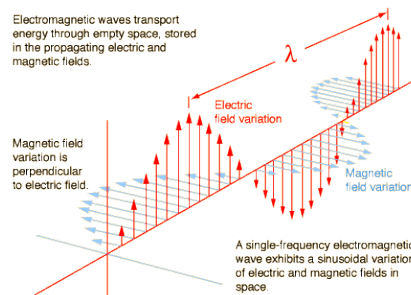


## Polarization



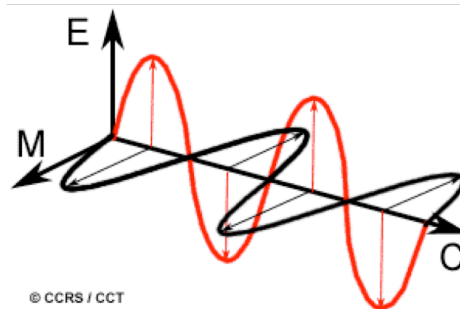
## Lecture outline

- Why is polarization important?
- Classification of polarization
- Four ways to polarize EM waves
- Polarization in active remote sensing systems



## Definitions

- Polarization is *the phenomenon in which waves of light or other radiation are restricted in direction of vibration*
- Polarization is *a property of waves that describes the orientation of their oscillations*

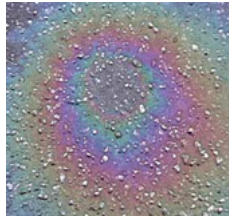


## Coherence and incoherence

- **Coherent radiation** originates from a single oscillator, or a group of oscillators in perfect synchronization (phase-locked)
- e.g., microwave ovens, radars, lasers, radio towers (i.e., artificial sources)
- **Incoherent radiation** originates from independent oscillators that are not phase-locked. Natural radiation is incoherent.

## Why is polarization important?

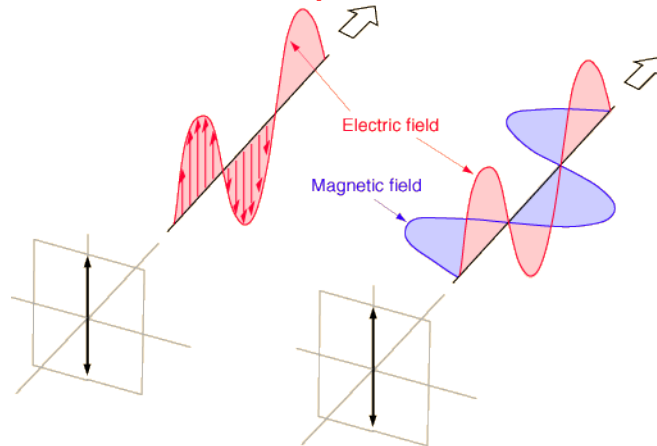
- Bohren (2006): *'the only reason the polarization state of light is worth contemplating is that two beams, otherwise identical, may interact differently with matter if their polarization states are different.'*
- Interference only occurs when EM waves have the same frequency and polarization (i.e., they are *coherent*)
- Used by active remote sensing systems (radar, lidar)



## Classification of polarization

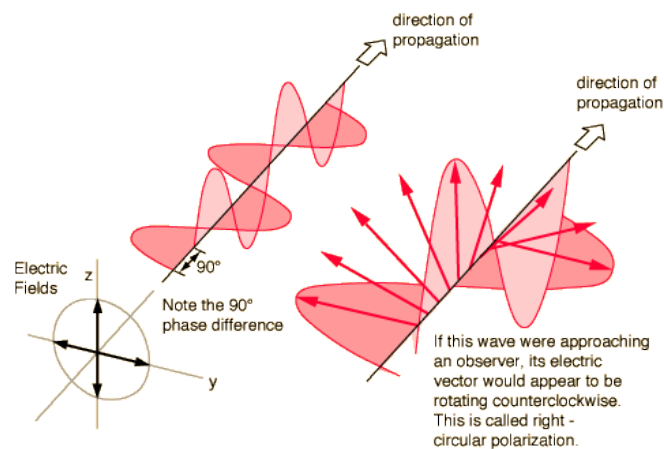
- Linear
- Circular
- Elliptical
- 'Random' or unpolarized

## Linear polarization



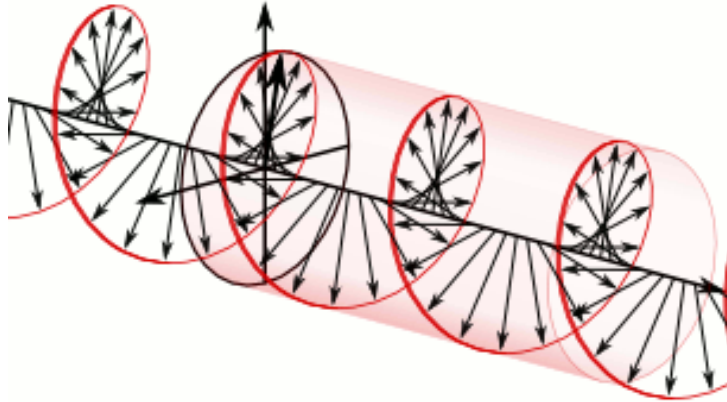
- Plane EM wave – linearly polarized
- Trace of electric field vector is linear
- Also called plane-polarized light
- Convention is to refer to the electric field vector
- Weather radars usually transmit linearly polarized radiation

## Circular polarization



- Two perpendicular EM plane waves of equal amplitude with  $90^\circ$  difference in phase
- Electric vector rotates counterclockwise  $\rightarrow$  right-hand circular polarization

