NYMS
Polarized Light Workshop
October 16, 2010

Mary McCann, McCann Imaging
mccanns@tiac.net

First a Review: The Nature of Light

- Light is an electromagnetic vibration

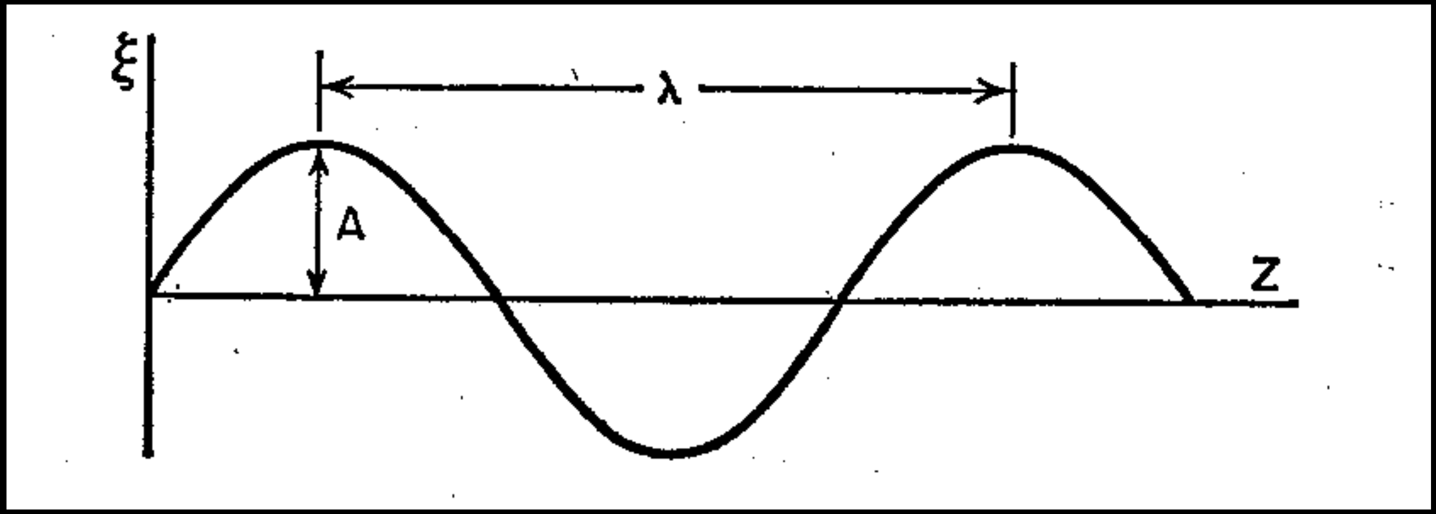
- The electric and magnetic fields vibrate at right angles to the direction of propagation -- usually only the electric field is depicted.

- Descriptors for light vibrations are:

  Wavelength, λ Frequency, ν Propagation direction
  Velocity of Propagation
  Electric Field Vibration direction

  Intensity

Wavelength and Frequency



A is the amplitude of the electric field.
The wavelength, λ, indicates the distance between two identical points on the wave, usually measured in nanometers, nm.

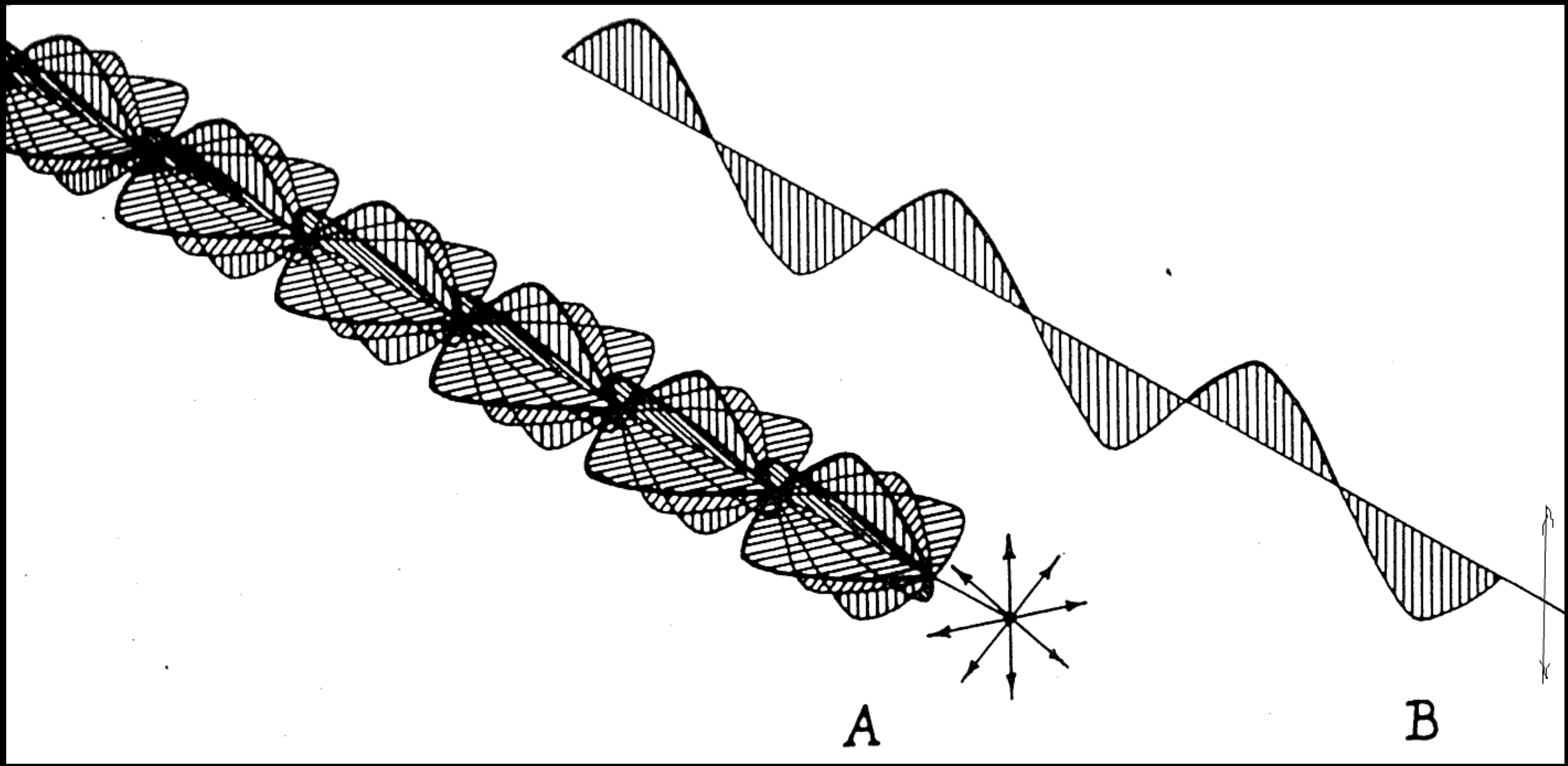
$$\xi = A \sin(\omega t - 2\pi z/\lambda)$$

The equation describing ξ, the magnitude of the electric field at any given time t, and any given position z, in terms of ω, the angular frequency (2π times the frequency ν in cycles/unit time)

Snapshots of Polarized Light

- Beam A is unpolarized. The electric field is vibrating in many directions

- Beam B is linearly polarized. Light is vibrating in a single plane



Sectional Patterns of Polarized Light

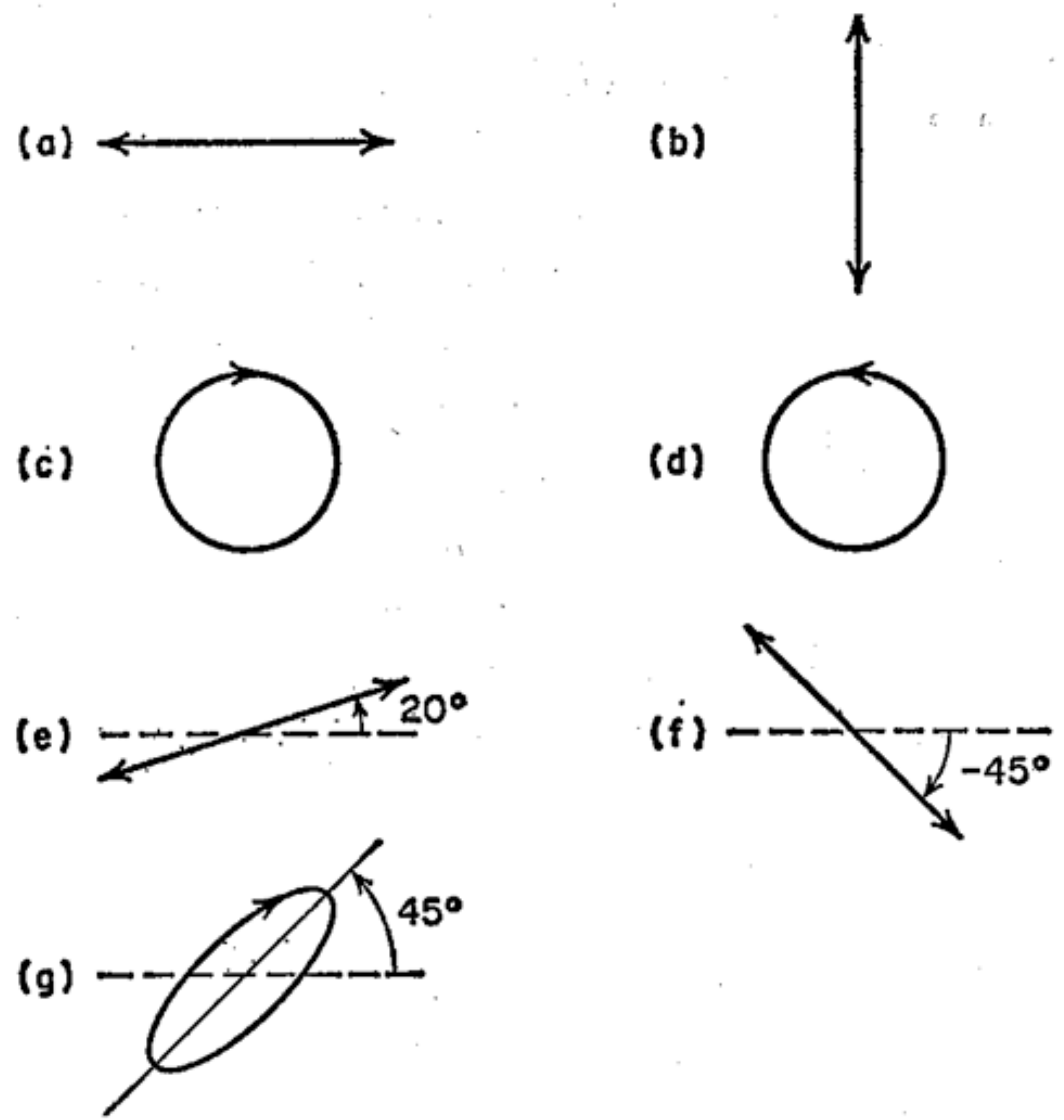


FIG. 1-2 Sectional pattern of a beam polarized (a) linearly, horizontally, (b) linearly, vertically, (c) right circularly, (d) left circularly, (e) linearly at 20°, (f) linearly at −45°, (g) right elliptically at 45°.

Production of Polarized Light by Reflection

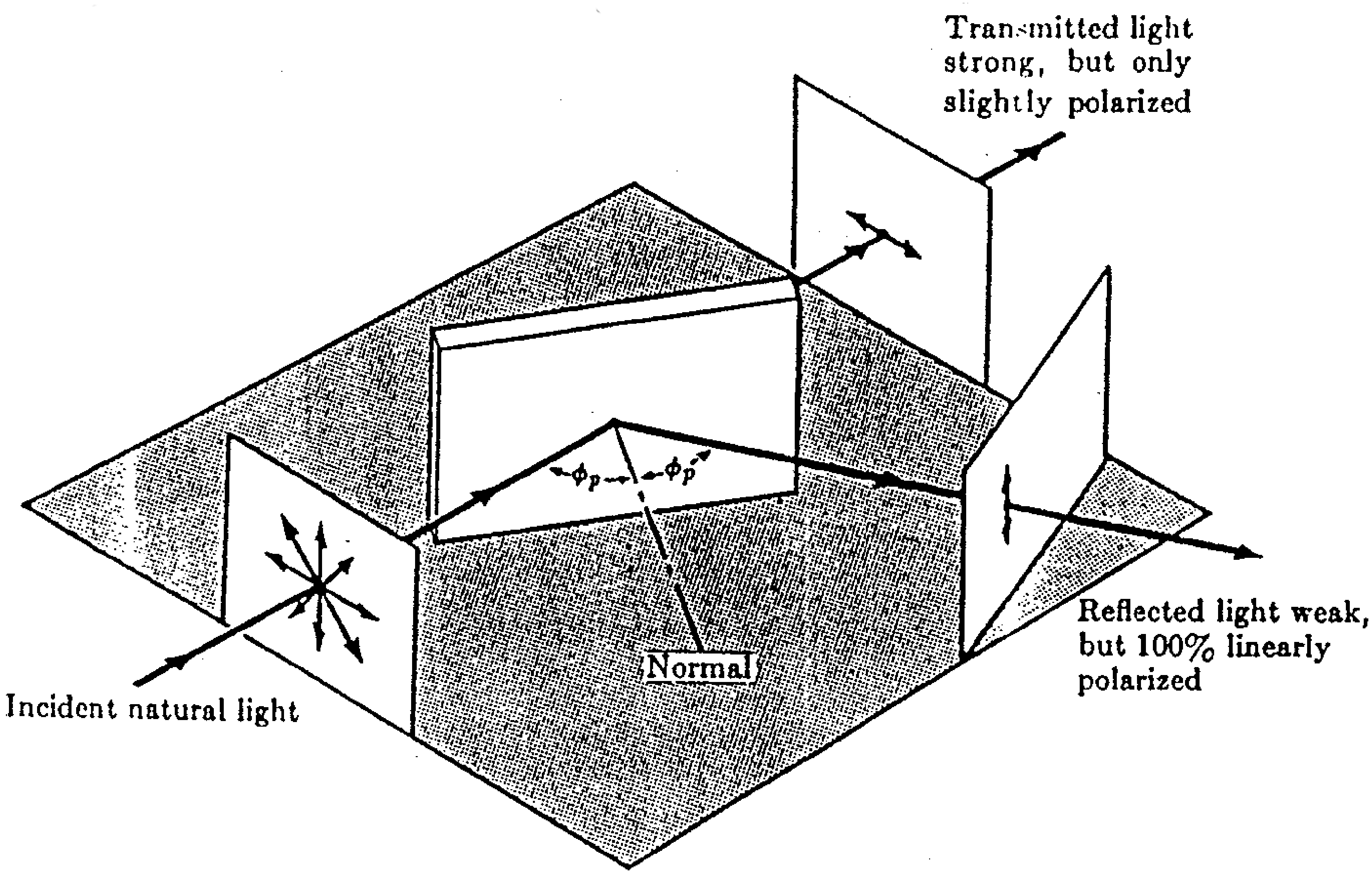
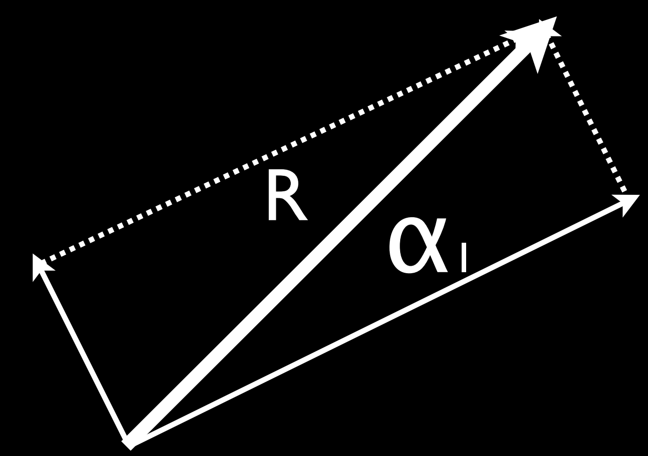
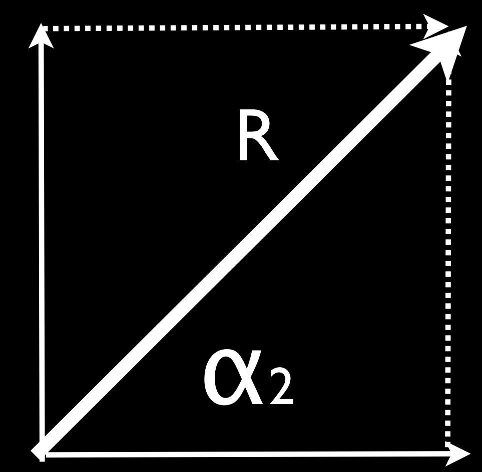


Fig. 47–3. When light is incident at the polarizing angle, the reflected light is linearly polarized.

