# Unit 13 · Polarization

STUDY NOTES

**WHAT NEB'S GRADE 12 EXAM ASKS**

- **CDC's grid (2078):** Waves and Optics (Units 6–13 together): 15 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** nothing from this unit
- **MCQ (1 mark)**
  - what polarization is; what can't be polarized (sound)
  - polarizers crossed at 90°: no light
  - at Brewster's angle: reflected light completely polarized, rays at 90°
  - $\theta_p$ from $\mu$; from a critical angle of 45° (54.7°)
  - an ideal polarizer stops 50 % of unpolarized light
  - turning the plane: optical activity
- **Short and long (5 or 8 marks, in parts)**
  - polarized vs unpolarized light, with examples
  - polarization by reflection, with a diagram
  - state and derive Brewster's law; why the reflected light is polarized
  - Polaroids and their uses; two Polaroids turned
  - an experiment showing light is transverse
  - numericals: $\mu = \tan\theta_p$, $\theta_p + r = 90°$, $v = c/\mu$

## Key terms

**Polarization**: restricting light's vibrations to one direction across the ray; only transverse waves can be polarized.

**Unpolarized light**: vibrations in all directions across the ray (Sun, flame, bulb).

**Plane-polarized light**: vibrations in one direction only (LCD screen; glare, partly).

**Partially polarized light**: more vibration in one direction than at right angles to it (blue sky, reflections).

**Polarizer / analyzer**: the filter that polarizes / the second one, turned, that tests the light.

**Optic axis**: the direction in tourmaline whose vibrations pass.

**Plane of vibration**: contains the vibration ($\vec{E}$) and the ray.

**Plane of polarization**: contains the ray, at right angles to the plane of vibration.

**Polarizing (Brewster's) angle** $\theta_p$: the angle of incidence at which reflected light is completely polarized.

**Polaroid**: a stretched, iodine-dipped plastic film that polarizes light (Land, 1929; H-sheet 1938).

**Double refraction**: a crystal (calcite) splits a ray into two, polarized at right angles.

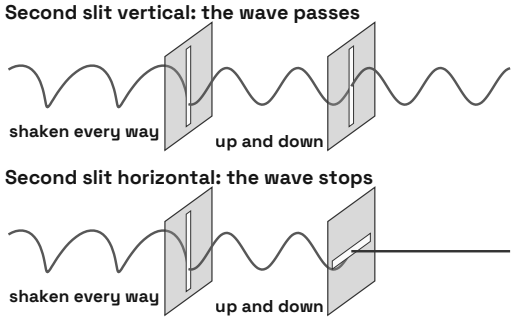
**Optical activity**: turning of the plane of vibration (quartz, sugar solutions).

## Formulas

| | |
|---|---|
| $\mu = \tan\theta_p$ | glass 56.3°, water 53.1°<br>**Use:** Brewster's law |
| $\theta_p + r = 90°$ | reflected ⊥ refracted<br>**Use:** at $\theta_p$ |
| $\tan\theta_p = \mu_2/\mu_1$ | from medium 1 to 2<br>**Use:** two media |
| $\sin C = 1/\mu$ | then $\tan\theta_p = \mu$<br>**Use:** critical angle |
| $I = I_0\cos^2\theta$ | 45°: half<br>**Use:** Malus's law |
| $I = I_0/2$ | ideal; real ~40 %<br>**Use:** unpolarized through one |

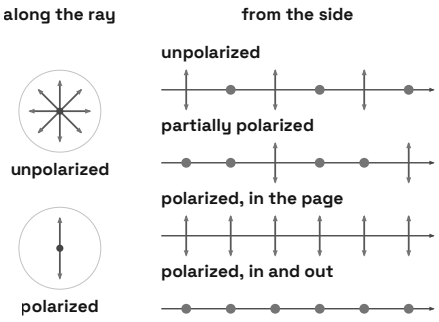
## Polarized and unpolarized

- interference and diffraction: light is a wave; polarization: a **transverse** wave
- sound is longitudinal: nothing across the ray to sort, can't be polarized
- light's vibration = its electric field $\vec{E}$, across the ray



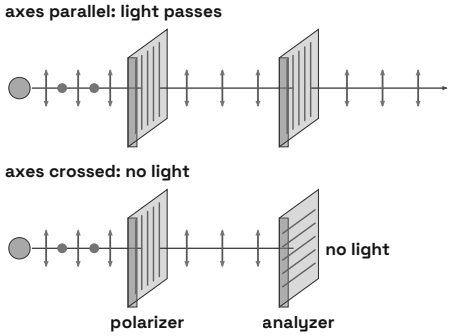

A rope shaken every way through a vertical slit: beyond it only up and down; a horizontal slit stops it.

- a rope shaken only up and down is already polarized




Along the ray: unpolarized a star of arrows, polarized one; from the side: arrows (in the page) and dots (in and out).

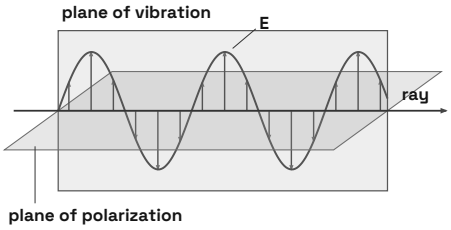
## Tourmaline: polarizer and analyzer




Axes parallel: the polarized light passes; crossed at 90°: none.