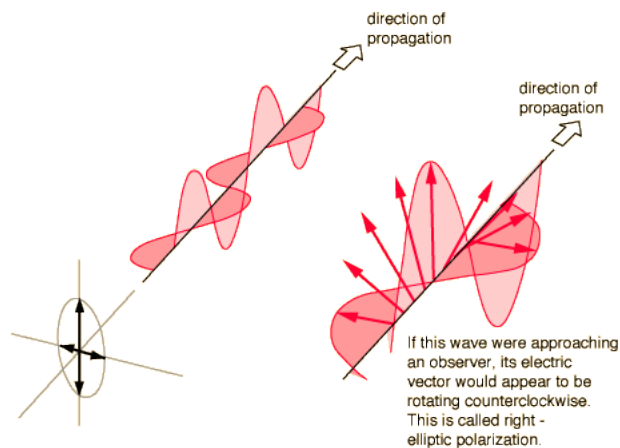
## Circular polarization



- Two perpendicular EM plane waves of equal amplitude with  $90^\circ$  difference in phase
- Electric vector rotates counterclockwise  $\rightarrow$  right-hand circular polarization

<http://physics.info/polarization/polarization-circular.html>

## Elliptical polarization



- Two plane waves not in phase, either with different amplitudes and/or not  $90^\circ$  out of phase
- The most general state of complete polarization is elliptical

## Natural EM radiation

- Generally a mixture of different types of polarization
- Randomly polarized component
  - Direction of the electric field vector changes randomly on very short timescale
  - 'Unpolarized' radiation
  - Bohren (2006): '*Light is unpolarized if the successive vibration ellipses traced out over many periods of oscillation of the field exhibit no regular pattern*'
- Ratio of intensity of polarized component of a beam to the total intensity is the **degree of polarization**
- Any oscillating electric field lying in a plane can be resolved into two orthogonal components, e.g., one vertical, one horizontal

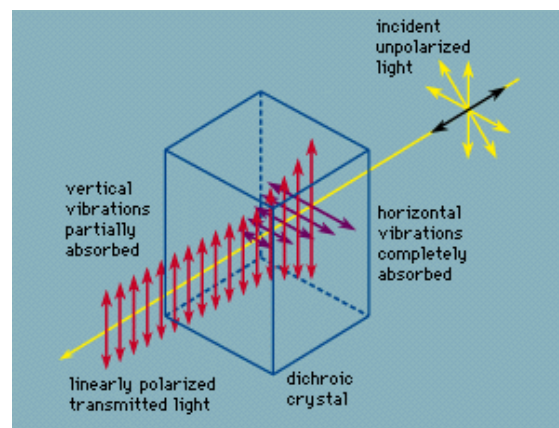
## Fresnel-Arago Laws

- French scientists Augustin Fresnel (1788–1827) and Dominique Francois Jean Arago (1786–1853)
1. Two orthogonal, coherent linearly polarized waves cannot interfere.  
(the intensity of the resulting beam is the sum of the intensities of each individual beam)
  2. Two parallel coherent linearly polarized waves will interfere in the same way as natural light.
  3. The two constituent orthogonal linearly polarized states of natural light cannot interfere to form a readily observable interference pattern, even if rotated into alignment (because they are incoherent).
- **Coherence**: two EM waves are coherent if there is a definite and fixed phase relation between them
  - **Intensity is proportional to the square of amplitude**

## Four ways to polarize EM waves

- Selective absorption (dichroism)
- Reflection
- Scattering
- Birefringence (double refraction) in crystalline materials

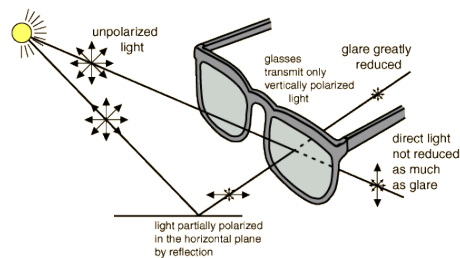
## Selective absorption - dichroism



- Some crystalline materials absorb more light in one incident plane than another, so that transmitted light is polarized. This anisotropy in absorption is called **dichroism**.
- There are naturally occurring and artificial dichroic materials (e.g., polaroid)
- Such materials are used to produce polarized light in remote sensing instruments

## Dichroic materials

- **Dichroic** materials absorb more light in one polarization state than another. The mineral tourmaline (boron silicate) is the best known of natural dichroic materials.
- **Polaroid** is produced by heating and stretching a sheet of polyvinyl alcohol, which aligns the long polymeric molecules in the stretch direction. After dipping in an iodine solution, the iodine atoms provide electrons which can move easily along the chains, but not perpendicular to them. Thus the material becomes an efficient electrical conductor along the chains. Light waves with electric fields parallel to these chains are strongly absorbed because the energy is dissipated by the along-chain electron motion. Perpendicular to the chains, the electrons cannot move freely to absorb energy, and light waves pass through.



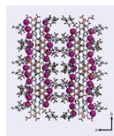
## Polaroid structure

CERN COURIER

Aug 25, 2009

### Researchers finally uncover the structure of polaroid

A better understanding of the history of polaroid could lead to breakthroughs in nanotechnology, now that the detailed crystalline structure of the substance has been determined.



Polaroid is made from a crystalline material called herapathite, which was first discovered in 1852 when tincture of iodine was dropped into urine from a dog that had been fed quinine in the laboratory of toxicologist William Bird Herapath. He realized that the resulting crystals made excellent polarizers, however, it was not until the 1920s that Edwin Land, of Polaroid fame, ground the crystalline material into a fine powder and extruded it into polymers to make polarizing filters. Surprisingly, the structure of herapathite has only now been unravelled, thanks to Bart Kahr and colleagues of the University of Washington, Seattle.

Kahr has also discovered that Bernotar, an analogue of polaroid that was made independently by Ferdinand Bernauer (1892–1945) and marketed by Karl Zeiss, seems to be a single crystalline film of herapathite. This is just the kind of material needed for organic electronics these days, but nobody knows how Bernauer did it.