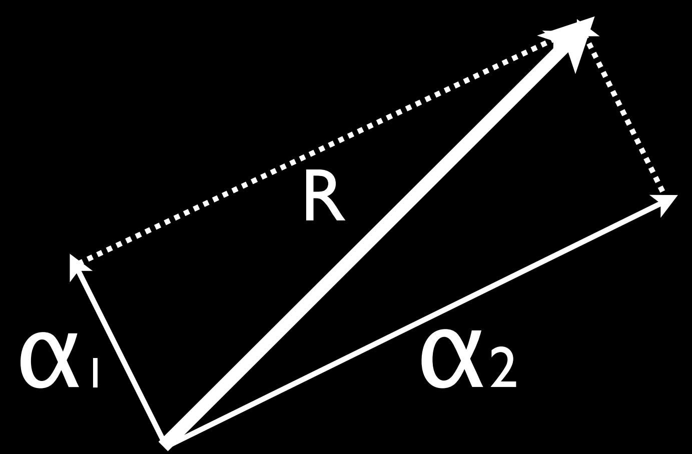
Vector Properties of Light

- The electric field has both magnitude and direction.
- A vector has magnitude and direction.
- A vector can be resolved into two orthogonal components.
- The electric field of polarized light can be resolved into two orthogonal components

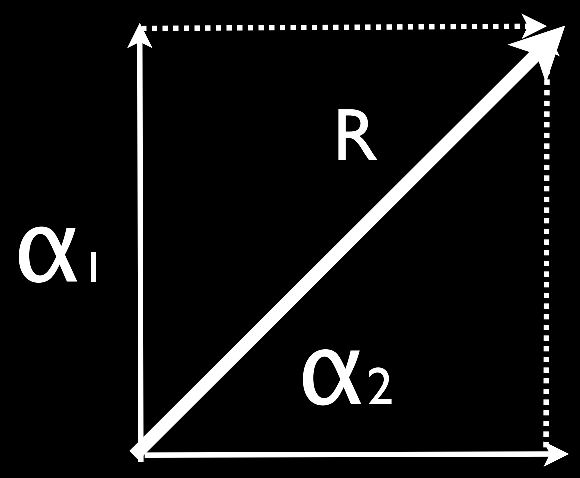




Vector Properties of Light, continued



- Two orthorgonal vector components can be added to give their resultant.



- Two orthogonal electric fields can be added at any instant to give the resultant field.

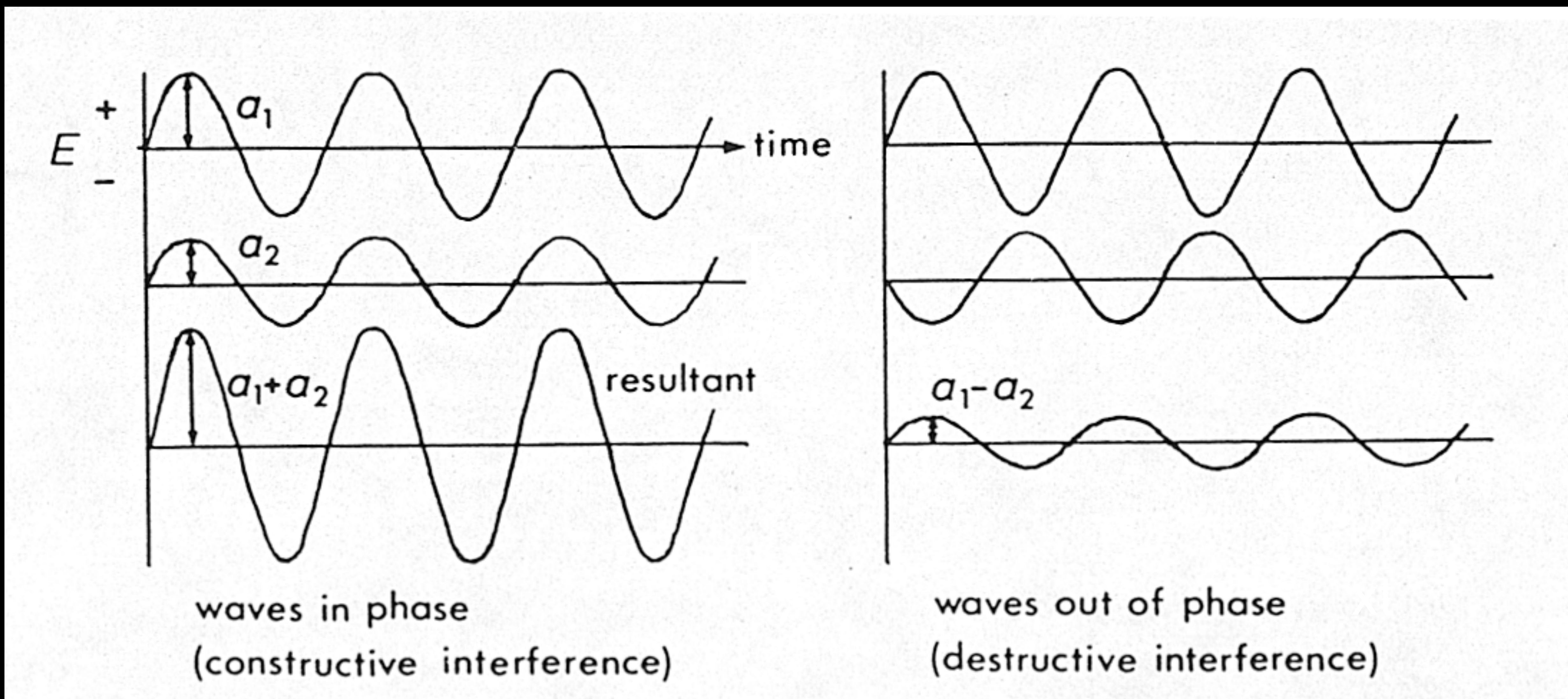
Resolving Components in the Microscope

- Unpolarized Light is emitted from the lamp
- The Polarizer resolves the light into two components and absorbs the N-S component, transmitting the E-W component
- The birefringent sample resolves the E-W light into two components that vibrate in permitted directions through the crystal. The two components travel through the sample at different speeds
- The Analyzer resolves both beams into two components, absorbs the E-W components, and transmits the N-S components
- Since we have now satisfied the interference condition of same frequency, same direction and same polarization, (N-S), interference takes place and interference colors may be seen.

Requirements for Interference

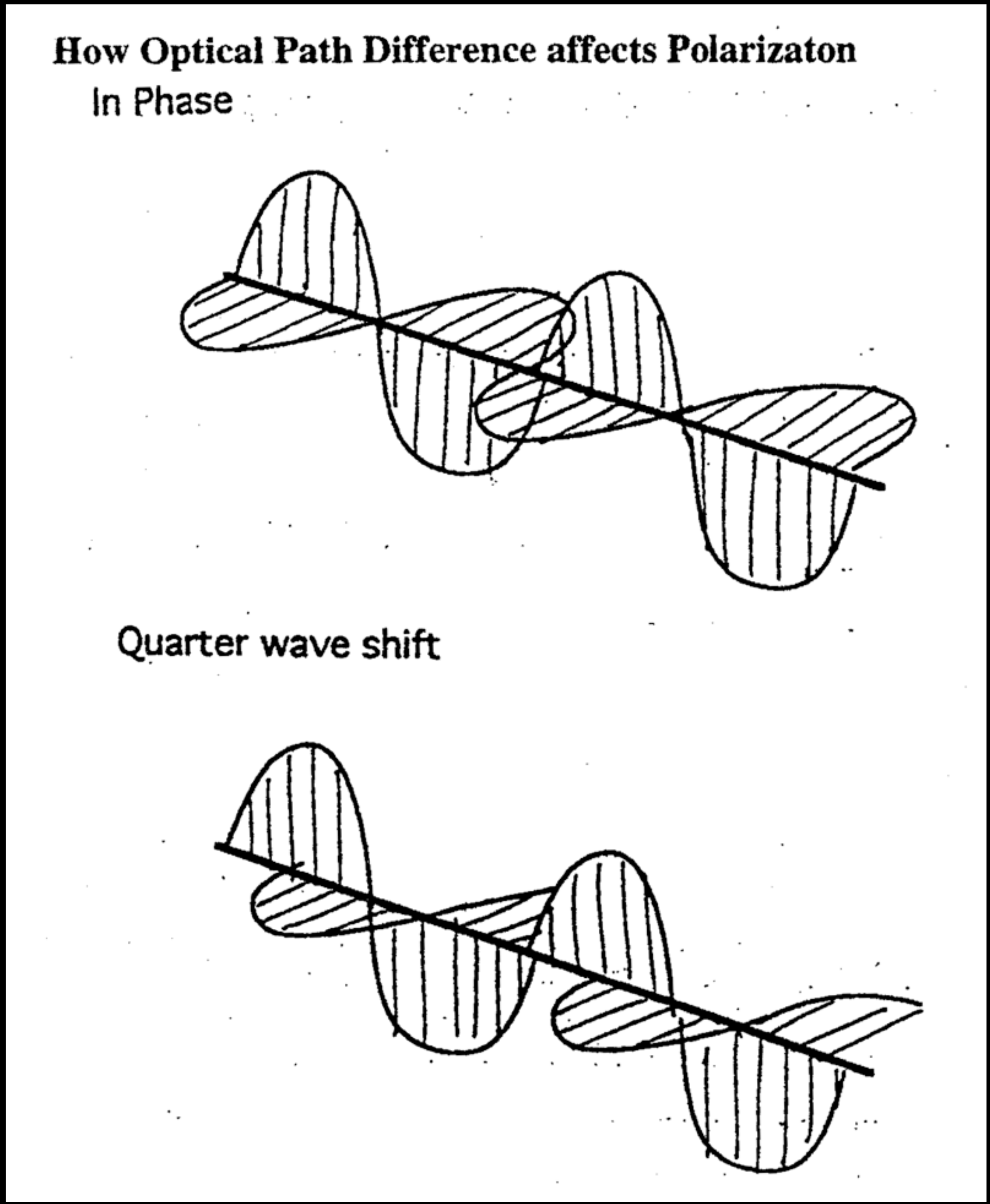
- In order for two beams of light to interfere, they must
  - Have the same frequency
  - Be traveling in the same direction
  - Have the same vibration direction (polarization)

Examples of Interference



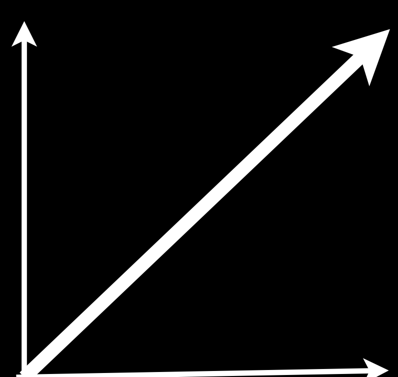
An Exercise for the Student

- The upper drawing has both components in phase with each other
- The lower drawing has one component shifted by one quarter wavelength
- What are the sectional views of the two waves?



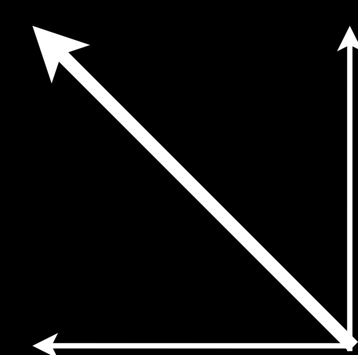
- Exercise for the Students: A Three Step Process
  - Resolution of Plane Polarized Light into two components
  - Shift Phase Relationship of the two components
  - Add the Two Components to Find the New Resultant

1.

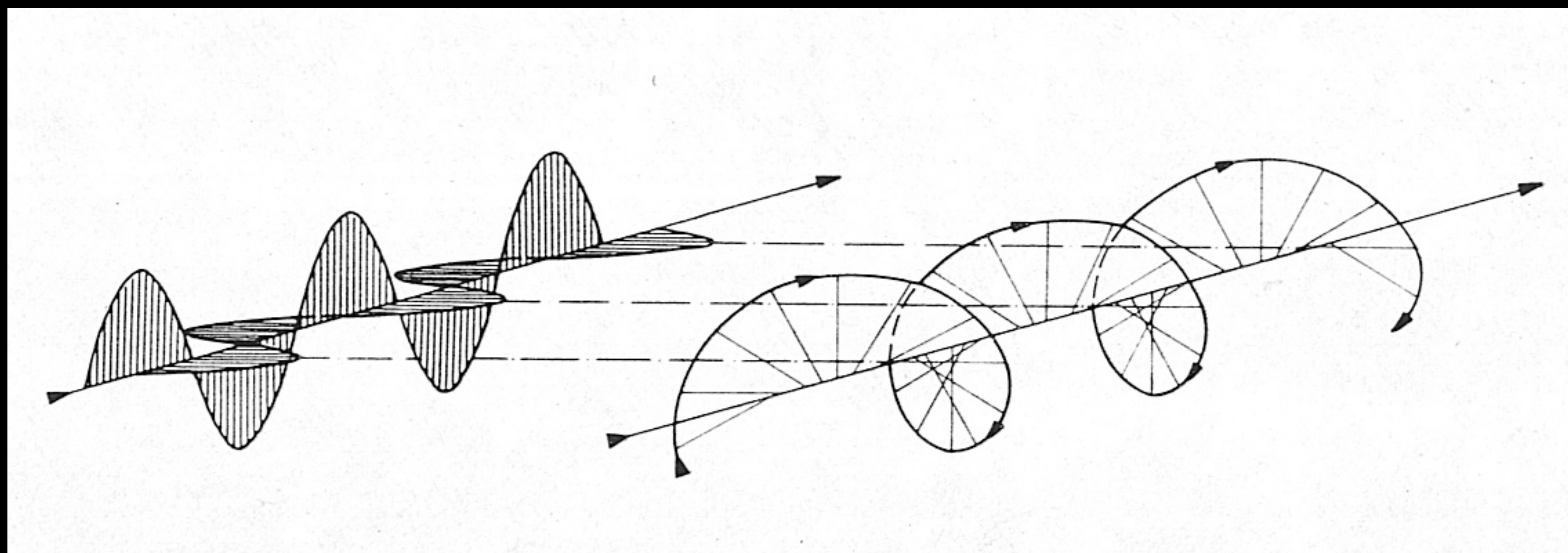


2. Introduce Phase Shift

3.



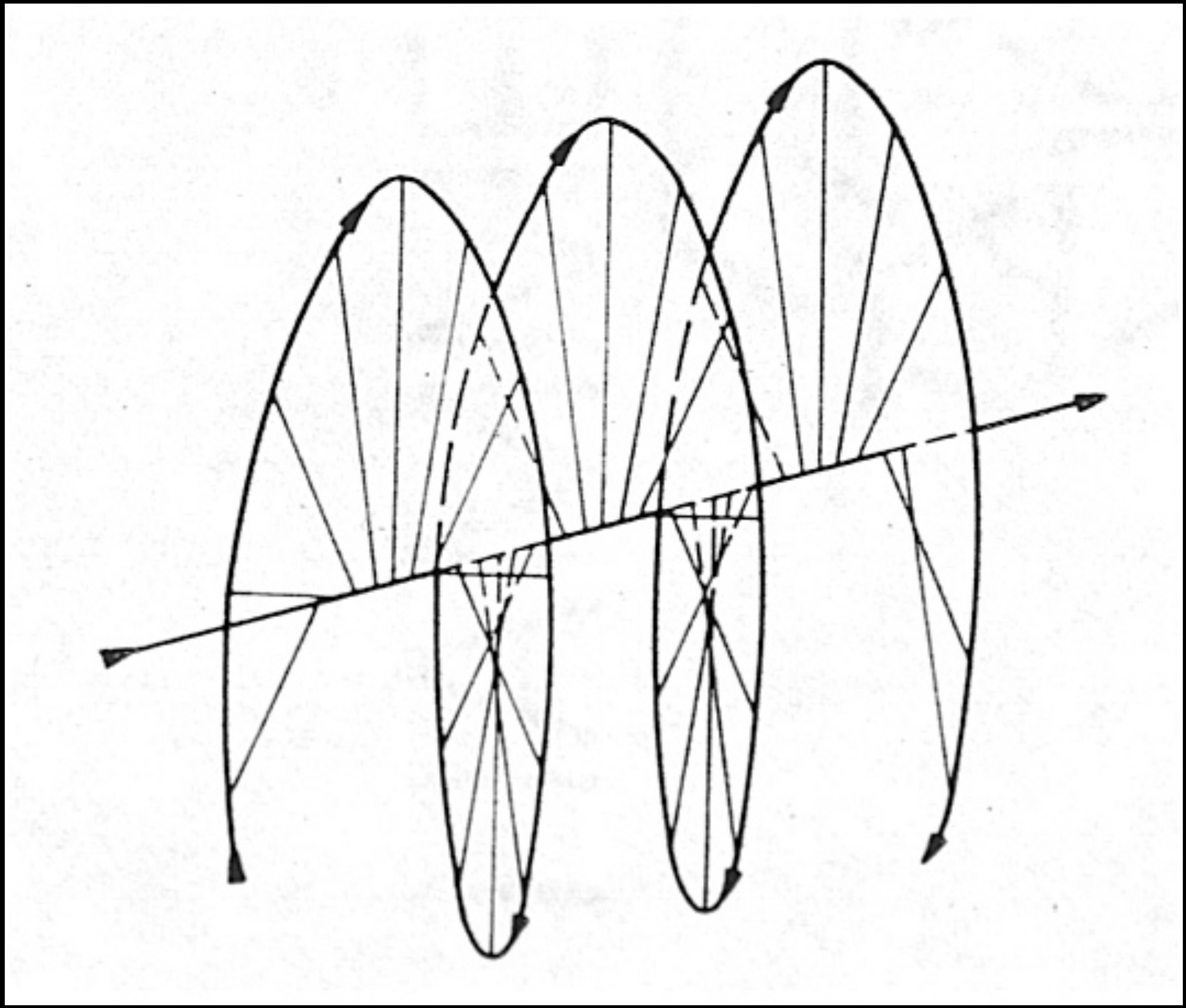
Circularly Polarized Light



- Circularly Polarized Light is Made up of two linearly polarized beams with a phase difference of $\lambda/4$
- At amplitude of the beam is constant and the direction of vibration traces a helix

