Chapter 15
Production of Polarized Light

Lecture Notes for Modern Optics based on
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Polarization

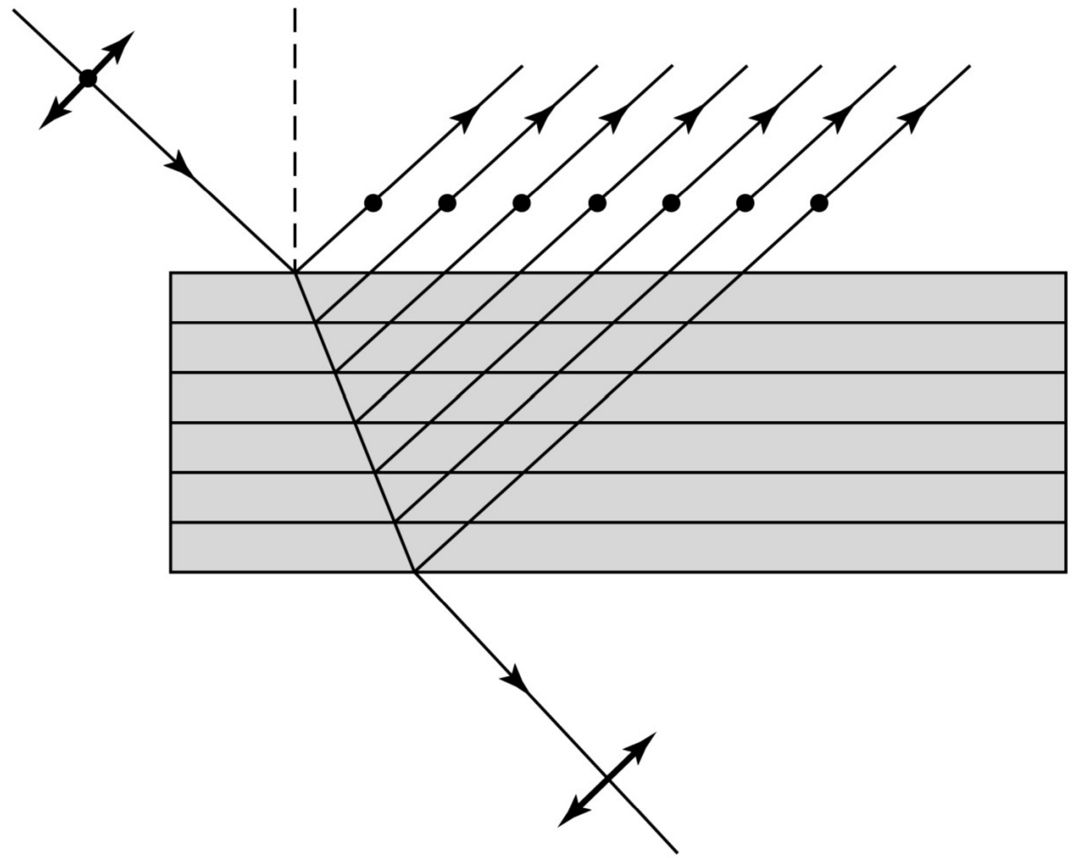
Polarization is the result of interaction of light with matter that have asymmetric optical properties along directions perpendicular to the propagation axis of light.

Processes that produce polarized light:

1) Dichroism
2) Reflection
3) Scattering
4) Birefringence

Optical activity

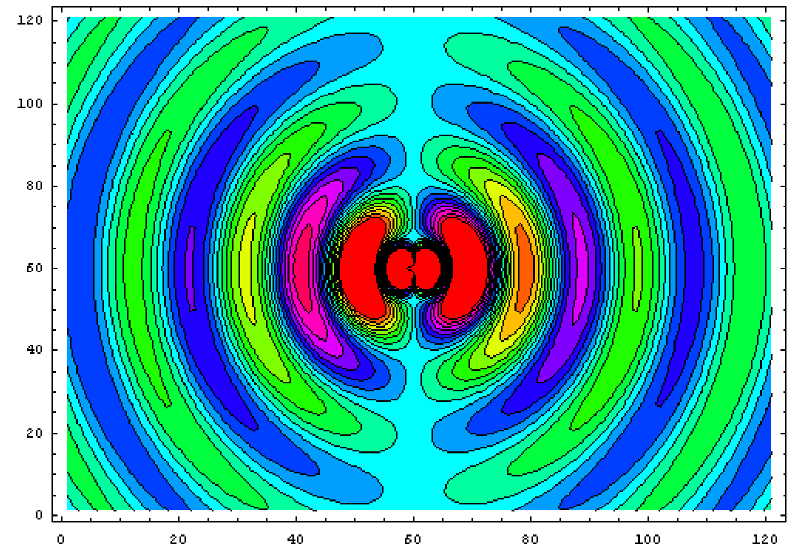
Photoelesticity



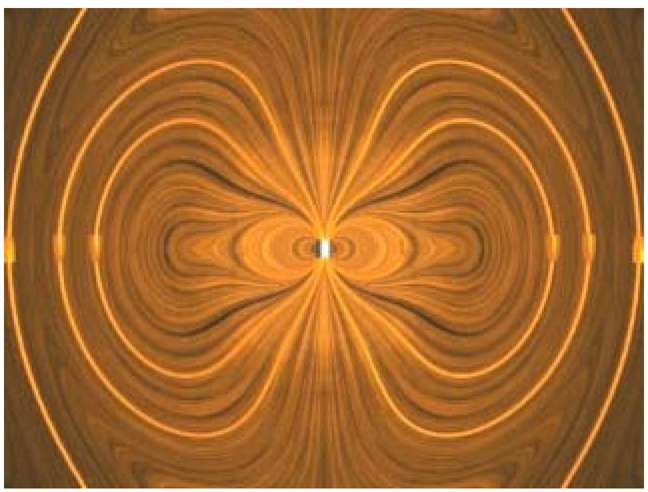
Dipole radiation

Accelerated electric charges radiate EM waves.

When positive and negative charges of an atom are separated, they form a dipole. Oscillating dipoles emit EM radiation



Electric field of an oscillating electric dipole. The dipole is located at the center in the graph, oscillating at 1 rad/s (~0.16 Hz) in the vertical direction