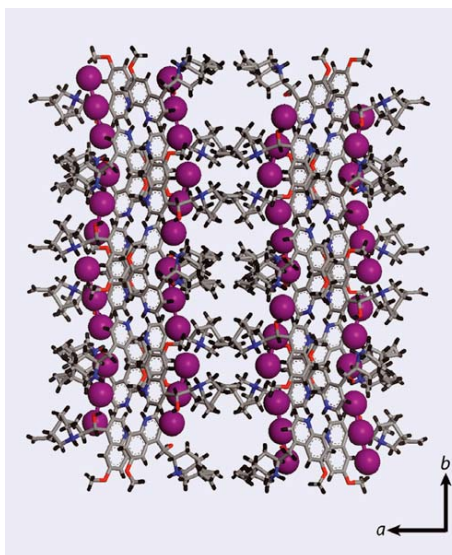
#### About the author

Compiled by John Swain, Northeastern University.

#### Further reading

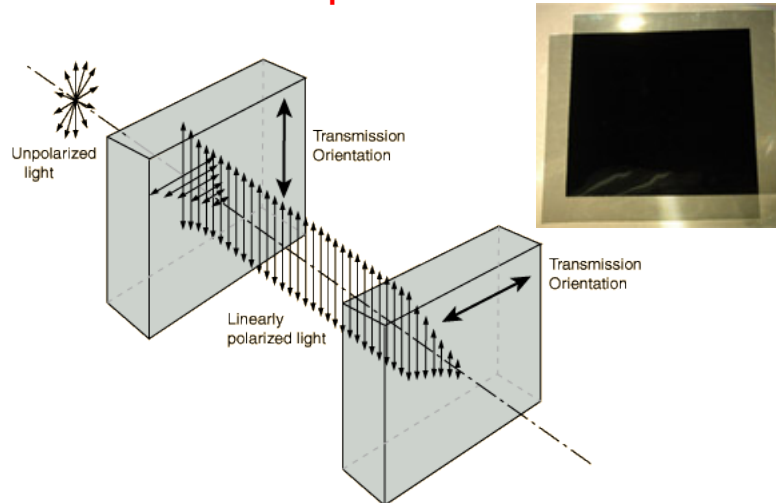
B Kahr et al. 2009 *Science* 324 1407.

Jyllian Kemsley 2009 *Chemical and Engineering News* June 22 43.



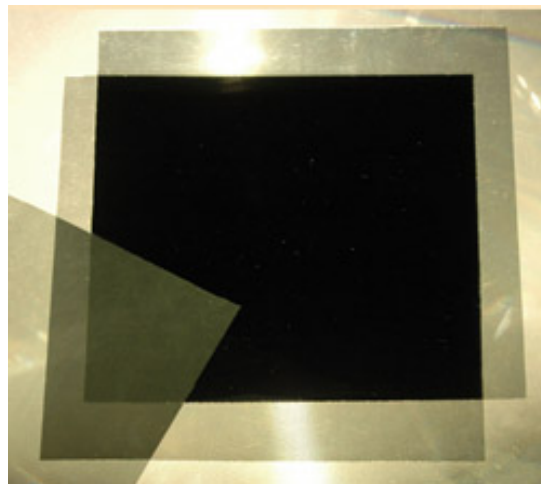


## Crossed polarizers

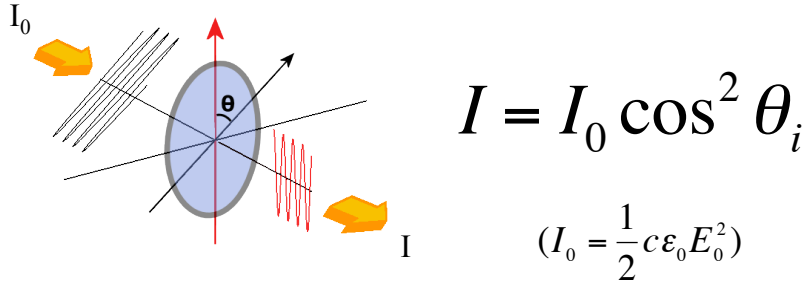


No light is transmitted when two ideal polarizers (e.g., polaroid sheets) are 'crossed' (placed at right angles)

## Interposing a third polarizer at 45°...

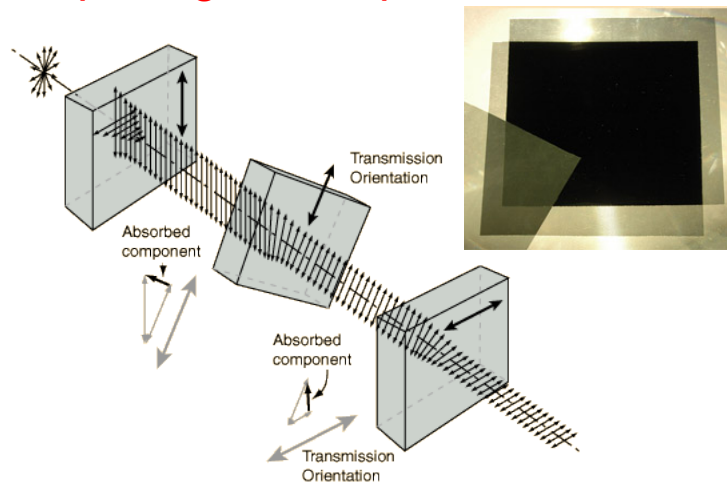


## Malus' Law



- Etienne-Louis Malus (1775-1812): French engineer, physicist and mathematician
- $I$  = intensity of light transmitted by a perfect polarizer,  $I_0$  = initial light intensity,  $\theta$  = the angle between the light's initial plane of polarization and the axis of the polarizer
- A beam of unpolarized light can be thought of as containing a uniform mixture of linear polarizations at all possible angles. Since the average value of  $\cos^2\theta$  is  $1/2$ , ~50% of such light is transmitted.
- For crossed polarizers,  $\theta = 90^\circ$  so no light is transmitted.