Elliptically Polarized Light

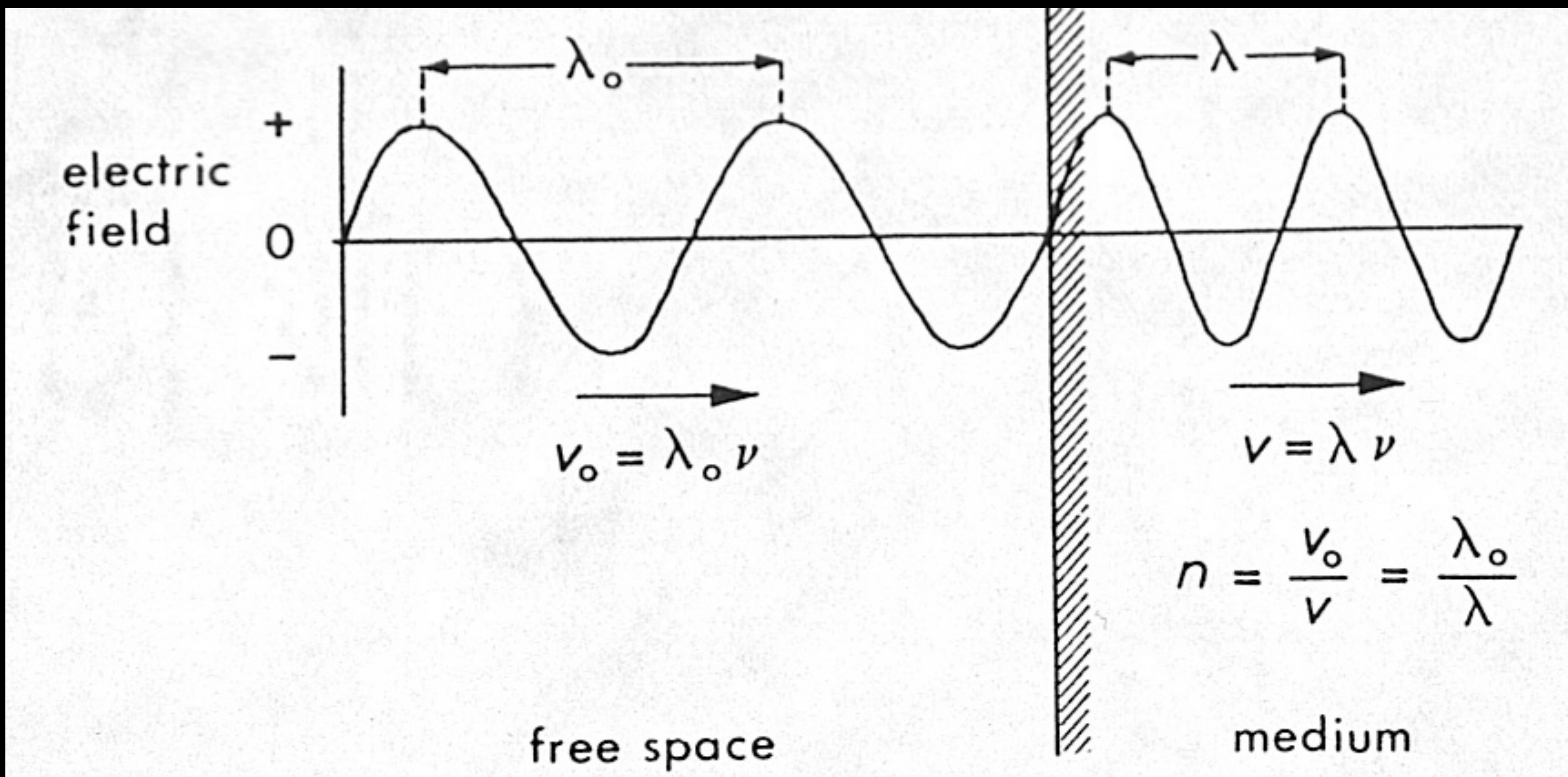
At any sequence of time, the light vibrates in a different direction, and has a different amplitude.



Velocity of Light

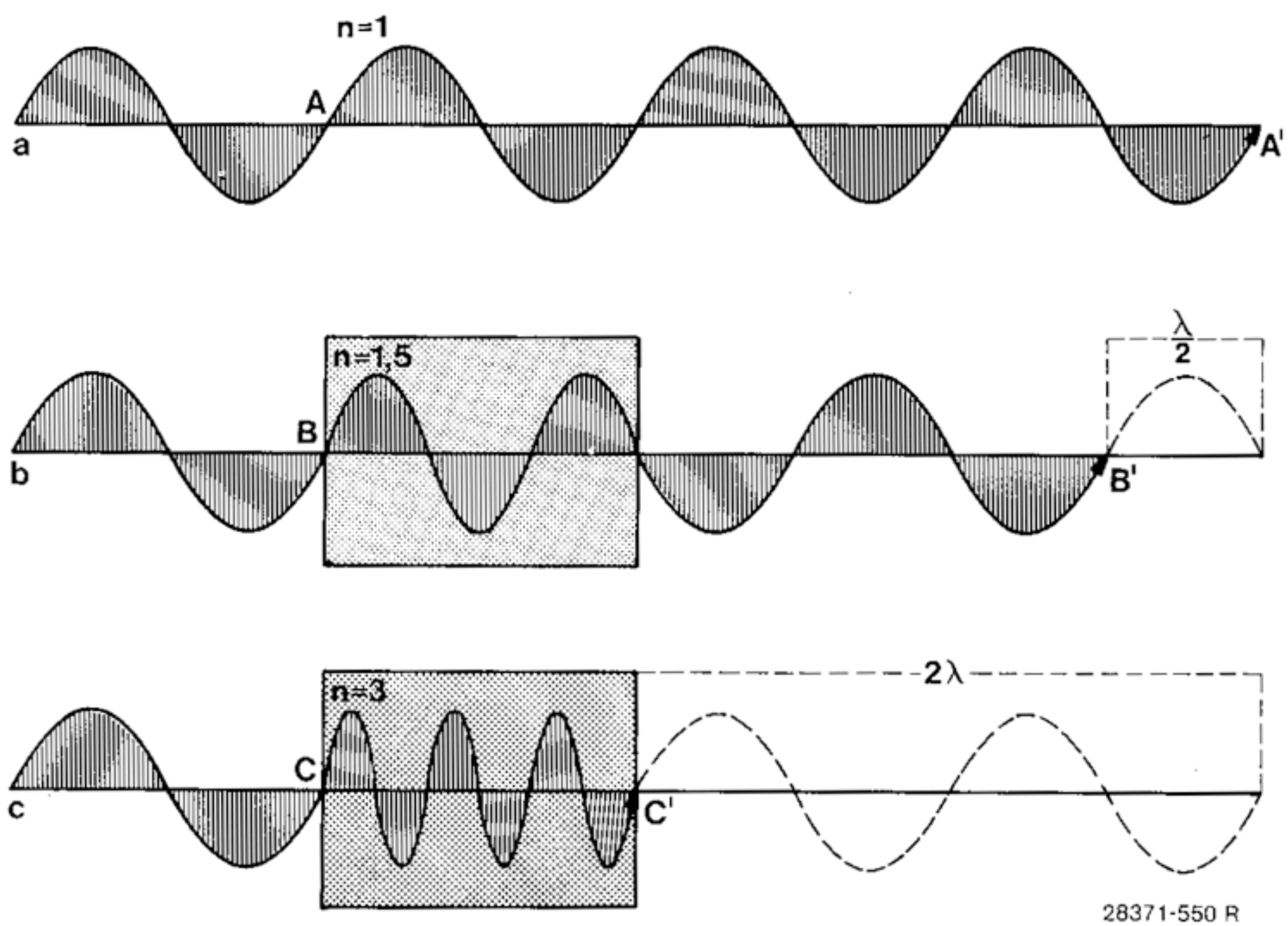
- Velocity of Light in a Vacuum, $C = 3 \times 10^8$ m/sec
- Velocity of Light $= \lambda\nu$
  - λ is 400 to 700 nm in the visible region, frequency in the visible range is 4 to 7.5×10^{14} cps
- Velocity of Light in a material, $= C/n$, where n is the refractive index of the material
- The velocity of light in water, with refractive index of 1.33, is $3 \times 10^8/1.33$ or 2.25×10^8 m/sec
- The velocity of light in a material with refractive index of 1.5, is $3 \times 10^8/1.50$ or 2×10^8 m/sec

Change of Velocity at a Boundary



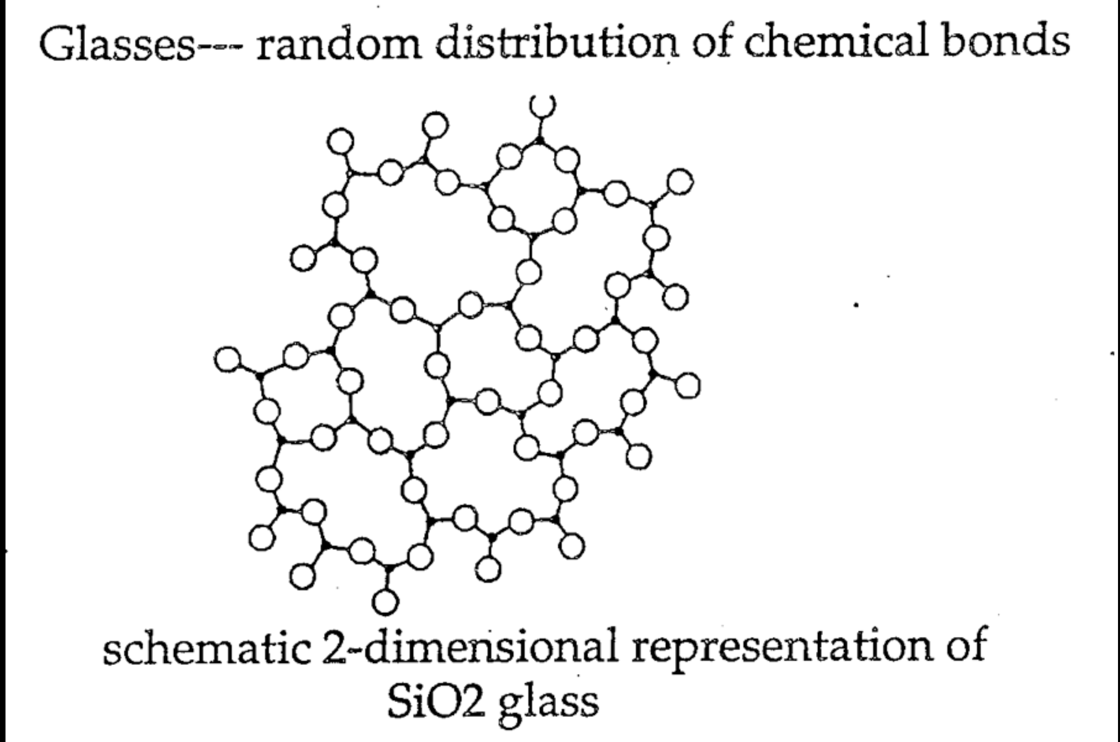
Optical Path Length and Phase Difference or OPD

Fig. 7:
Retardation of a wave front (phase displacement) after passage through media of various refractive indices:
a) Vacuum (retardation 0)
b) Medium of refractive index n = 1.5 (retardation $\lambda/2$)
c) Medium of refractive index n = 3 (retardation 2λ)

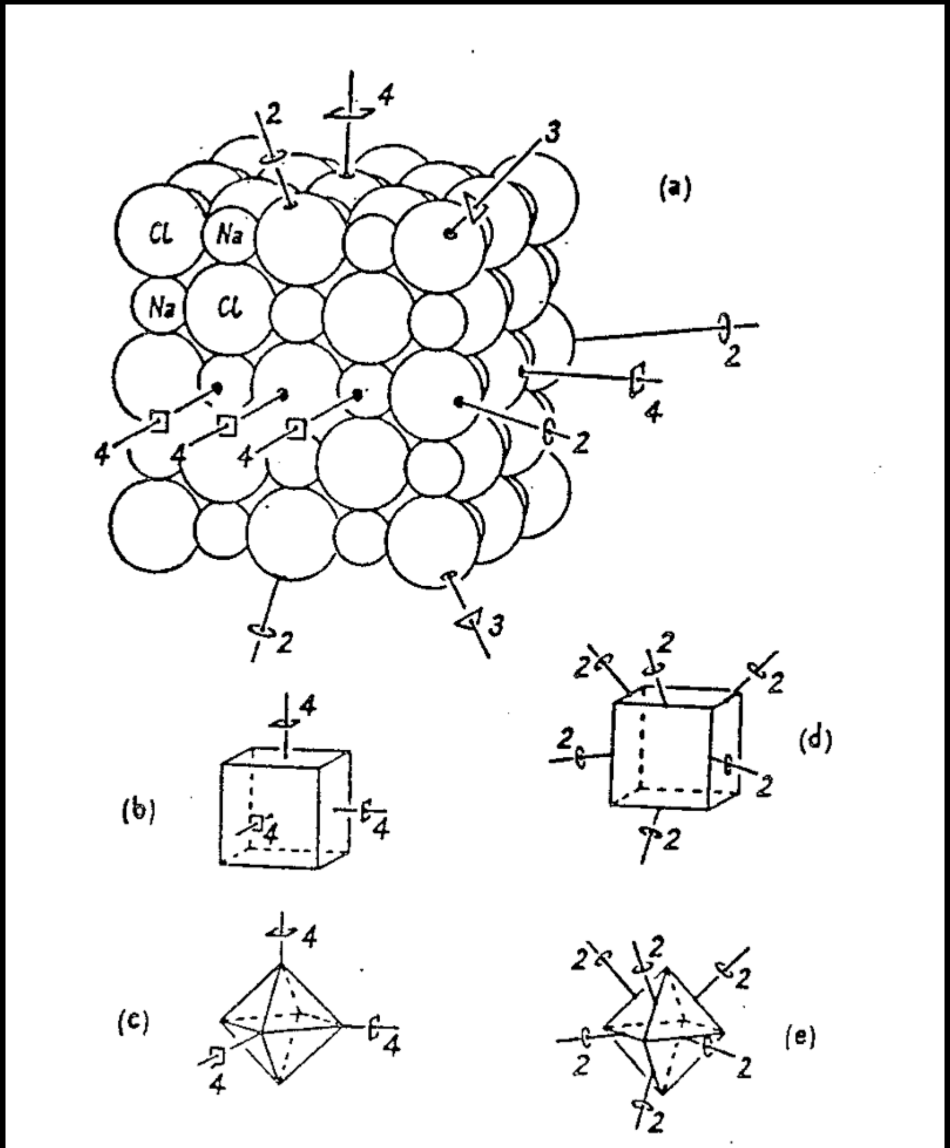


Isotropic Materials
Having only one Index of Refraction

- Gases and liquids
- Glasses, non crystalline



- Cubic Crystals



Anisotropic Crystals are Doubly Refracting Materials

- They exhibit more than one index of refraction, depending on the light's direction of travel.

- For each direction of travel through the crystal, there are two permitted vibration directions of light, 90 degrees apart. The crystal *resolves the light* into two components.

- There are one or two directions of travel through the crystal, with no beam-splitting takes place. These are the optic axes of the crystal.

  - Uniaxial materials have one direction where no beam-splitting takes place.

  - Biaxial materials have two directions where no beam-splitting takes place.