1. unpolarized light → first crystal (polarizer) → plane-polarized, dimmer
2. second crystal (analyzer), axes parallel → passes
3. turn it: less light; at 90° (crossed) **none**
4. on: back to brightest at 180°

- unpolarized light through one turning crystal: the same at every angle
- this experiment shows light is **transverse**

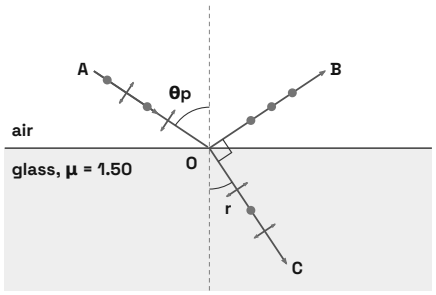



Plane of vibration: the vibration and the ray; plane of polarization: the ray, at 90° to it.

- the two planes both contain the ray and are at right angles
- some modern books (lasers) call the plane with $\vec{E}$ the plane of polarization: say which you mean

## Brewster's law

- reflection from glass or water: partially polarized (Malus 1808); completely at one angle (Brewster 1815)
- reflected light vibrates **along the surface**, perpendicular to the plane of incidence (dots)
- why: electrons in the glass, set vibrating by the refracted light, send the reflected ray; at 90° to the refracted ray, the in-plane vibration would be along its own line, and a vibrating electron sends nothing along its line




Glass, $\mu = 1.50$: $\theta_p = 56.3°$, reflected OB dots only, refracted OC ($r = 33.7°$) partially polarized; OB ⊥ OC.

### Derivation

1. Snell: $\mu = \frac{\sin\theta_p}{\sin r}$
2. reflected ⊥ refracted: $\theta_p + 90° + r = 180° \rightarrow r = 90° - \theta_p$
3. $\sin r = \cos\theta_p \rightarrow \mu = \frac{\sin\theta_p}{\cos\theta_p} = \tan\theta_p$

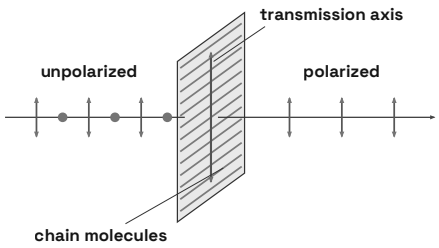
- completely polarized only at $\theta_p$, and only the reflected light; refracted always partially

- glass reflects ~15 % of the along-surface part; a **pile of plates** strips more
- 1.49 → 56.1°; 1.66 → 58.9°, $v = 1.81 \times 10^8$ m/s; 56° → $\mu$ 1.48, $v = 2.02 \times 10^8$ m/s
- $r = 33.7°$: $\theta_p = 56.3°$, $\mu = 1.50$
- critical angle 45°: $\mu = \sqrt{2}$, $\theta_p = 54.7°$
- denser to rarer, rays at 90°: $\tan i = 1/\mu = \sin C$

**Uses**

1. polarizing sunglasses, axis vertical: cut horizontal glare
2. camera filters: no reflections, darker sky
3. gas lasers' Brewster windows: no loss, polarized beam
4. $\mu$ of an opaque material from $\tan \theta_p$
5. thin films on surfaces (oxide on a chip)

## Polaroids




Chains absorb the vibration along them; the light out vibrates across them, along the transmission axis.

- PVA film stretched (chains line up), dipped in iodine: chains conduct along their length
- $\vec{E}$ along the chains drives electrons → absorbed; across → passes
- transmission axis **across** the chains (unlike the rope's slit); passes ~40 % of unpolarized light, grey tint
- two Polaroids: half after the first; crossed, dark; turned to parallel, brighter and brighter ($\cos^2 \theta$)

**Uses**

1. sunglasses; camera filters
2. 3D films: each eye its own picture
3. LCD screens: liquid crystal turns the plane pixel by pixel
4. polarizing microscopes: rocks, crystals, fibres
5. stress analysis: coloured fringes in strained plastic models
6. windows that control the light

## Two more effects

- **double refraction**: calcite shows print twice; o-ray obeys Snell ($\mu$ 1.66), e-ray doesn't (1.49–1.66); both plane-polarized at 90° to each other; Nicol prism
- **optical activity**: quartz, sugar turn the plane; angle $\propto$ length $\times$ concentration; polarimeter measures sugar in a solution

**COMMON MISTAKES**

✗ sound can be polarized
✓ only transverse waves; sound is longitudinal.

✗ a rope shaken up and down is unpolarized
✓ it is polarized; unpolarized is every direction.

✗ plane of polarization = plane of vibration
✓ at **right angles** to it.

✗ at Brewster's angle the refracted ray is unpolarized
✓ **partially** polarized.

✗ reflected and refracted rays at Brewster's angle are parallel
✓ at **90°**.

✗ Brewster's law, 1811
✓ 1815.

✗ a Polaroid passes light vibrating along its chains
✓ **across** them.

✗ an ideal polarizer stops all unpolarized light
✓ **half**.

✗ $\tan^{-1} 1.66 = 59.7°$
✓ 58.9°.