## Interposing a third polarizer...

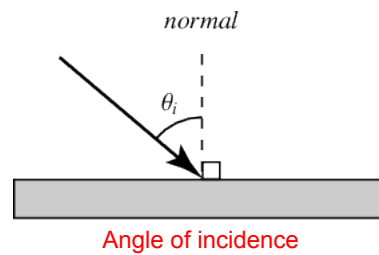


Using the Law of Malus twice, 25% of the incident light will be transmitted

## Polarization on reflection

When an unpolarized EM wave is reflected by a surface, the reflected light may be completely polarized, partially polarized, or unpolarized, depending on the *angle of incidence*.

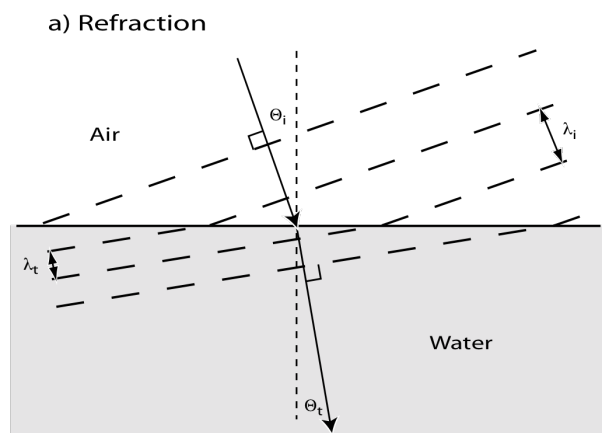
If the angle of incidence is zero (nadir, or normal), the reflected beam is unpolarized. For all but one other angle of incidence the beam is partially polarized. For one unique incidence angle, the reflected beam becomes completely polarized.



Useful for fishermen, water sports etc.

## Refraction

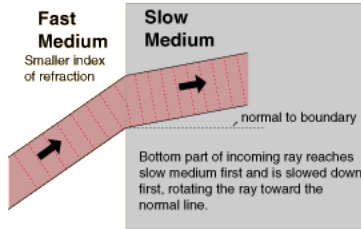
- Refraction is the bending of an EM wave upon entering a medium where its speed changes. Responsible for image formation by lenses and eyes.



Continuity constraint: wavefronts must be continuous at the boundary

## Refractive Index

- The deviation of the beam depends on the **refractive index (n)** of the medium; the speed of light in a vacuum (c) divided by the speed of light in the medium (v). Usually  $\geq 1$ .



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

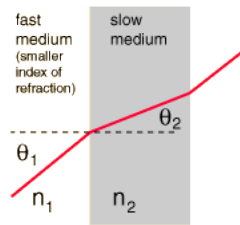
### Some refractive indices for visible light

Vacuum	1.000	Ethyl alcohol	1.362
Air	1.000277	Glycerine	1.473
Water	4/3	Ice	1.31
Carbon disulfide	1.63	Polystyrene	1.59
Methylene iodide	1.74	Crown glass	1.50-1.62
Diamond	2.417	Flint glass	1.57-1.75

- Speed of light is reduced in the slower medium (higher RI); wavelength also reduced but *frequency unchanged* ( $v = \lambda f$ ).

## Snel's Law (note spelling!)

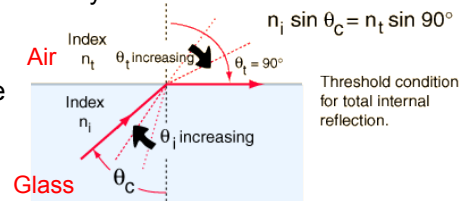
$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$$



- Relates refractive indices of two media to the direction of propagation of the refracted beam [Willebrord Snel (1591-1626)]
- Fast  $\rightarrow$  Slow medium: beam refracted towards the normal
- Slow  $\rightarrow$  Fast medium: beam refracted away from the normal

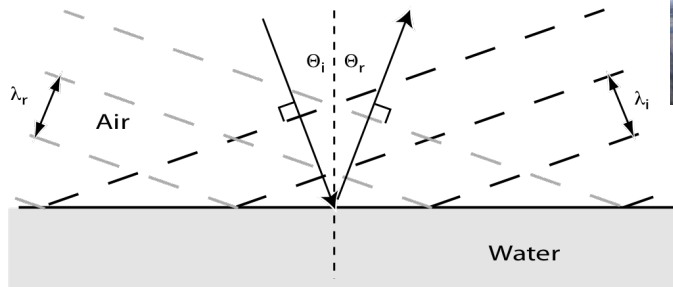
- In latter case, total internal reflection can occur above a threshold incidence angle

- Exploited in **fiber optics**



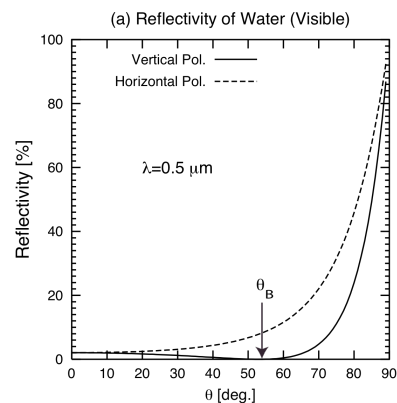
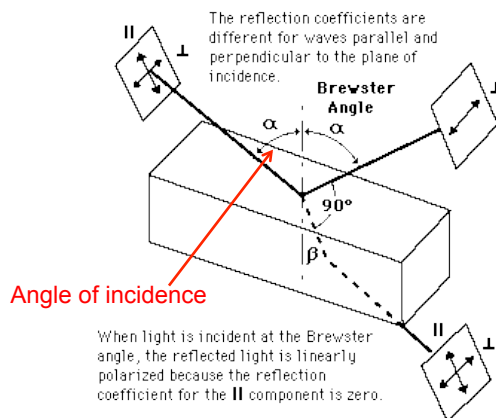
## Law of reflection

### b) Reflection



- **Law of reflection:** when a ray of light reflects off a surface, the angle of incidence is equal to the angle of reflection (*specular reflection*)
- Applies when surface is *smooth* relative to the wavelength of the incident light
- For visible light, mirrors and water are smooth