Action of Birefringent Crystal

Production of Polarized Light by a Doubly Refracting Crystal

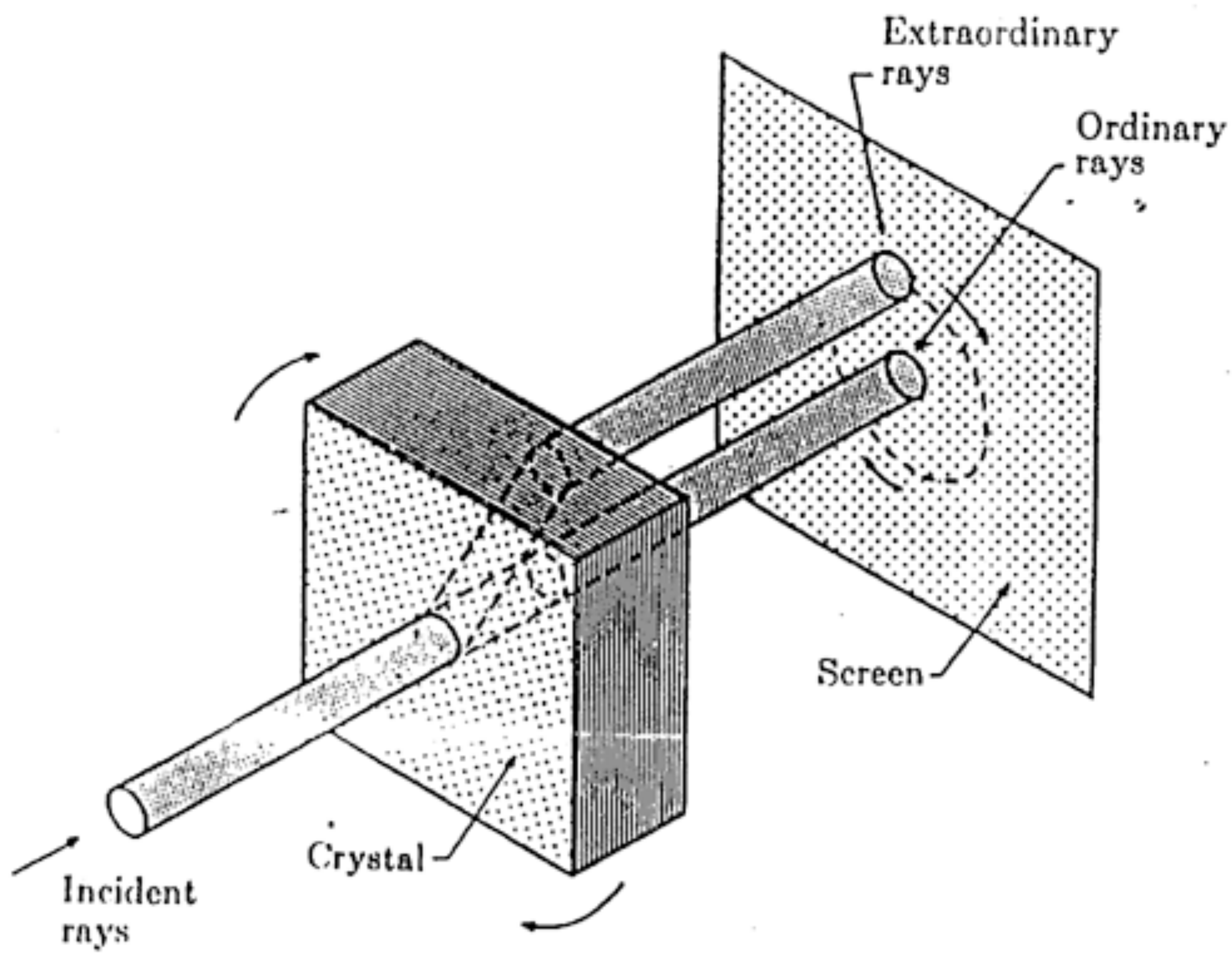
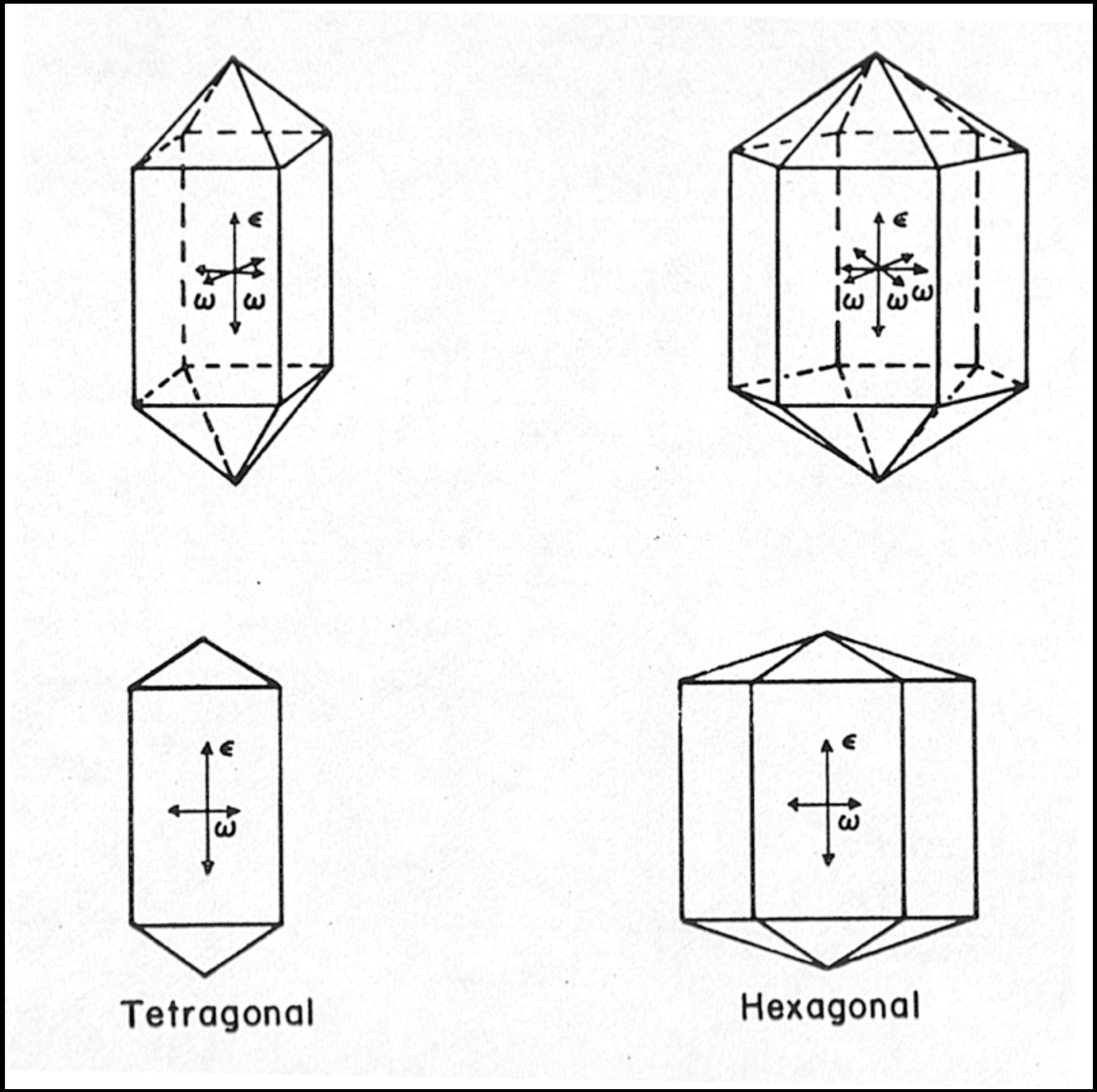


Fig. 47–7. A narrow beam of natural light can be split into two beams by a doubly refracting crystal.

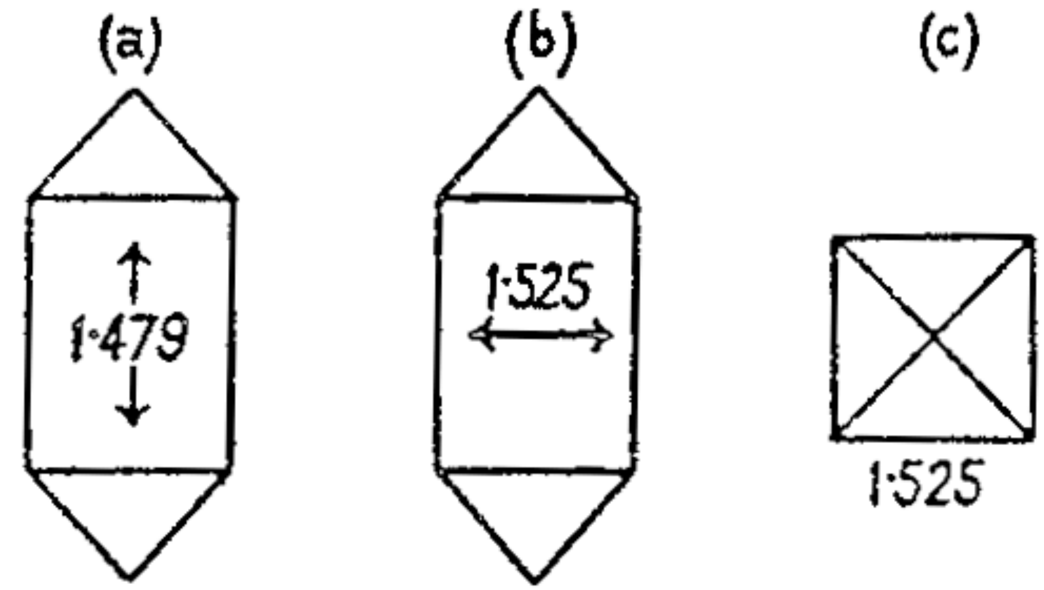
Uniaxial Materials - A Single Optic Axis
Tetragonal and Hexagonal Crystals, and Drawn Fibers

- Tetragonal crystals have one direction with 4-fold symmetry
  - the optic axis is along the 4-fold axis
- Hexagonal crystals have one direction with 6-fold symmetry
  - the optic axis is along the 6-fold axis



Tetragonal and Hexagonal Crystals are Uniaxial

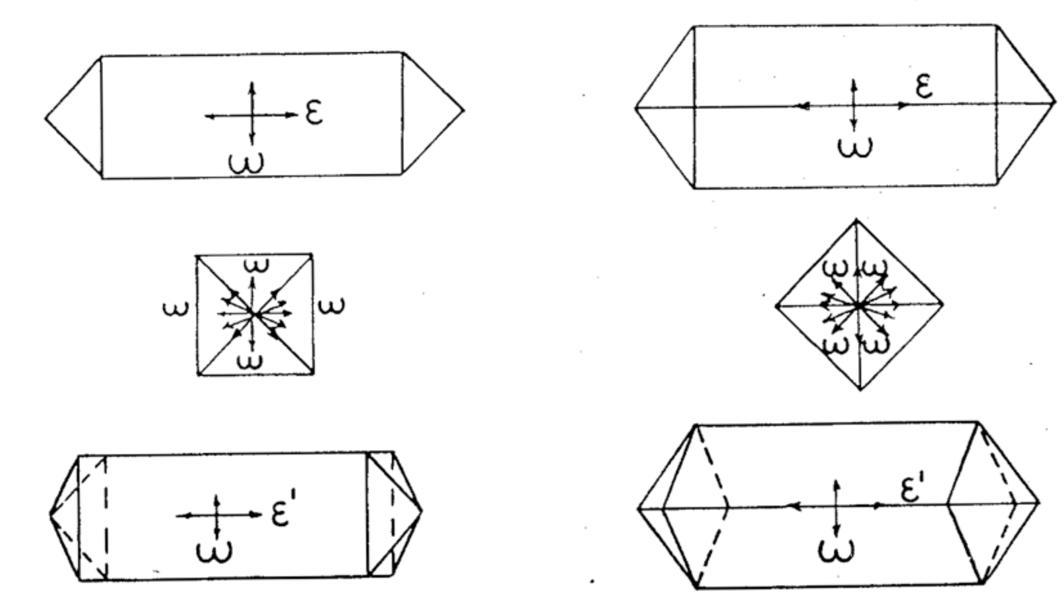
- Light traveling down the optic axis experiences only one refractive index, regardless of the direction of vibration
- Light traveling perpendicular to the optic axis is split into two components, vibrating at right angles to each other.
- One experiences a refractive index ω, and the other experiences a refractive index ε.



Refractive indices of monammonium phosphate, $NH_4H_2PO_4$. Arrows indicate vibration directions.

Uniaxial Crystals May Show Intermediate Refractive Indices

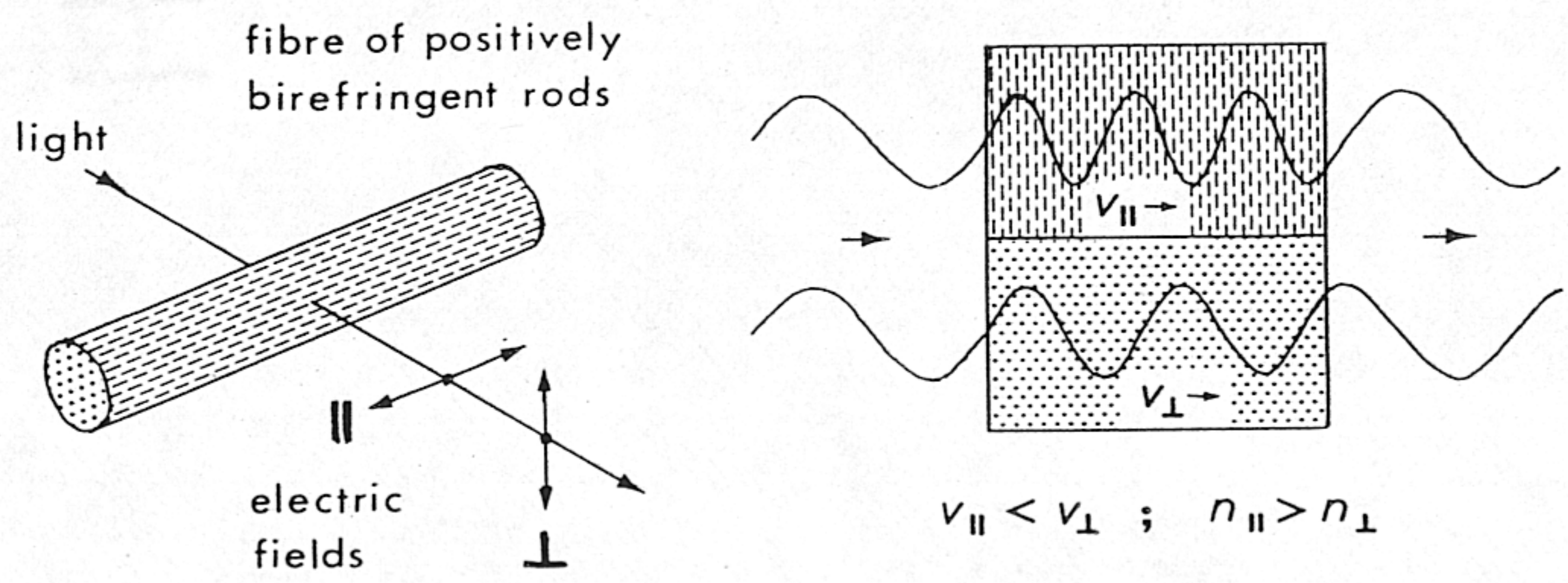
- ω will always be evident, while ε will be the extreme of the other value measured
- If the crystal is lying on its side or on an edge, ε and ω will be evident.
- If the optic axis is tilted out of the plane of the slide, an intermediate value of ε' will be exhibited



Refractive indices shown by a tetragonal crystal in different orientations

Other Uniaxial Materials

- Drawn polymer fibers often have radial symmetry
- *Convention:* The fiber is "positive" if the refractive index parallel to the direction of the fiber is larger than the refractive index perpendicular to the fiber



Positive birefringence in a fibre.

Anisotropic Materials - Biaxial Crystals

- These crystals are in the orthorhombic, monoclinic and triclinic systems
- There are two directions within the crystal along which the light travels with zero birefringence, the two optic axes
- Biaxial crystals have three principal indices of refraction, α, β, and γ -- Only two indices are evident in one particle at one time.

Bragg's Theory

Consider the effect of a diatomic molecule or ion on light passing through it.

When the vibration direction of the light is parallel to the line joining the atoms, each atom becomes polarized.

