entirely, allowing only the E-waves to pass through. This results in the transmission of **plane-polarized light**, where the light vibrates in a single plane. The process, known as **selective absorption**, is one of the methods used to achieve polarization.
  - **Dichroism**: In dichroic materials, the differential absorption of light waves is due to the crystal's internal structure, which interacts with the different wave components in such a way that one type of wave is absorbed more strongly than the other. This creates a situation where only the wave with the lesser absorption (such as the E-wave in the case of tourmaline) emerges, polarized in a single plane.

- **Thickness Control**: By cutting or shaping the crystal to an appropriate thickness, the intensity of the absorbed O-waves can be minimized or completely blocked. This ensures that only the desired E-wave, which experiences less absorption, is transmitted, leading to plane-polarized light.
- **Applications**: Such dichroic crystals are used in various optical devices, such as
  a. Polarizers and optical filters, to create or manipulate polarized light.
  b. Windshields of cars and aircraft to reduce glare of light.
  c. Sunglasses, certain types of 3D glasses, cameras
  d. Liquid Crystals Display (LCD)

1.11. Role of Malus Law in Stress Analysis (Photoelasticity)

- **Malus's Law** plays a key role in **stress analysis**, particularly in techniques like **photoelasticity**, which is used to measure stress distribution in transparent materials.
- Photo elasticity is an experimental technique used to measure the stress distribution in a material. The method involves creating a model of the structure in a birefringent material and then subjecting it to stress.
- Photoelasticity is based on the birefringence (double refraction) that materials exhibit under mechanical stress, and Malus's Law helps quantify the intensity of polarized light passing through such stressed materials.
- When a transparent, non-crystalline material is subjected to stress, it becomes **optically anisotropic**, meaning it exhibits different optical properties in different directions due to the applied stress. This causes the material to show stress-related characteristics. Specifically, the material's **refractive index** becomes dependent on the direction of light passing through it, and the extent of this change in the refractive index is directly related to the level of strain applied to the material.
- When this stressed model is placed between polarized light, it produces patterns of light and dark fringes known as isochromatic fringes.
- Polarized Light: The model is illuminated with polarized light, which becomes elliptically polarized when it passes through regions of different stress.

- Analyzer: An analyzer (another polarizer) is placed after the model to observe the light emerging from the model. The intensity of the light varies according to the stress-induced birefringence in the model.
- Interference Patterns: The variations in light intensity observed through the analyzer result from the differences in the optical path lengths in the stressed material, creating fringe patterns.

Useful Definitions:

Optically Anisotropic: Normally, non-crystalline materials (like glass or plastic) are **isotropic**, meaning their optical properties are uniform in all directions. However, when stressed, they become anisotropic, meaning their optical behavior changes based on the direction of light relative to the stress applied. This is because the stress affects the internal arrangement of molecules, causing them to behave differently depending on the direction in which they are observed.

Directional Refractive Index: The **refractive index** of a material is a measure of how much it bends (refracts) light. In a stressed anisotropic material, this bending of light varies depending on the direction the light travels through it. The stress causes the material to behave like a birefringent crystal, splitting light into two components that travel at different speeds and are refracted differently.

Proportional to Strain: The greater the strain (deformation) in the material, the larger the change in the refractive index. This relationship between stress and optical properties forms the basis of techniques like **photoelasticity**, where the optical changes in a material are used to visualize and measure internal stresses.

References

1. https://isaacphysics.org/concepts/cp_superposition?stage=all
2. https://www.physics-and-radio-electronics.com/physics/beats-waves-physics.html
3. https://byjus.com/question-answer/define-coherent-sources-of-light/

4. https://study.com/cimages/multimages/16/snellslawpicture10.png
5. https://www.animations.physics.unsw.edu.au/jw/light/thin-film-interference-and---reflections.html
6. Engineering Physics, p. 6, Technical Publications
7. https://www.google.com/url?sa=i&url=https%3A%2F%2Fslideplayer.com%2Fslide%2F15061276%2F&psig=AOvVaw1Tw9ZQQOeYtpD7X0pIY8f&ust=1727263540740000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCJjI_a-824gDFQAAAAAdAAAAABAD
8. https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.geeksforgeeks.org%2Fsnells-law
9. https://stsci-opo.org/STScI-01F9MEJ8XZ6W7B6YJQHKWZH2Z4.png
10. https://www.google.com/url?sa=i&url=https%3A%2F%2Fbyjus.com%2Fphysics%2Fpolarisation-byscattering%2F&psig=AOvVaw2CbT6l347HRRNOwJ_Ofe9q&ust=1726898584831000&source=images&cd=vfe&opi=89978449&ved=0CBQQjRxqFwoTCPidnOns0IgDFQAAAAAdAAAAABAE
11. https://encryptedtbn0.gstatic.com/images?q=tbn:ANd9GcSh88GPeYhwiYSQTNW78Ns2O-hsTjniN_h3Q&s