## Polarization on reflection

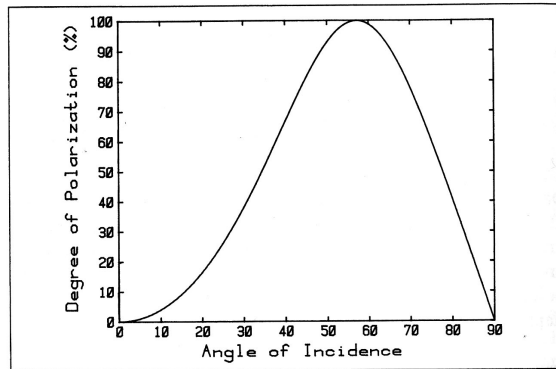


- **Brewster angle (or polarizing angle):** when angle between reflected and refracted (transmitted) light is  $90^\circ$ , the reflected light is 100% linearly polarized perpendicular to the plane of incidence [Sir David Brewster, 1781-1868]
- Dependent on material and wavelength (affect refractive index)
- For light originating in air, Brewster angle given by  $\tan^{-1}$  (refractive index of reflecting medium);  $\sim 56^\circ$  for air-glass interface;  $\sim 53^\circ$  for air-water interface

## Polarization on reflection

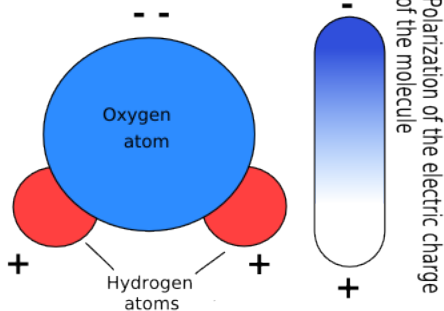
**Figure 4.3**

Over a wide range of angles of incidence around the Brewster angle (about 57 degrees), initially unpolarized light acquires a high degree of polarization upon reflection by glass.



- Over a 40° interval around the Brewster angle, the degree of polarization of reflected light exceeds 50%
- Explains efficacy of polarizing sunglasses

## Polarization on reflection



- Explanation for the Brewster angle - scattering by a dipole array
- **Dipole**: separation of positive and negative charge, e.g., molecular dipoles
- No light transmitted in the direction of dipole oscillation

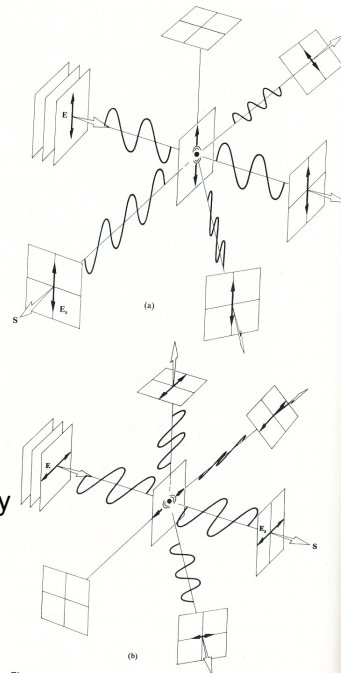


Fig. 8.36 Scattering of polarized light by a molecule.

## Reflectivity

- **Fresnel relations**: used to calculate fraction of beam that is reflected at a **smooth** interface between two homogeneous media
- *Polarization of the incident radiation is important.*

$$R_p = \left| \frac{\cos \theta_t - m \cos \theta_i}{\cos \theta_t + m \cos \theta_i} \right|^2$$

Light polarized parallel to the plane of incidence

$$R_s = \left| \frac{\cos \theta_i - m \cos \theta_t}{\cos \theta_i + m \cos \theta_t} \right|^2$$

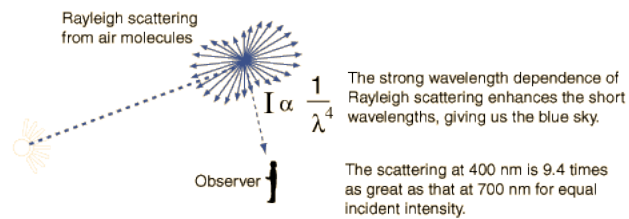
Light polarized perpendicular to the plane of incidence

$m$  is the relative refractive index of the two media:  $n_2/n_1$  (and can be complex!)

## Rayleigh scattering

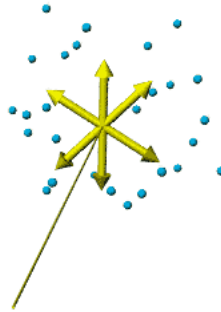


Atmospheric composition: N<sub>2</sub> (78%), O<sub>2</sub> (21%), Ar (1%)  
 Size of N<sub>2</sub> molecule: 0.31 nm  
 Size of O<sub>2</sub> molecule: 0.29 nm  
 Size of Ar molecule: 0.3 nm  
 Visible wavelengths ~400-700 nm



- Scattering of light off air molecules is called Rayleigh Scattering
- Involves particles much smaller than the wavelength of incident light
- Responsible for the blue color of clear sky

## Polarization on scattering



- **Scattering:** EM radiation redirected by a material/medium
- *Single* scattering of light by air molecules produces linearly polarized light in the plane perpendicular to the incident light – look at sky with polarized glasses
- The scatterers can be visualized as tiny antennae (dipoles) which radiate perpendicular to their line of oscillation

## Birefringence

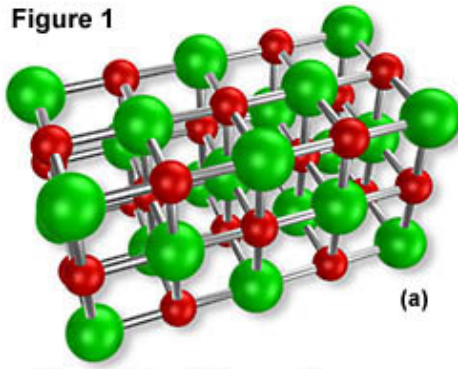
- An amorphous material such as glass has a single refractive index
  - Speed of propagation of EM wave is the same in all directions (*isotropic*)
- Some mineral crystals (e.g., calcite, quartz) have two distinct indices of refraction and are called **birefringent**
- Birefringence is formally defined as the *double refraction of light in a transparent, molecularly ordered material, which is manifested by the existence of orientation-dependent differences in refractive index*