If the vibration direction of the light is perpendicular to the line joining the atoms the polarization of the two atoms is smaller

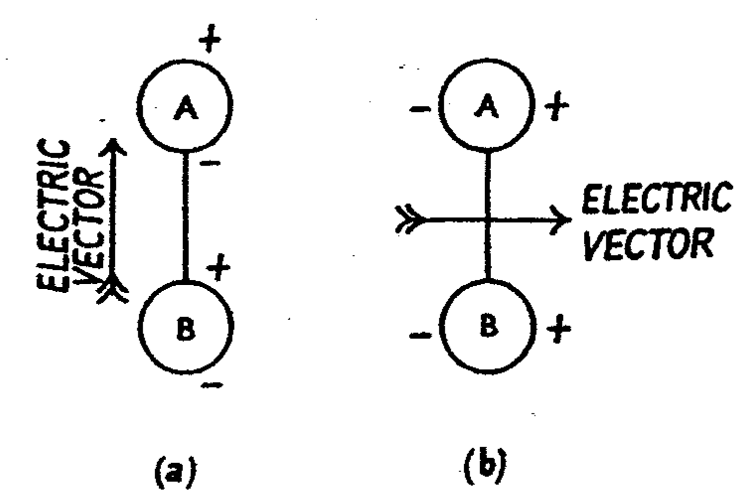


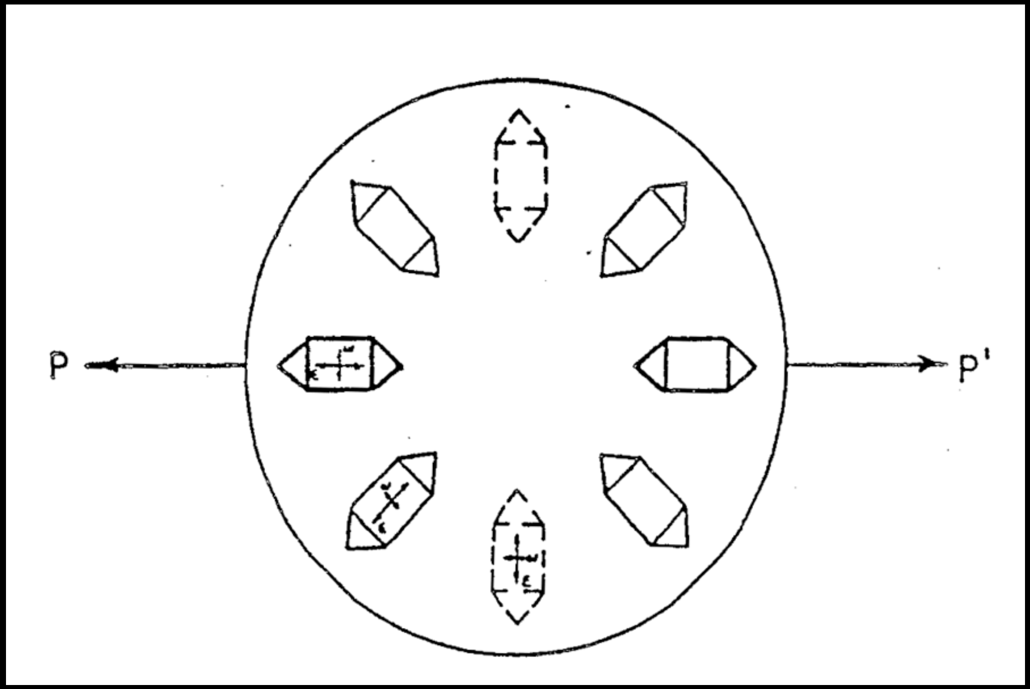
Fig. 168. Illustrating Bragg's theory of the refractive indices of crystals.

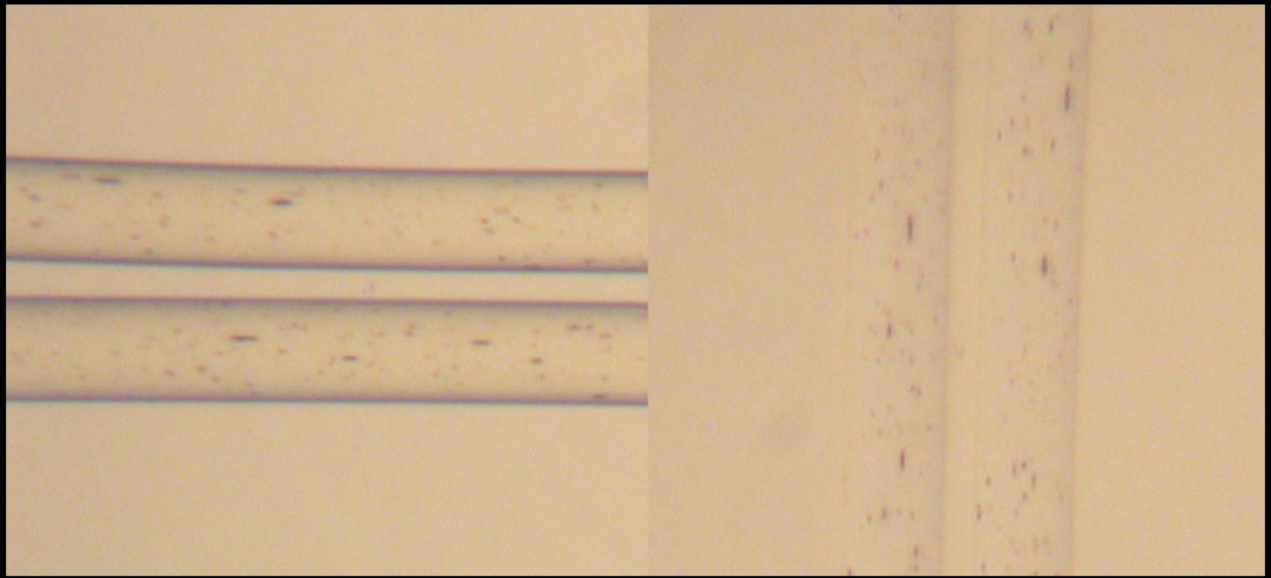
Bond polarizabilities

	$p_L \times 10^{25}\ cm^3$	$p_T \times 10^{25}\ cm^3$	*Ref.*
C—C	9·7	2·5	1
C═C	29·0	10·7	2
C≡C	35·4	12·7	2
C—C aromatic	22·5	4·8	2
C(arom.)—C(aliph.)	14·0	3·0	3
C—N	13·8	2·2	3
C—O	14·6	1·7	3
C═O	20·0	10·0	3
C—H	8·2	6·0	1
N—H	5·8	8·4	2
O—H	4·8	8·0	3
C—F	15·0	4·0	4
C—Cl	36·7	20·8	2
C—Br	50·4	28·8	2

A Birefringent Crystal Rotated, with One Polarizer in Light Path

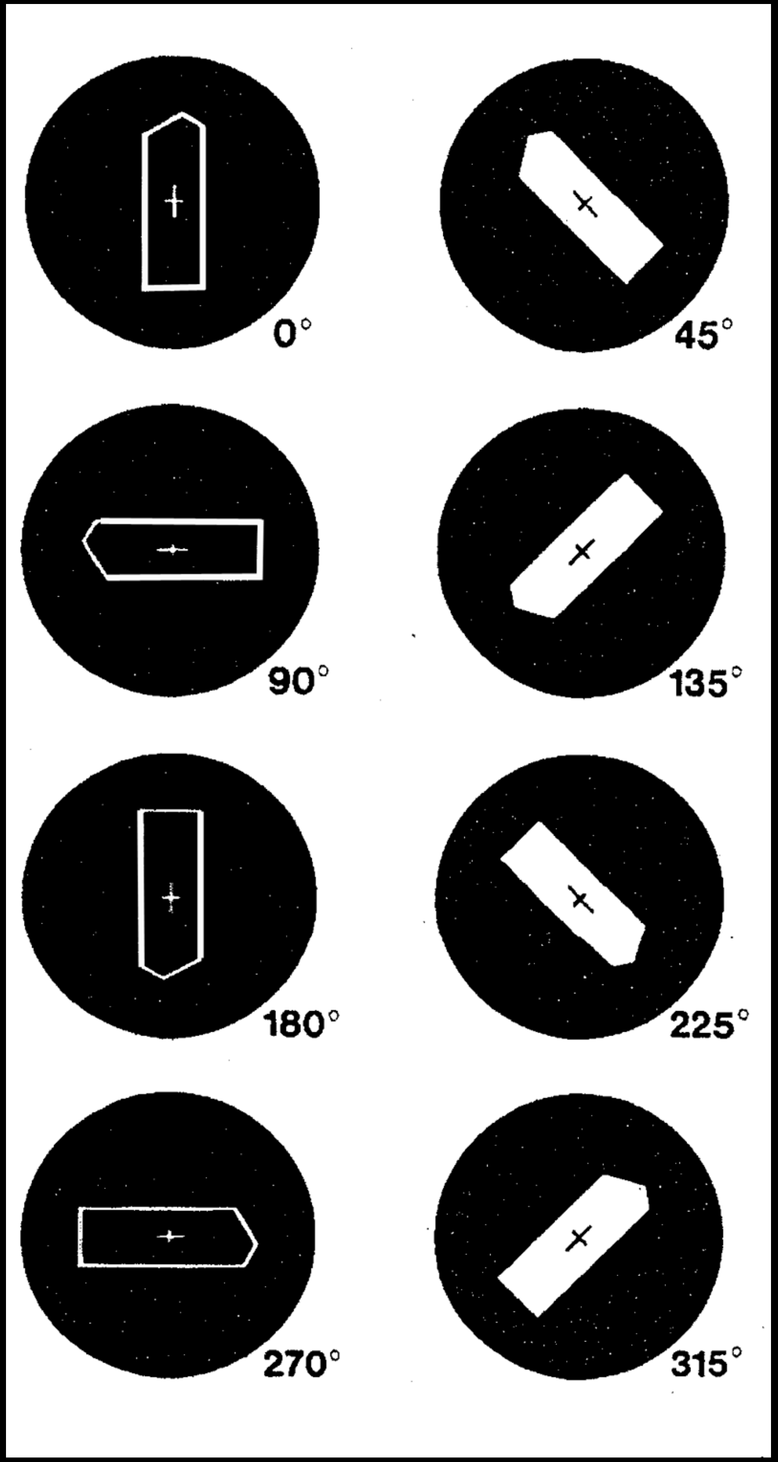
- The Polarizer transmits only light vibrating in the E-W direction
- When the crystal is in the 12 and 6 o'clock positions only ω is experienced
- When the crystal is in the 3 and 9 o'clock positions, only ε is experienced
- Different Relief is shown with the different RI's



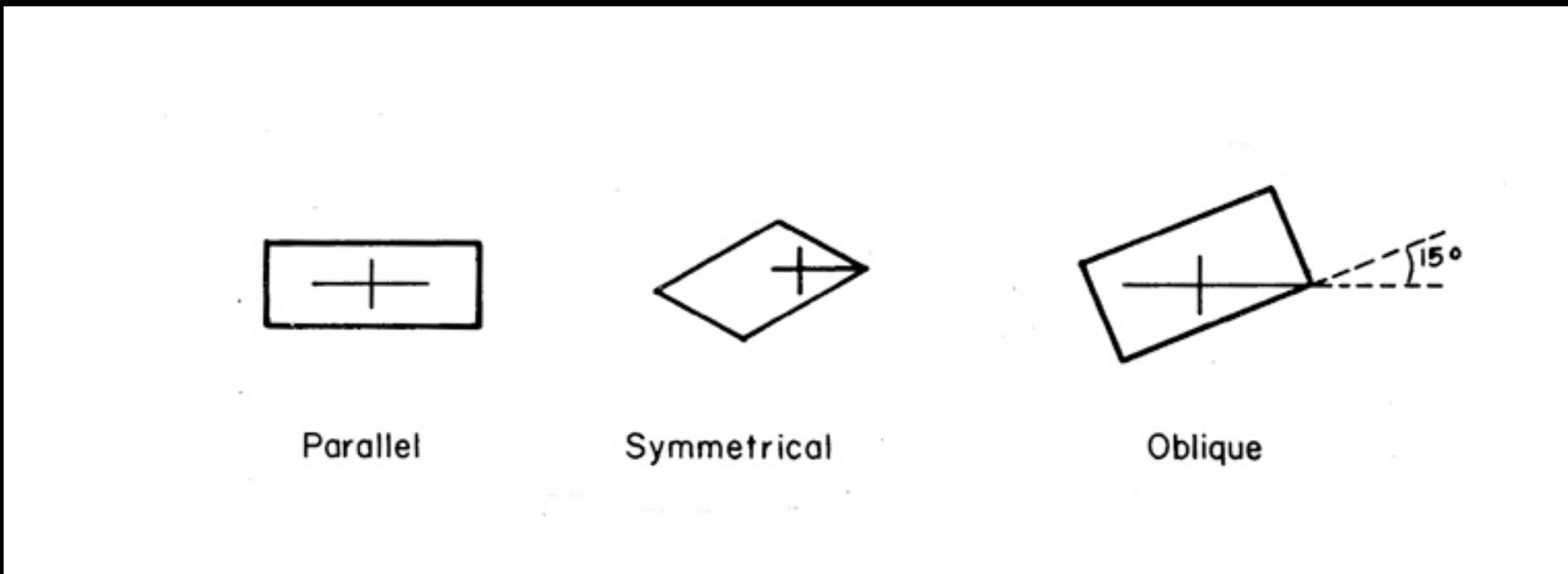


Birefringent Crystal is Rotated with Two Polarizers in the Light Path

- When both polarizer and analyzer are in the light path and they are crossed, the field is black
- When a birefringent crystal is rotated between crossed polarizers, it is dark in its extinction positions, and brightest at the diagonal positions, at 45 degrees away