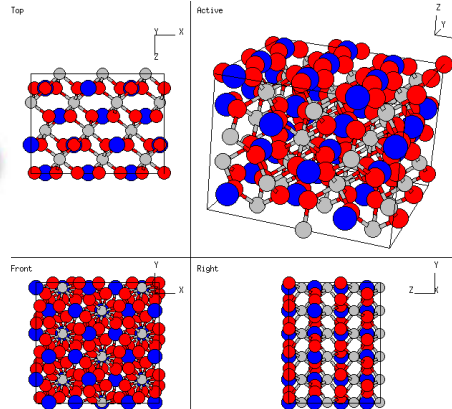
## Birefringence

- Birefringence relates to anisotropy in the binding forces between atoms in a crystal - atoms have stronger attraction in some orientations

Figure 1

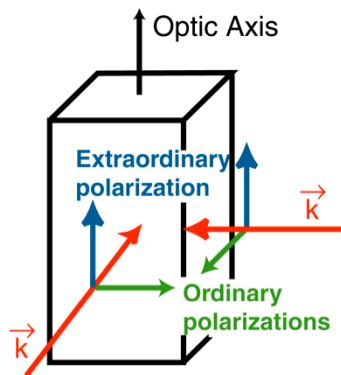


Sodium chloride – NaCl - isotropic



Calcite – CaCO<sub>3</sub> - anisotropic

## Uniaxial crystals have an optic axis



**Uniaxial crystals** have one refractive index for light polarized along the **optic axis** ( $n_e$ ) and another for light polarized in either of the two directions perpendicular to it ( $n_o$ ).

Light polarized along the optic axis is called the **extraordinary ray**, and light polarized perpendicular to it is called the **ordinary ray**. These polarization directions are the **crystal principal axes**.

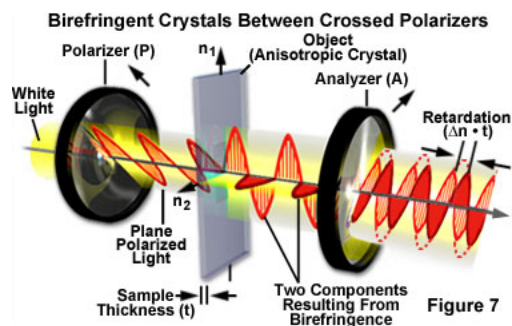
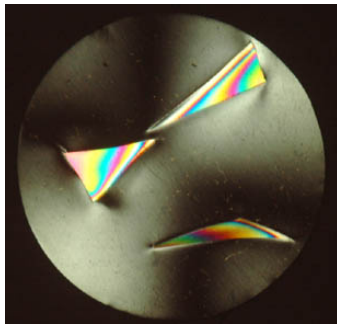
*Light with any other polarization must be broken down into its ordinary and extraordinary components, considered individually, and recombined afterward.*

## Birefringent Materials

**TABLE 8.1 Refractive indices of some uniaxial birefringent crystals ( $\lambda_0 = 589.3$  nm).**

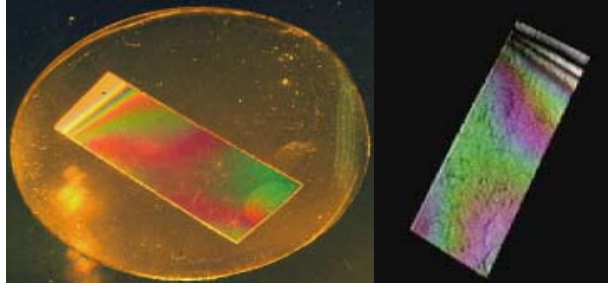
Crystal	$n_o$	$n_e$
Tourmaline	1.669	1.638
Calcite	1.6584	1.4864
Quartz	1.5443	1.5534
Sodium nitrate	1.5854	1.3369
Ice	1.309	1.313
Rutile (TiO <sub>2</sub> )	2.616	2.903

## Interference colors



- Light passed through a polarizer to produce linearly polarized light, then passed through a birefringent material
- Light broken up into two components; that with larger index of refraction will lag in phase (**retardation**)
- Light then passed through a crossed polarizer, only that part of each of the components in the transmission plane emerges → two coplanar components with a phase difference (dependent on wavelength)
- Some colors undergo destructive interference and some constructive, giving an interference pattern of varying colors (depends on thickness of material)

## Photoelasticity



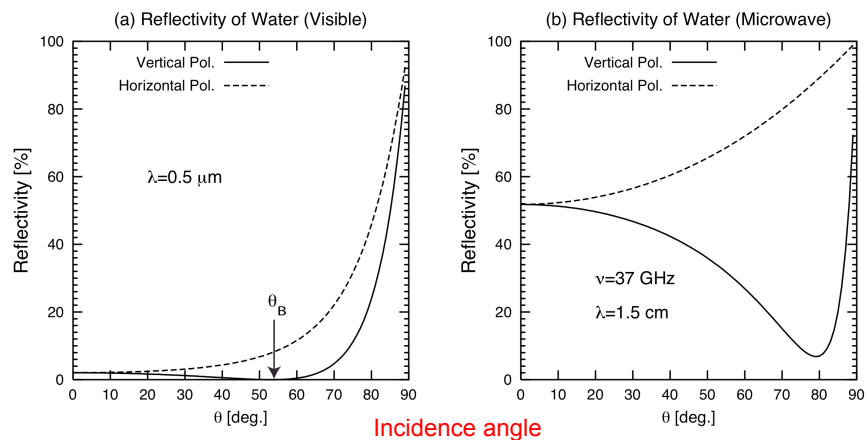
- Some materials become optically anisotropic when mechanical stress is applied
- Referred to as photoelasticity, stress birefringence, or mechanical birefringence
- Useful for the visualization of mechanical stress in otherwise transparent materials
- Colors are seen when the stressed materials are placed between crossed polarizers
- Bohren (2006), ch 3: stressed airplane windows