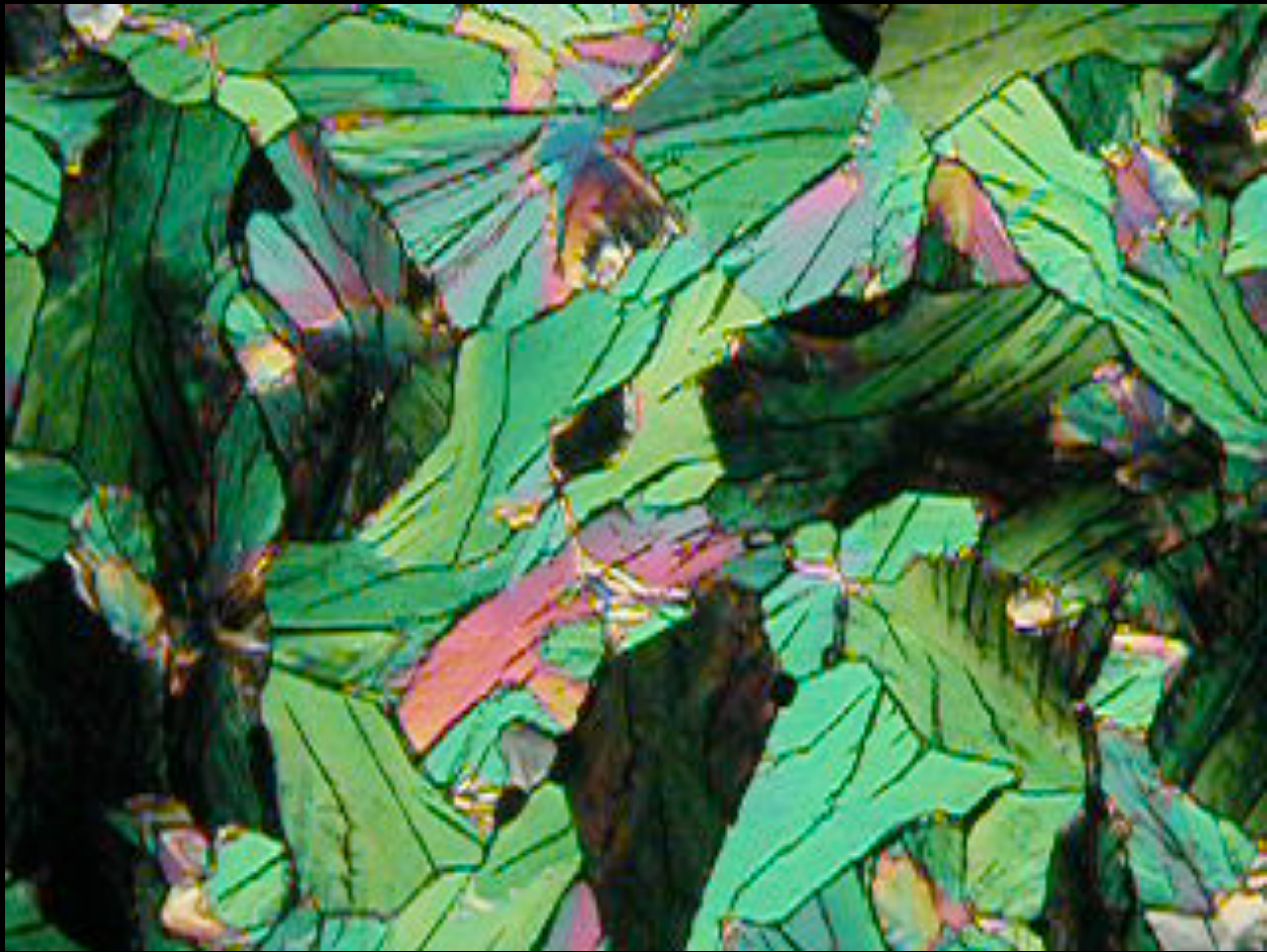
Extinction in Anisotropic Crystals



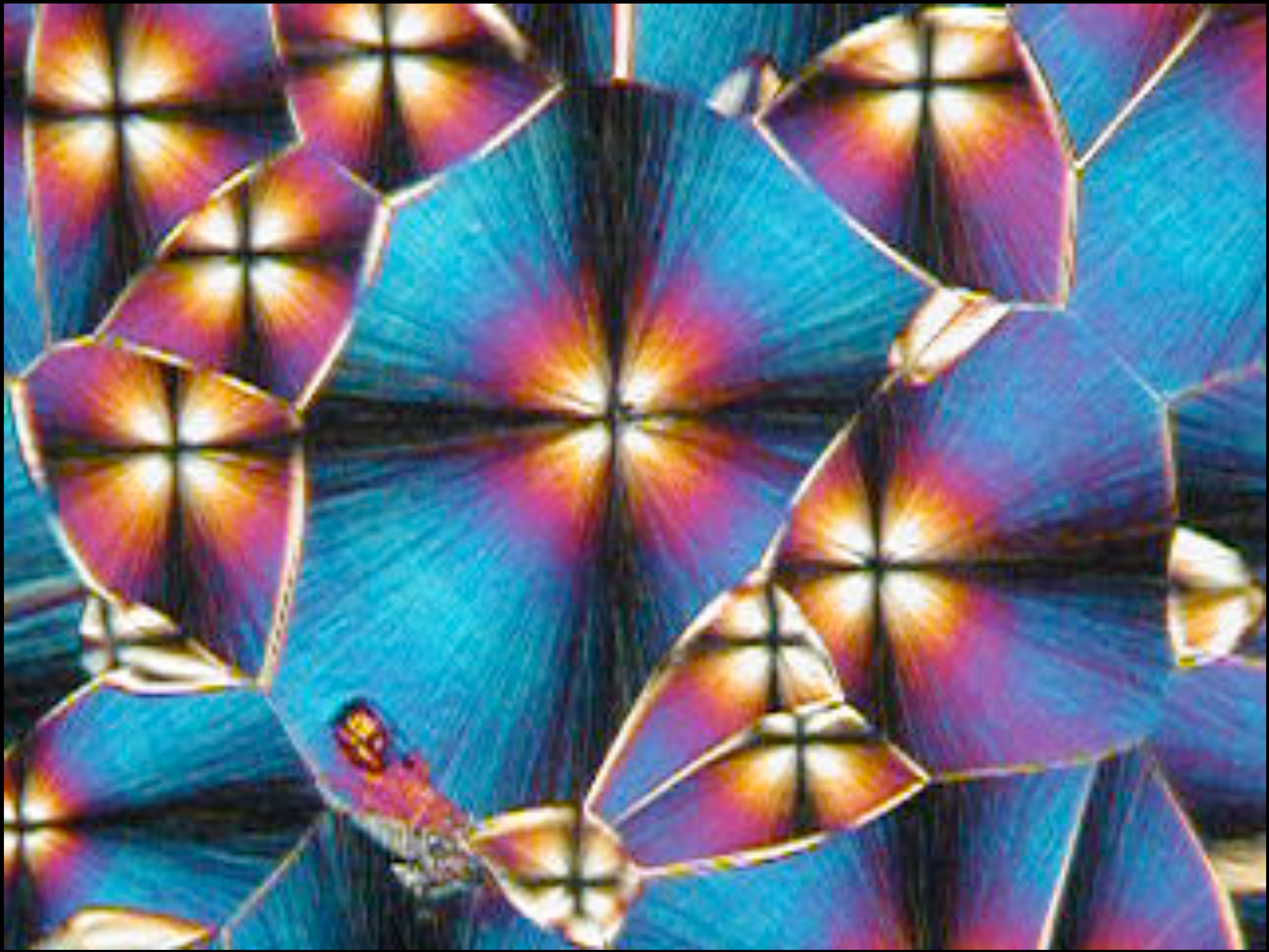
Birefringent Crystal is Rotated with Two Polarizers in the Light Path

- Crystals at various orientations show the twinkling effect as the stage is rotated
- When crystal is dark, its principal axes are parallel to polarizer or analyzer
- When crystal is brightest it is at the diagonal position 45 degrees from extinction

What's Happening Here?



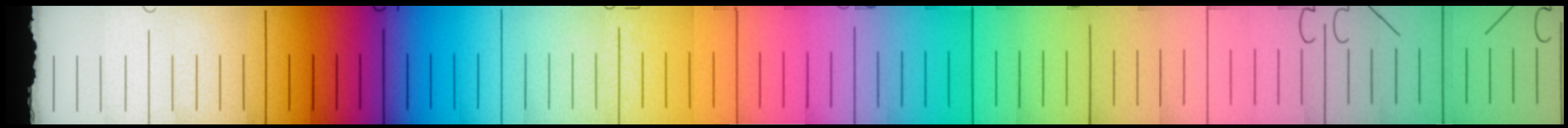
And What's Happening Here?



Where Do These Colors Come From?

- We'll Use a Quartz Wedge to Illustrate

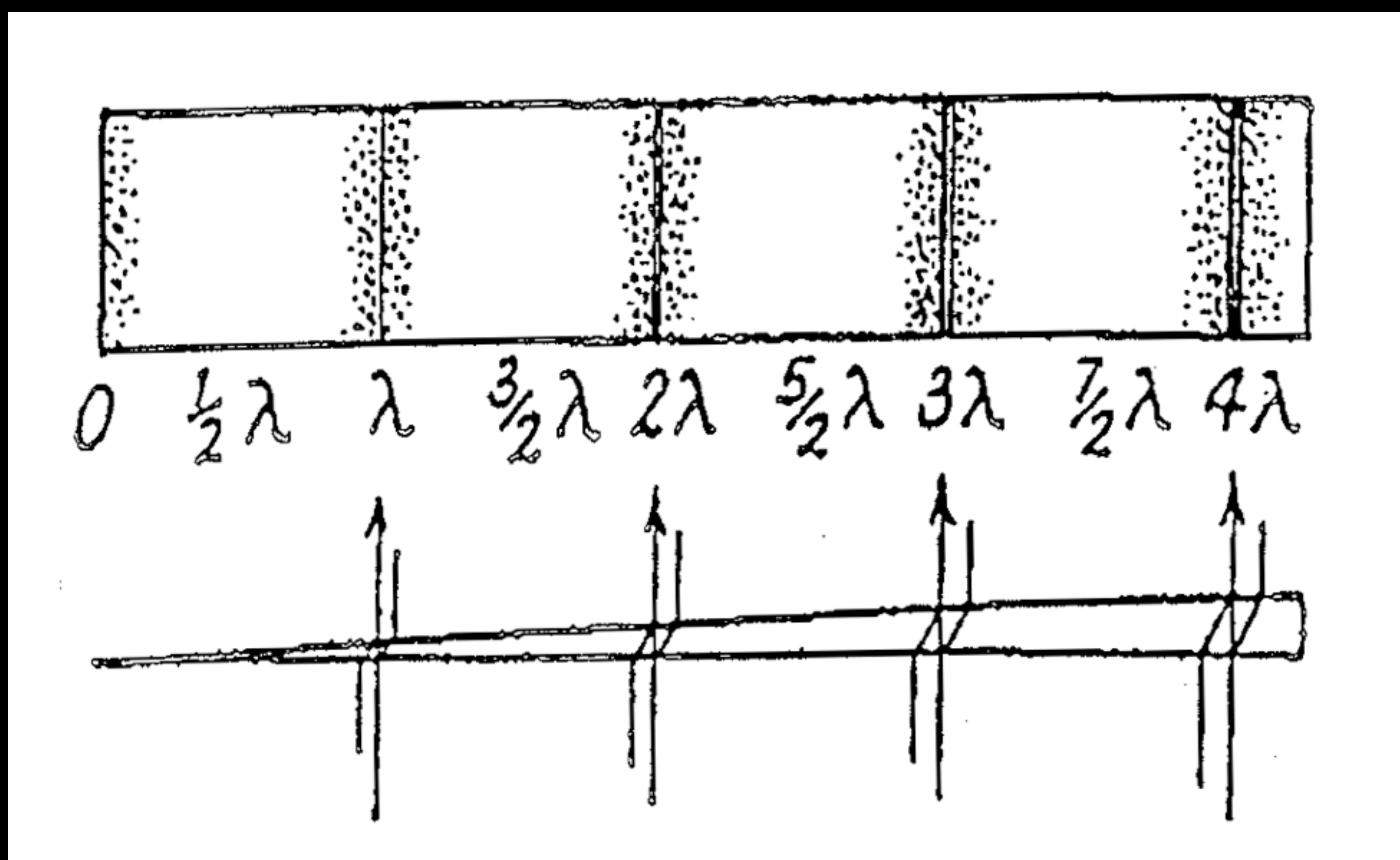
The Quartz Wedge



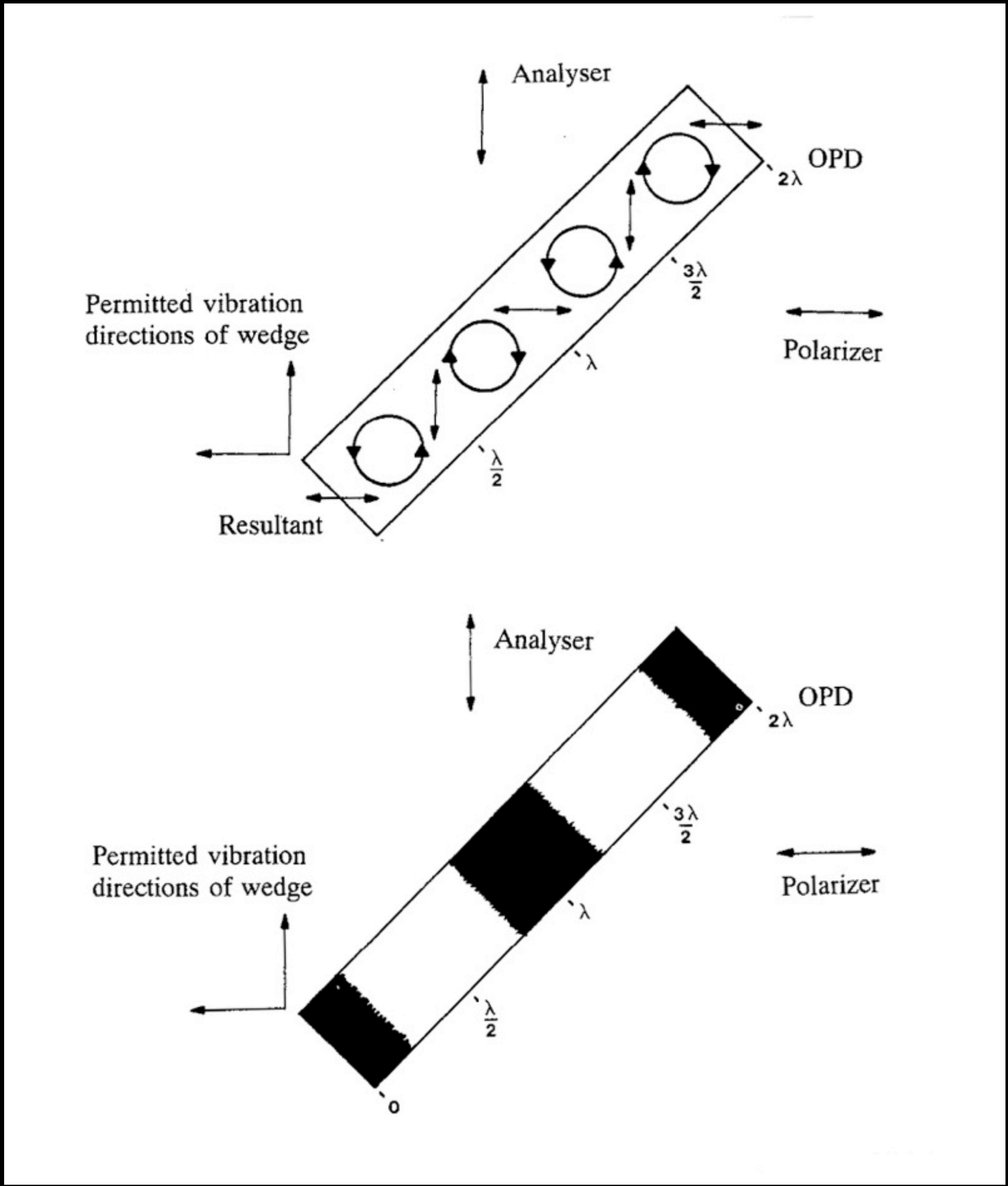
- A single crystal of quartz with gradually increasing thickness
- It is cut normal to the optic axis so light encounters two refractive indices
- When it is viewed in white light with crossed polarizers, a range of colors are visible

Quartz Wedge in Monochromatic Light

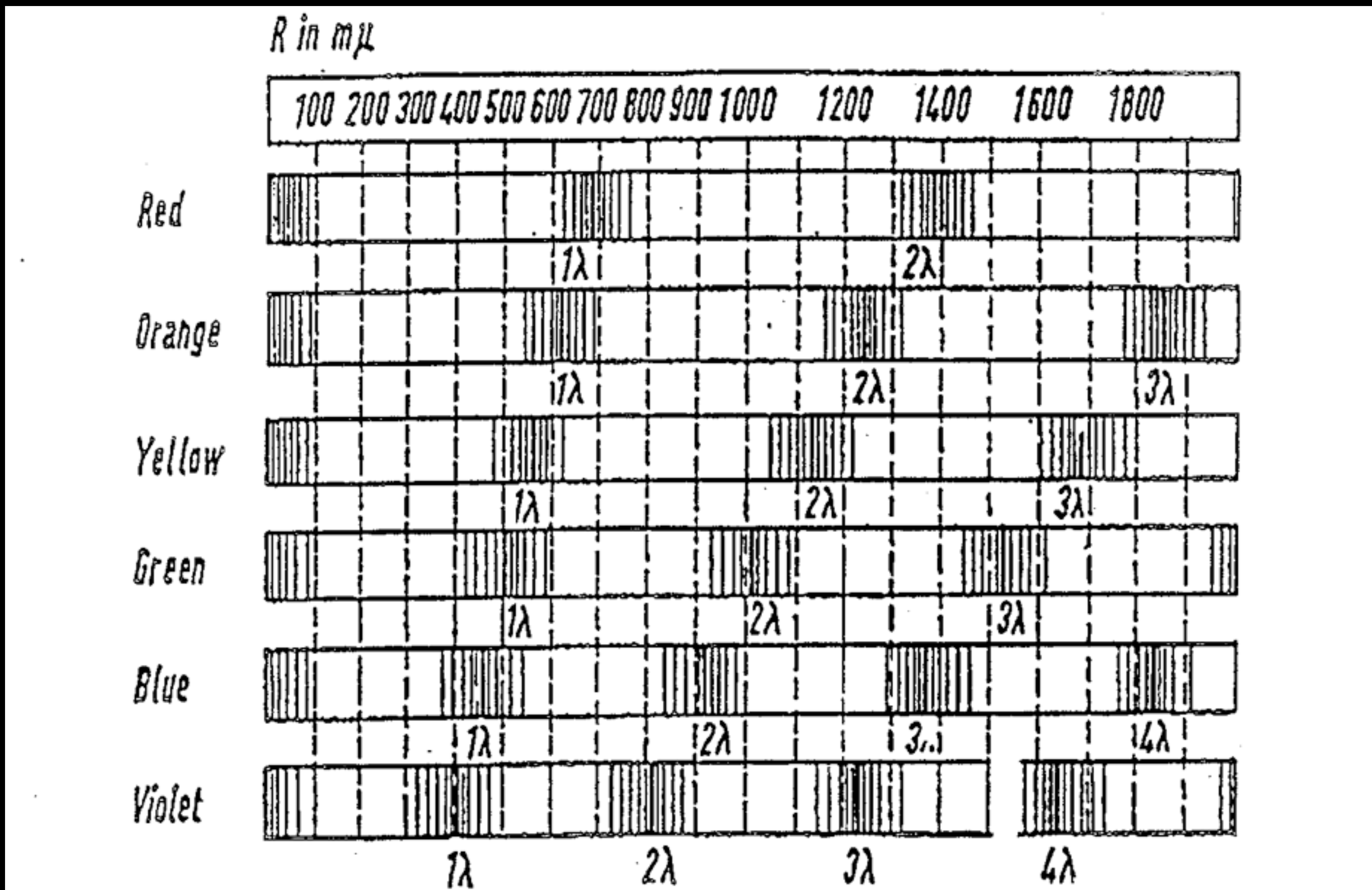
OPD



Resultant Vibration Directions in Wedge



Quartz Wedge in Monochromatic Light



Michel-Levy Chart

- The Michel-Levy Chart provides a means for quantitative analysis of the polarization colors observed in birefringent samples

- The Michel Levy Chart shows the sequence of polarization colors along with the retardation value associated with each color, and provides the relationship between the thickness of the sample and its birefringence

- Retardation or OPD introduced by the sample is

$$\Gamma = t \times (n_1 - n_2)$$

- An interactive Java tutorial is available on the web at http://www.olympusmicro.com/primer/java/polarizedlight/michellevy/index.html