## Airplane windows



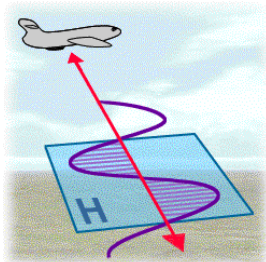
- Polarized light behind window (due to Rayleigh scattering of sunlight)
- Window is birefringent (due to mechanical stress) – retarder
- Polarization filter in front of the window - analyzer
- Bohren (2006), ch 3: stressed airplane windows

## Reflectivity of water



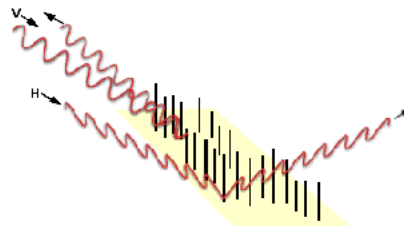
- Note dependence of reflectivity on polarization (and incidence angle)
- At microwave frequencies, the imaginary part of the refractive index is significant and contributes to increased reflectivity
- Water is no longer 'smooth' at microwave wavelengths

## Radar polarization



HH-polarization

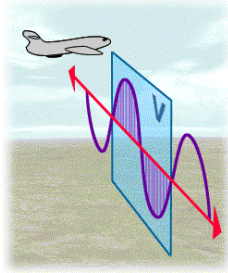
Horizontal transmit and receive



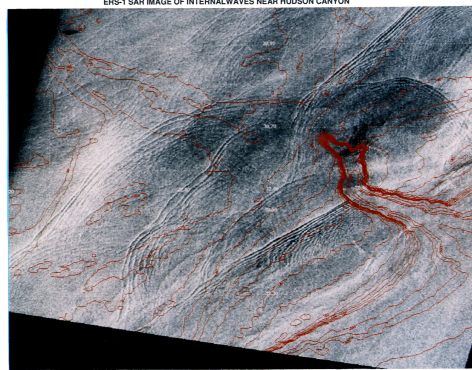
Interaction between radar waves and vertical dipoles

- HH is the preferred polarization combination for a number of applications
- **Soil moisture studies**: vertically oriented crops (e.g. wheat and barley) allow improved penetration by EM waves with horizontal polarization, so backscatter is dominated by the soil moisture rather than the crop
- HH also suitable for **separating sea ice and water**, since it is less sensitive to water roughness than VV polarization, providing improved contrast between ice and water
- HH better than VV for **ship detection**

## Radar polarization



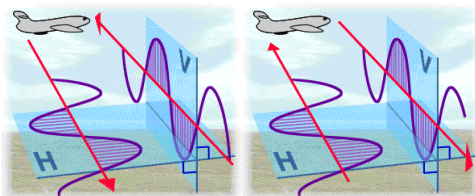
VV-polarization  
Vertical transmit and receive



ERS-1 SAR ORBIT 5206-3 18 JULY 1992 15:34:35 DEPTH CONTOURS - METERS  
Figure 4-5. ERS-1 C-band image of solitary waves generated by tidal flow against the continental shelf, with bathymetry shown in red; the deep indentation is the Hudson Canyon. Region shown is approximately 50 nmi (93 km) on a side (Ricky Chapman).

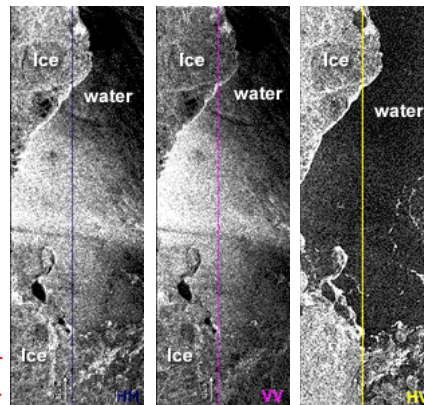
- VV is preferred when studying the small-scale roughness of capillary waves on the water surface
- Surface scattering effects give a higher signal on the VV channel. Thus VV is used extensively for oceanographic applications such as the **extraction of surface wind speeds**.
- Single-band VV radar systems include the European ERS and ENVISAT C-band satellites

## Radar cross-polarization



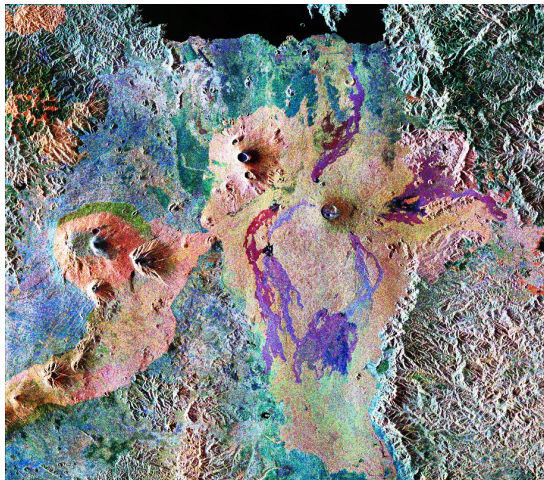
HV-polarization H transmit, V receive  
VH-polarization V transmit, H receive

Shuttle Imaging Radar (SIR-C) C-band radar  
Labrador Sea, April 1994



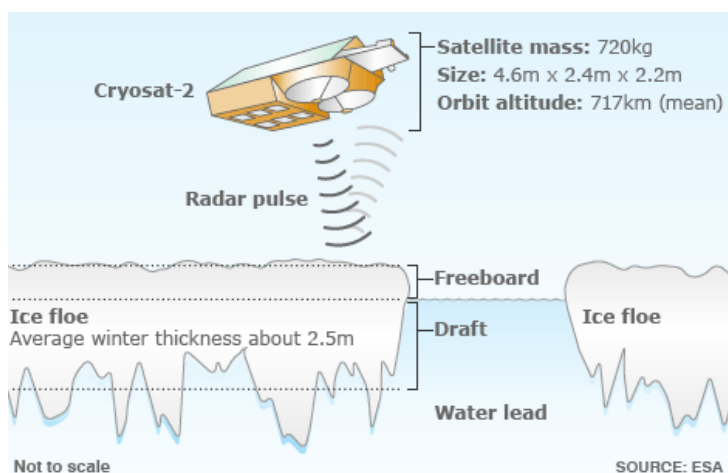
- Cross-polarized radar returns weaker than like-polarized returns
- HV backscatter from water much reduced compared to VV backscatter: HV useful for **detecting targets on the water surface** that create multiple scattering, e.g., ship superstructures and ice deformation (ridging, fractures and rubble)
- **Separation of broadleaf from grain crops** also uses cross-polarized radar, since the geometries of broadleaf vegetation cause multiple-bounce scattering, resulting in some cross-polarized backscatter

## Radar cross-polarization



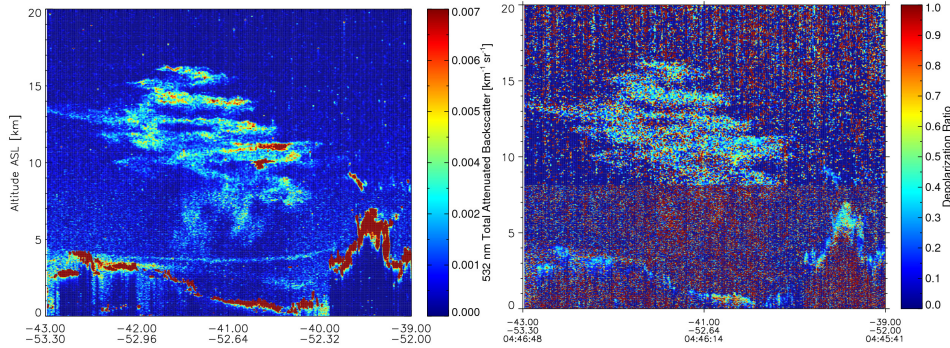
- Shuttle Imaging Radar (SIR-C) image: Virunga volcanic chain, DR Congo, 1994
- **Red**: L-band, HV polarization; **Green**: C-band, HH polarization; **Blue**: C-band, HH polarization.

## Cryosat-2



- Radar altimetry – measurements of ice thickness
- [http://www.esa.int/Our\\_Activities/Observing\\_the\\_Earth/CryoSat/Instruments](http://www.esa.int/Our_Activities/Observing_the_Earth/CryoSat/Instruments)

## Lidar depolarization



CALIPSO lidar ([www-calipso.larc.nasa.gov](http://www-calipso.larc.nasa.gov)): Chaiten (Chile) eruption cloud

- Lidar measurements of atmospheric depolarization can be used to **distinguish between liquid and solid phase particles in the atmosphere**
- Linear depolarization ratio is the ratio of perpendicular to parallel backscatter intensity wrt transmitter polarization axis
- Backscatter of linearly polarized laser beam from spherical particles is totally linearly polarized
- Non-spherical particles (ice, snow, dust etc.) produce a cross-polarized component

## CALIPSO lidar design

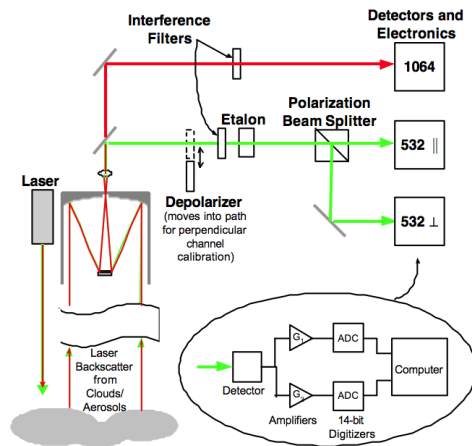
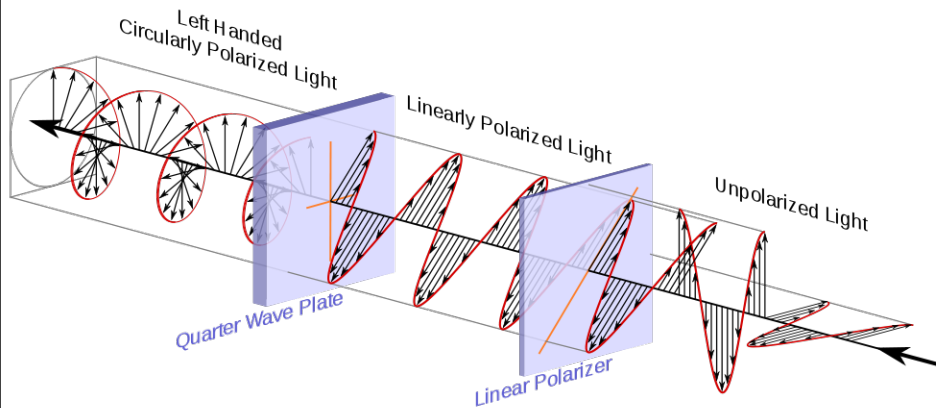


Figure 2. Functional block diagram of CALIOP.

CALIPSO lidar ([www-calipso.larc.nasa.gov](http://www-calipso.larc.nasa.gov))

## Creating circularly polarized light



The quarter wave plate introduces a  $90^\circ$  ( $\pi/2$ ) phase difference between two perpendicular components of the incoming linearly polarized light, using birefringence.

## Recap

- Classification of polarized light
  - Linear, circular, elliptical, unpolarized
- Four ways to polarize EM radiation
  - Selective absorption (dichroism)
    - Transforms amplitude (intensity)
  - Reflection
  - Scattering
  - Birefringent materials (retarders)
    - Transforms phase (refractive index differences)
- Use of polarization by active remote sensing systems
  - Radar and lidar