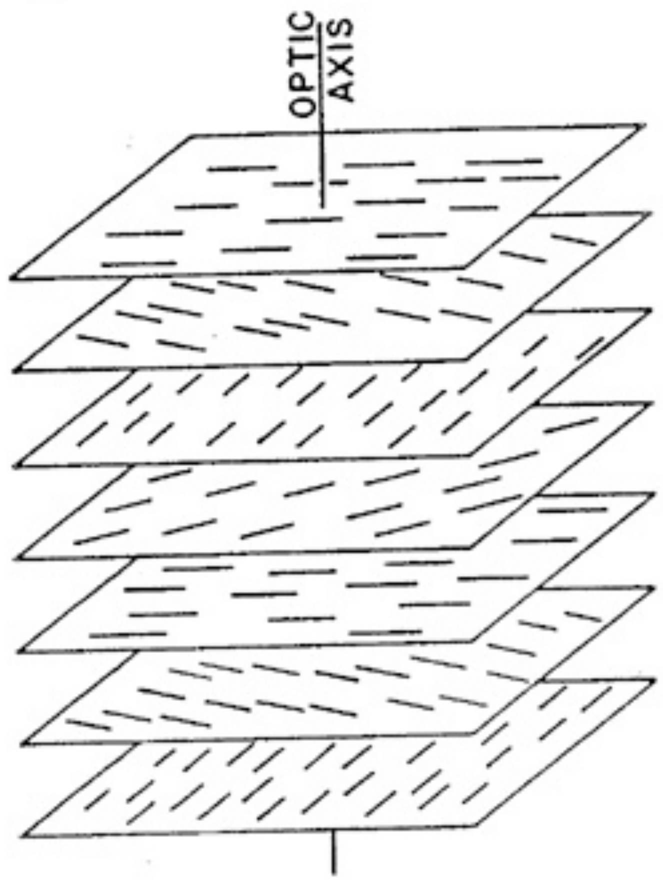
Refractive Index of Common Fibers

Table 2.4: RI of fibres

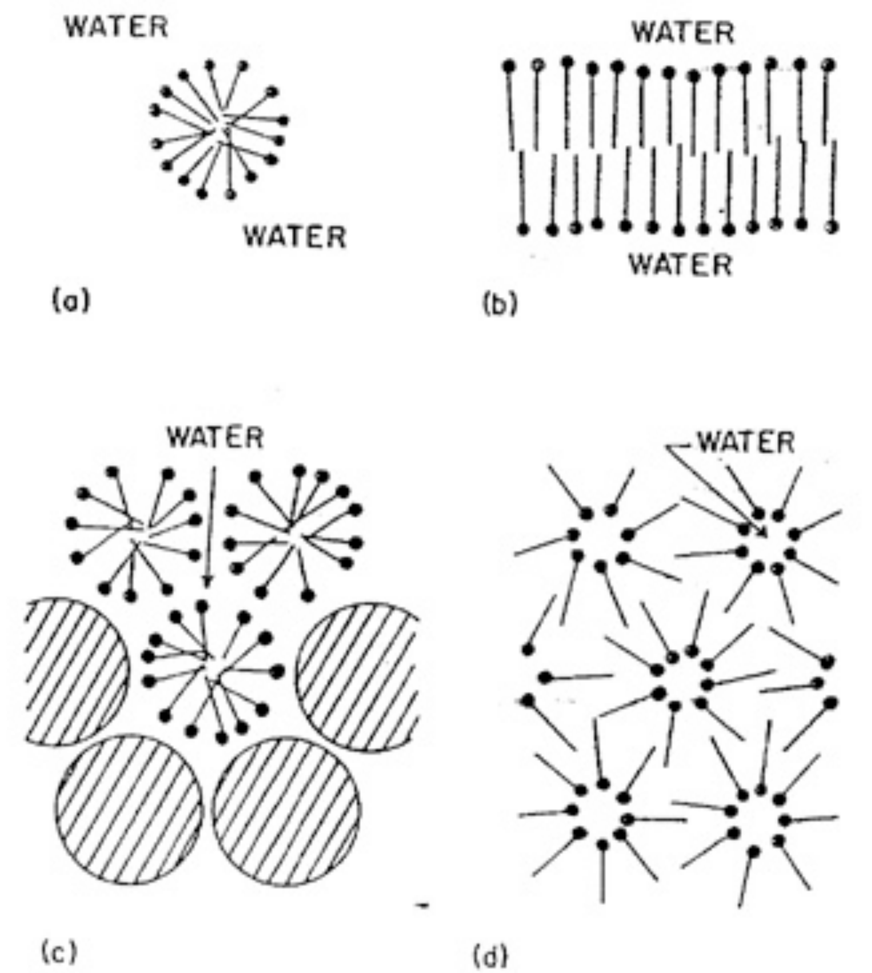
Fibre	$n\|\|$	$n\perp$	Birefringence
Acrylic	1.511	1.514	–0.003
Cellulose diacetate	1.477	1.472	0.005
Cellulose triacetate	1.469	1.469	0
Chlorofibre	1.541	1.536	0.005
Cotton	1.577	1.529	0.048
Flax	1.590	1.525	0.065
Modacrylic	1.520	1.516	0.004
Nylon 6	1.575	1.526	0.049
Nylon 6.6	1.578	1.522	0.056
Polyester	1.706	1.546	0.160
Polypropylene	1.530	1.496	0.034
Silk	1.591	1.538	0.053
Viscose (ordinary)	1.542	1.520	0.022
Wool	1.557	1.547	0.010

The values given are for guidance only and variations on these figures may be found in some cases.

More Liquid Crystals



Cholesteric structure (schematic), with right-hand twist. The planes mark levels in the structure between which a 45° rotation of the molecular axes occurs.



Main types of micelles in amphiphile-water systems. Only molecules with single lipophilic chains are shown but peg-shaped molecules would be arranged similarly, though such molecules are not known to form M_1 phases: (a) diametral section of spherical micelle, (b) smectic layer in neat phase, G, (c) middle phase, M_1, showing cross section of micellar rods (according to Luzatti), (d) inverse middle phase, M_2, showing cross section of micellar rods (according to Luzatti). (after Hartshorne and Stuart, Crystals and the Polarising Microscope, Arnold, 1970.)

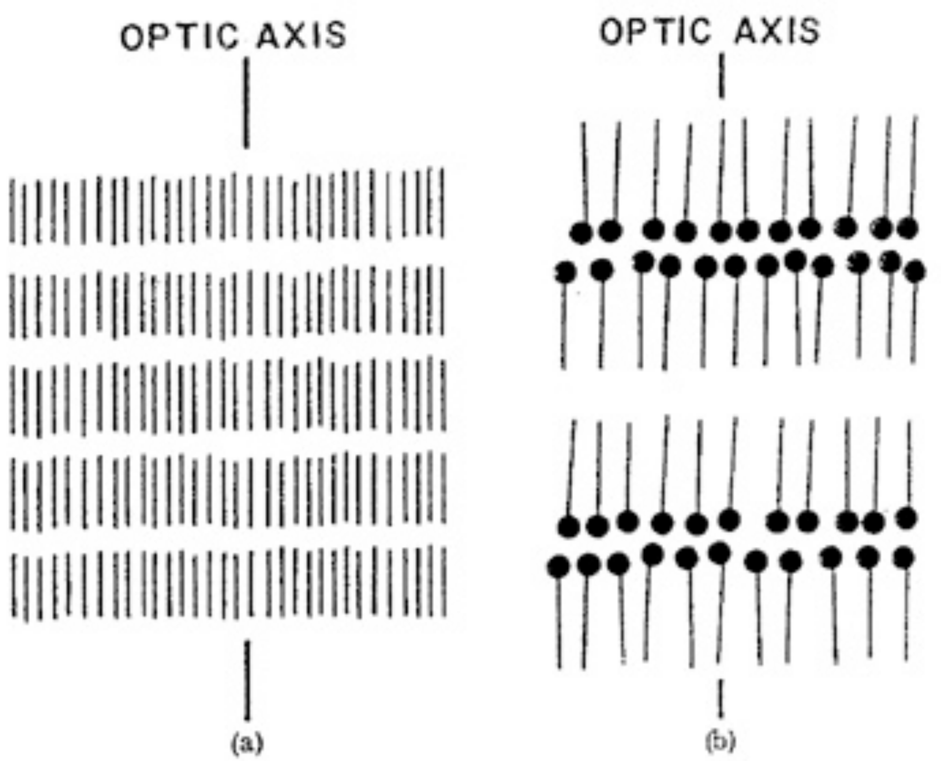
Animal Vegetable Mineral

- <u>Animal Materials</u> - bone, muscle, hair, fur feathers incorporated crystalline materials
- <u>Plant Materials</u> - fibers, cell walls, starches
- Inorganic Crystals - salts, metals, petrographic sections cements, fertilizers
- <u>Organic Crystals</u> - dyes, drugs, (most organic materials are birefringent
- <u>Polymers</u> - molded, extruded, drawn, coated , pressed, heated
- <u>Some Glasses</u> - oriented or strained glass

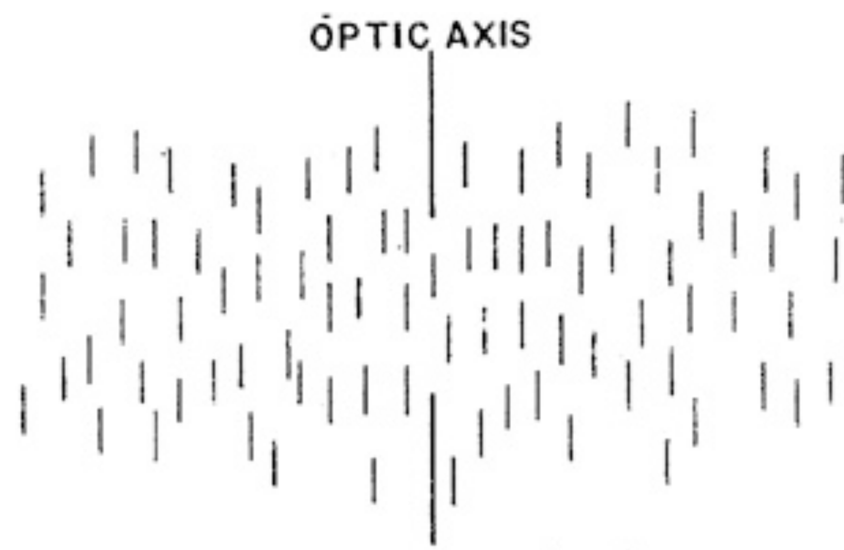
Special Materials for Polarized Light

Special Birefringent Forms - Liquid Crystals

They exhibit properties intermediate between those of a true liquid and a true solid - a mesomorphic state. *Thermotropic mesomorphism* results from a rise in temperature. *Lyotropic mesomorphism* occurs in liquid solutions.



Smectic structures (schematic). (a) Single layers (type-A phase). (b) Double layers as in soaps. (Terminal polar groups, e.g. -COONa, represented by blacked-in circles.)



Nematic structure (schematic).

Measurements in Polarized Light

NYMS Workshop
October 16, 2010

Instructor, Mary McCann,
McCann Imaging

Compensators

- Fixed and variable compensators are used as reference objects with known orientation of their fast and slow directions.
- The compensators are introduced on the diagonal in the tube slot of the microscope. The vibration direction of the slow ray, gamma, is engraved on the compensator.

Fixed Compensators

- Full Wave Plate, Red 1 plate, λ Plate, Sensitive Tint Plate, or Quartz or Gypsum plate introduces a phase difference of ~550nm.
- It is called sensitive tint because with the addition or subtraction of very small phase differences the interference color changes toward blue or yellow respectively

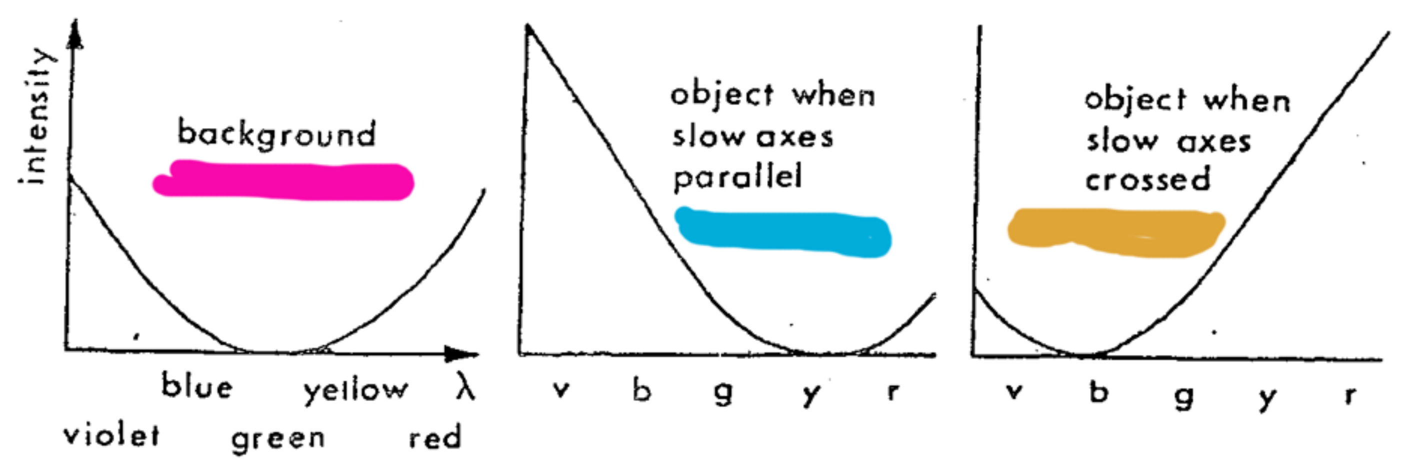
Compensators - The Use of Accessory Plates

- Accessory plates are used to determine whether a given vibration direction is the high or low index vibration direction in a crystal.
- The accessory plate is a birefringent plate of known magnitude and orientation, usually arranged with its fast and slow axes at 45degrees to the polarizer
- The retardation introduced by the plate either adds to or subtracts from the retardation introduced by the sample

Compensators

- The Gypsum or Quartz Red I Plate is cut to a thickness to give a retardation of ~550nm It is most useful with crystals showing first order retardation colors

Colors produced by a Red I plate and a sample giving ~100nm retardation.



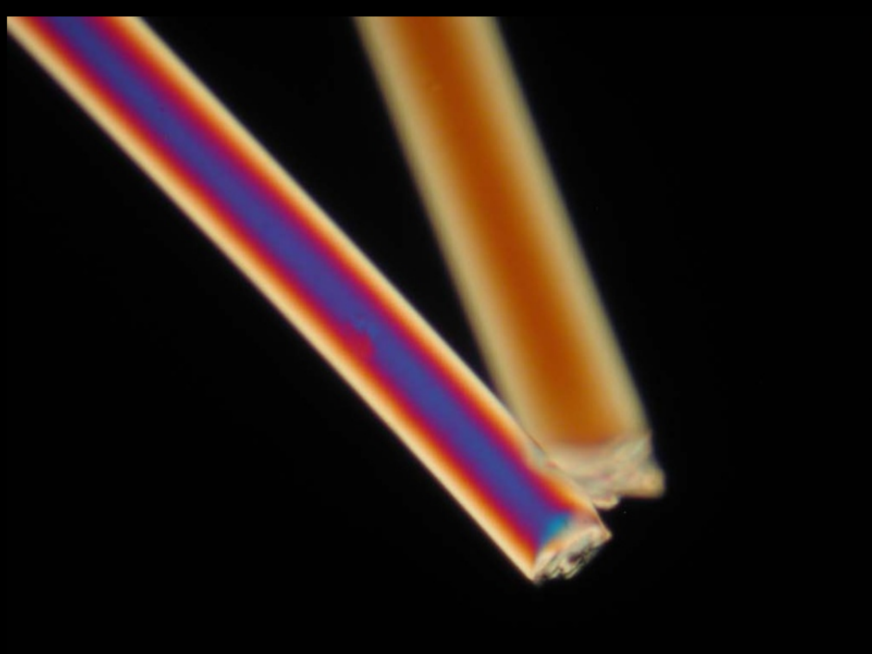
R = 550nm appears magenta

R = 650nm appears blue-green

R = 450nm appears yellow

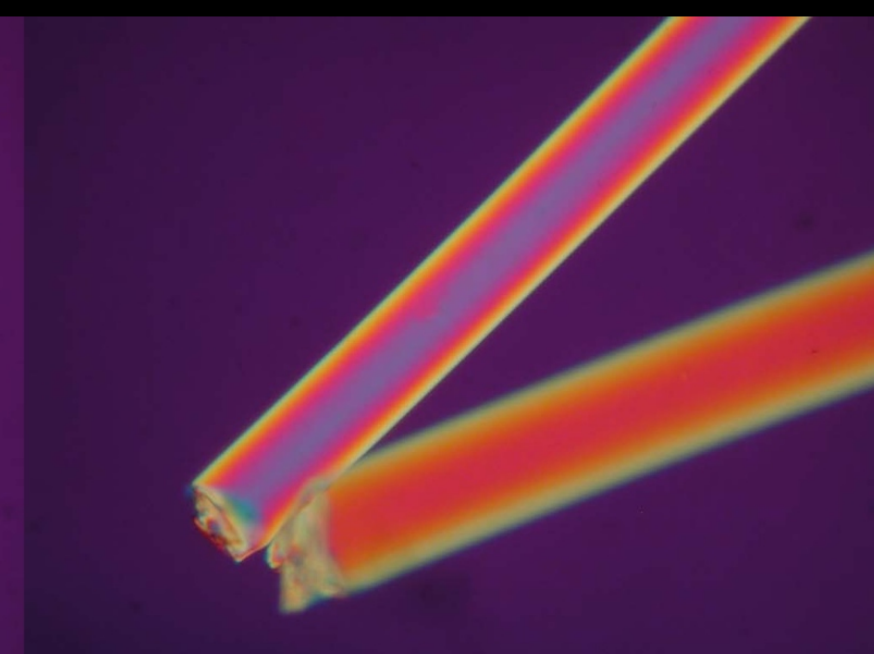
Red I Plate with Fiber

Crossed Polarizers



Slow Directions Subtract

Slow Directions Add



Compensators - continued

- The mica plate, marked "Glimmer" or "λ/4" introduces a retardation of ~140nm, producing a white interference color. It may be useful in determining the retardation of colors higher than first order

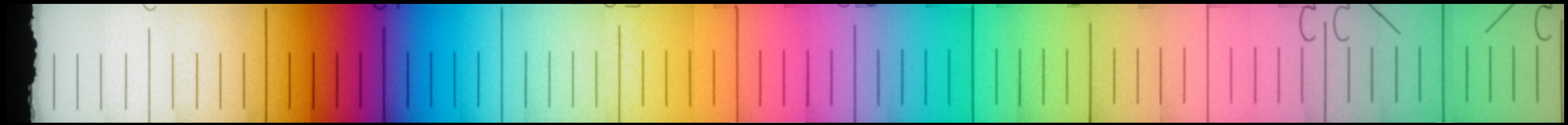
- The quartz wedge exhibits a variety of interference colors. Some wedges are marked with a graduated scale so that the retardation at exact compensation of a crystal or fiber can be determined

Fixed Compensator

- The Quarter Wave Plate has a phase difference of ~140nm. It produces a first-order grey. It may be useful in determining the retardation of colors higher than first order.

Variable Compensators

- The quartz wedge produces interference colors up to about fourth order. By adjustment of the wedge in the tube slot of the microscope differences of 0 to 4 orders can be determined.
- More accuracy is possible if used with a slotted ocular
- Many wedges are marked with a graduated scale so that retardation at exact compensation can be determined.
- For this wedge, First order interference for 546nm occurs at 14.5 and retardation increases at 29.7nm per division.
- The slow direction is along the length of the wedge.



Brace-Kohler Rotary Mica Compensators

- The Brace-Koehler Compensators are used for measuring specimens with extremely small path differences.
- Compensator plate is rotated around the microscope axis until compensation occurs.
- Zeiss described compensators to measure λ/10, (55nm), λ/20 (27nm), or λ/30 (18nm)

de-Senarmont Compensation

- For determining path differences, up to one wavelength
- Quarter wave plate for specific wavelength of either 589nm or 546nm.
- Orient the sample to a position of maximum brightness, 45 degrees from extinction.
- Use monochromatic light, 589nm or 546nm.

de-Senarmont Compensation continued

- The plate is inserted into the accessory slot; it is oriented so that the *vibration directions are parallel and perpendicular to that of the polarizer* . You will see no apparent change in the image.
- Rotate the analyzer to bring extinction to the required part of the specimen. (This is usually accomplished with the field aperture stopped down to illuminate only the area of interest.

de-Senarmont Compensation continued

- While this method measures only the phase difference up to one order, it can be used to measure larger OPD if interference colors or tilting compensators is used to determine the whole orders.

Tilting Compensators

- Berek compensator consists of a piece of uniaxial birefringent material that can be tilted about an axis parallel to the specimen stage.
- The slow direction is labeled on the holder.
- The tilt increases both thickness and the orientation of the optical indicatrix of the plate.
- They are calibrated in the factory for the C, D, e and F lines

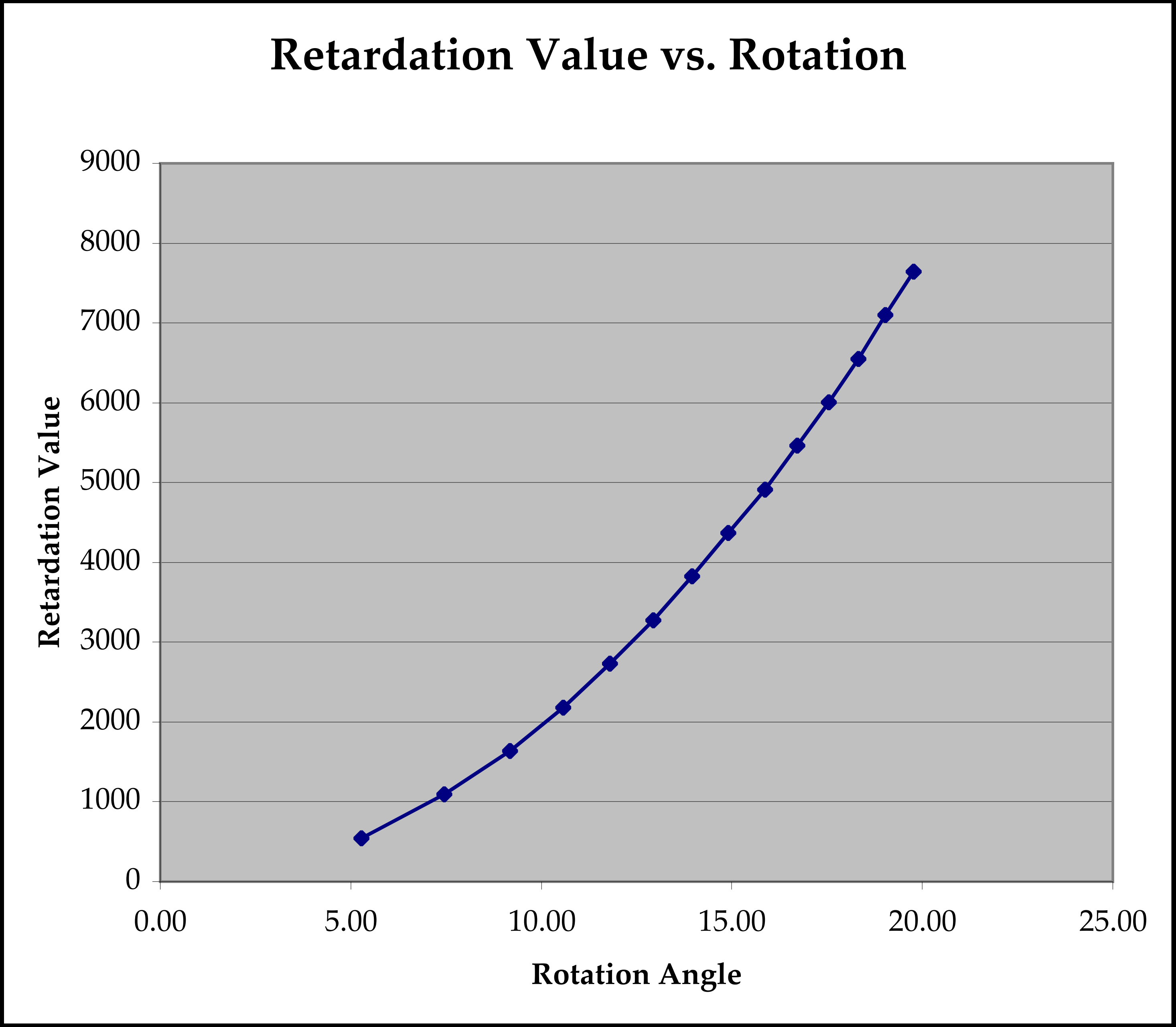
Tilting Compensators

- The Ehringhaus Compensator consists of two parallel-sided birefringent plates cut parallel to the optic axis and superimposed with their slow and fast vibration directions crossed.
- The Ehringhaus compsator is popular because the material for the two plates can be selected to giving low overall dispersion.

Ehringhaus Tilting Compensator

- Ehringhaus Compensator is calibrated at the factory for C, D, e and F lines.
- However, DIY calibration can keep it useful
- Readings should be taken in each direction for greater accuracy

Ehringhaus Compensator



Wright Eyepiece

- Permits very accurate setting of extinction
- Must be used in a straight tube so that no depolarization occurs with prisms.
- Wright Eyepiece has a rotating top analyser.
- Half-shadow plates and wedges can be inserted in the intermediate-image plane of the eyepiece.

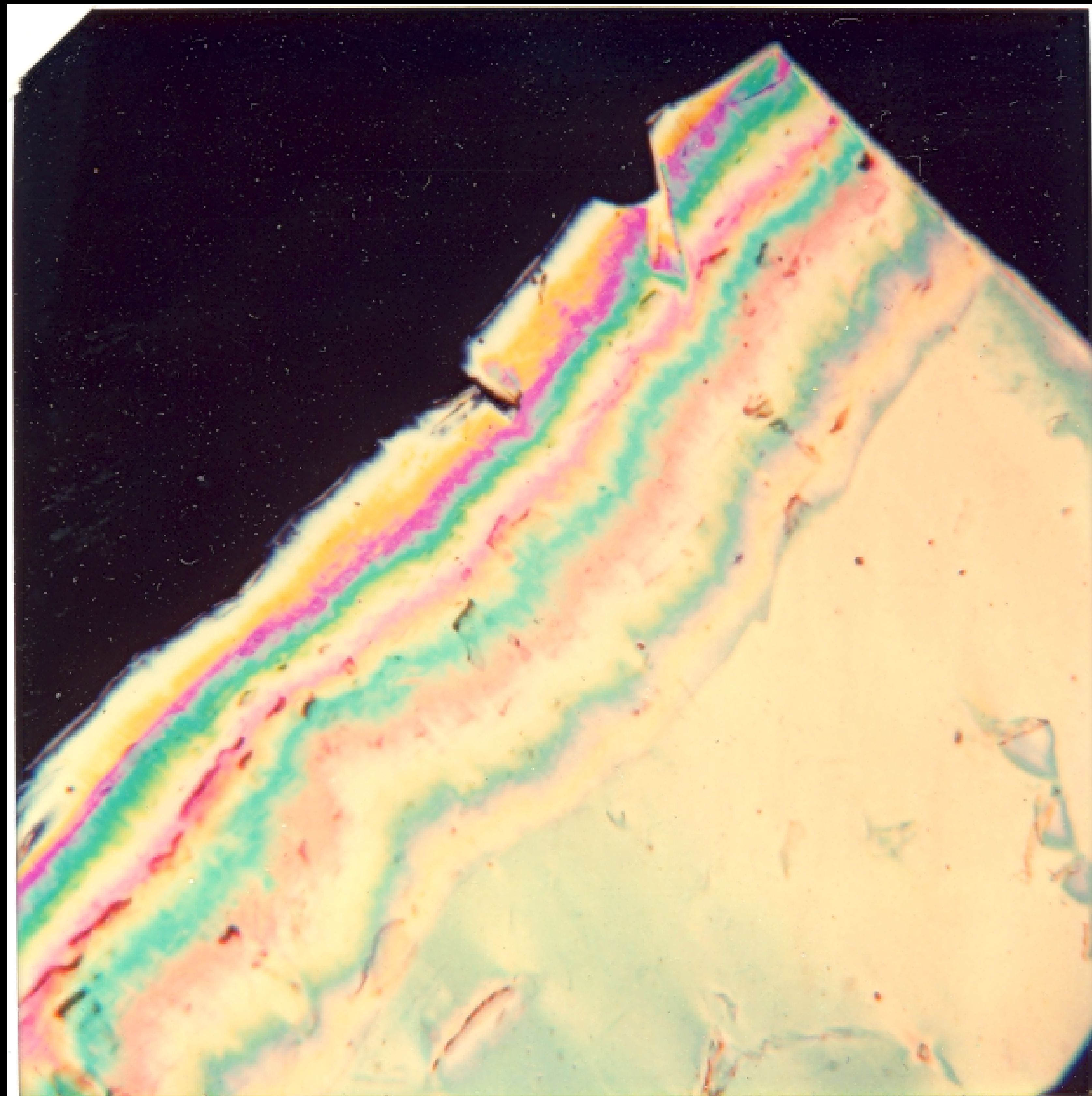
Nakamura Plate

- The two plates are thin and rotation is almost identical for all wavelengths.
- At precisely crossed polarizers or accurately set compensation position the two halves of the field appear in a grey tone.

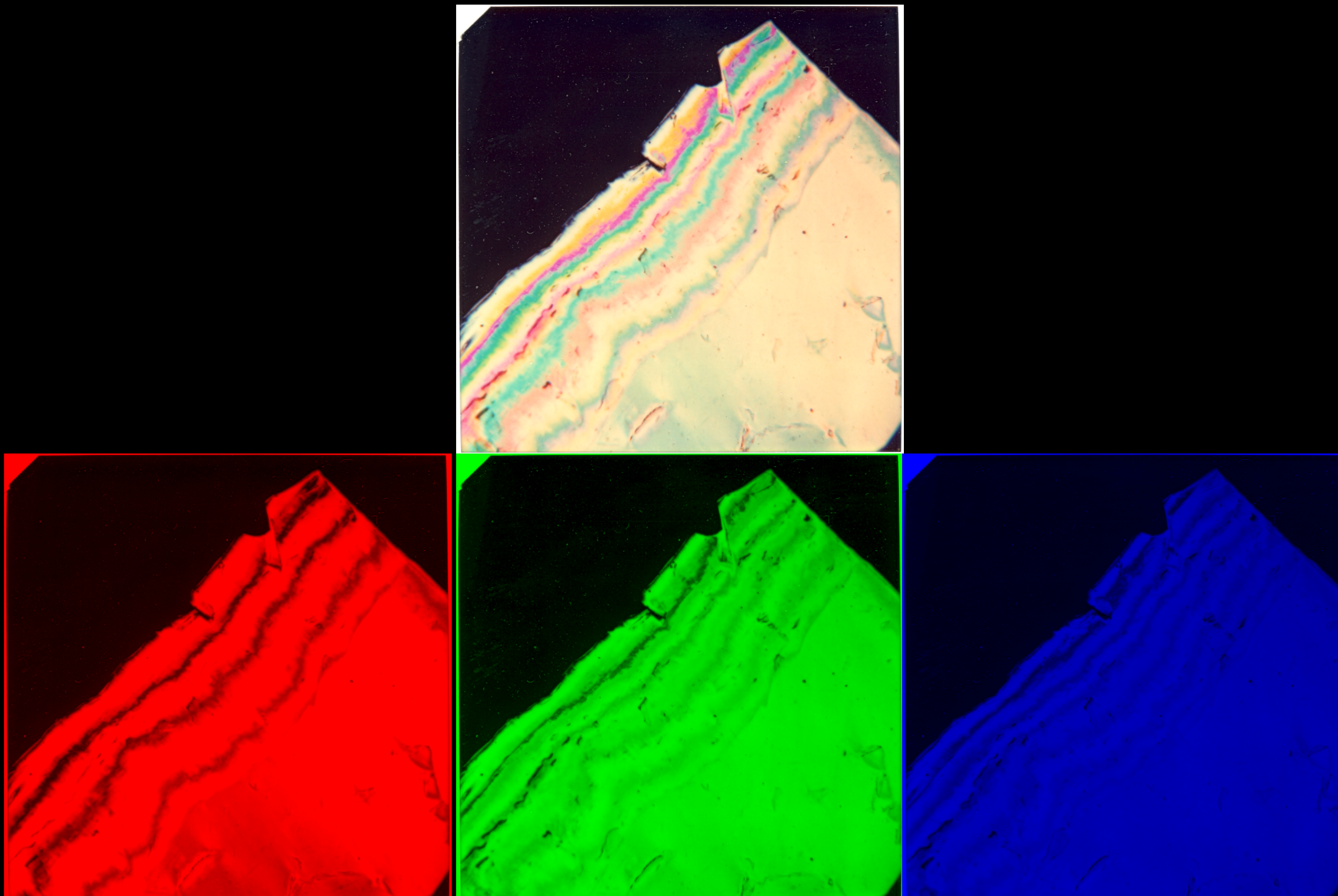
What to do with anomalous interference colors ?

- Cut a wedge - as uniform and as shallow as possible
- Use monochromatic light
- Count the fringes up the slope
- Repeat with different wavelength

Anomalous Dispersion



Anomalous Dispersion



References Describing Compensators

- The Polarizing Microscope, third edition, A. F. Halimond, Vickers Ltd., York England 1970
- Transmitted Polarised Light Microscopy, Christopher Viney, The Microscope Series, McCrone Research Institute, Chicago IL, 1990
- Polarized Light Microscopy, Principles, Instruments, applications, Walter J. Patzelt, Ernst Leitz Wetzlar, GMBH, Wetzlar