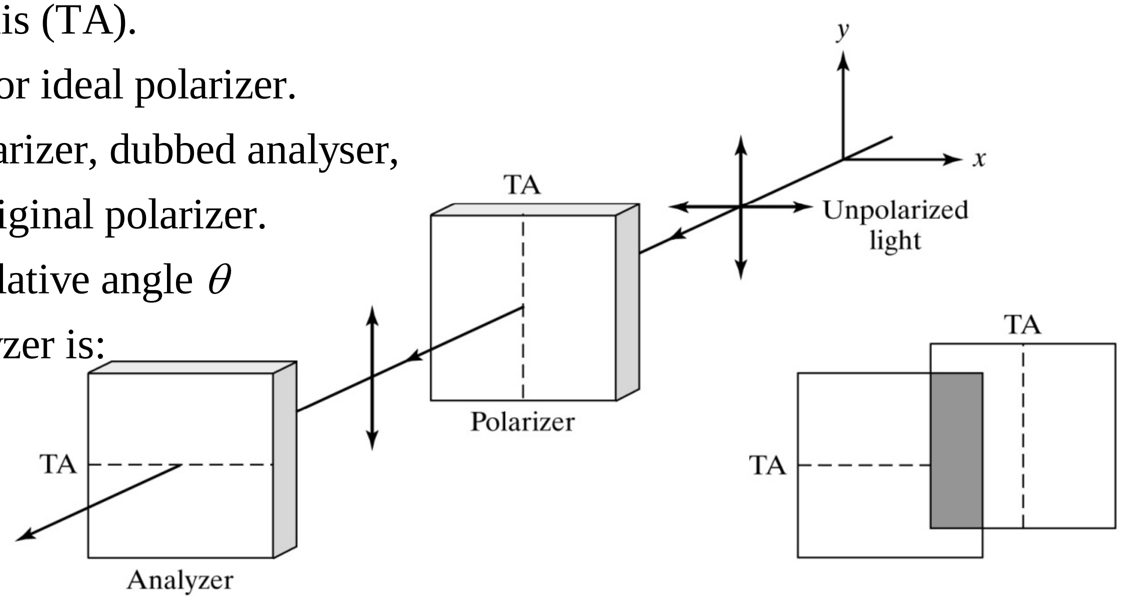
Dichroism or selective absorption

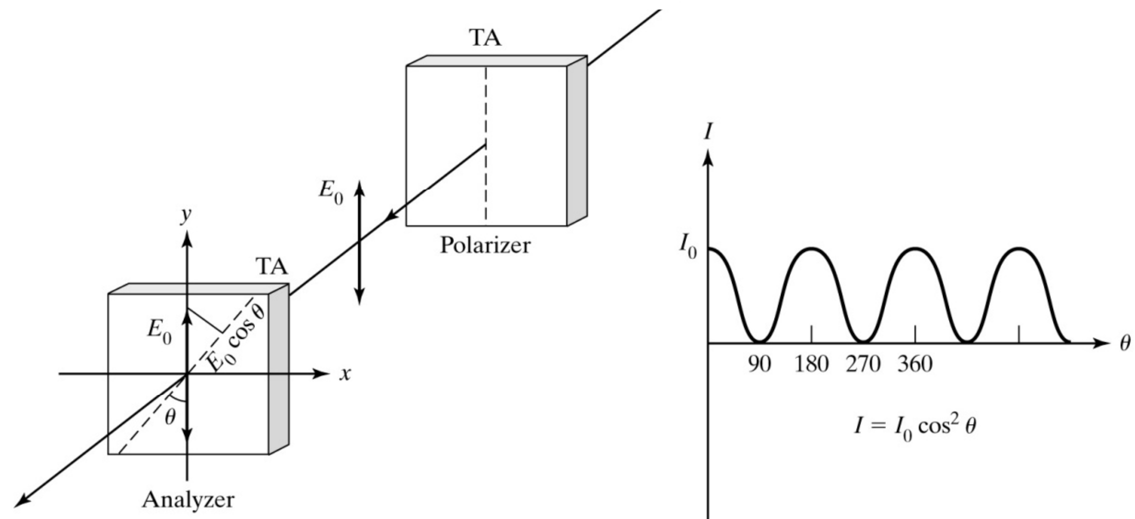
Dichroic material absorb light along a unique direction and transmit along the tramsmission axis (TA).
The result is a linearly polarized light for ideal polarizer.
The result can be tested by another polarizer, dubbed analyser, with TA perpendicular to that of the original polarizer.
Malus law states: irradiance for any relative angle θ between TAs of the polarizer and analyzer is:

$$\boxed{I = I_0 \cos^2 \theta}$$

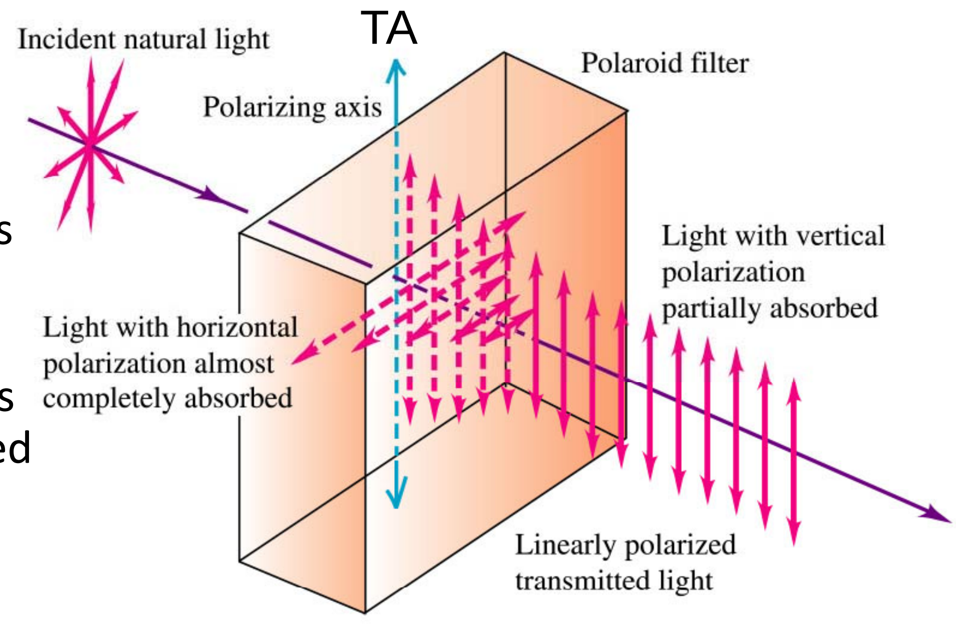
We can see from the graph that the amplitude of the light emerging from analyzer is $E_0 \cos\theta$
Thus the irradiance would be

$$I\left(W/m^2\right) = E_0^2 \cos^2\theta = I_0 \cos^2\theta$$

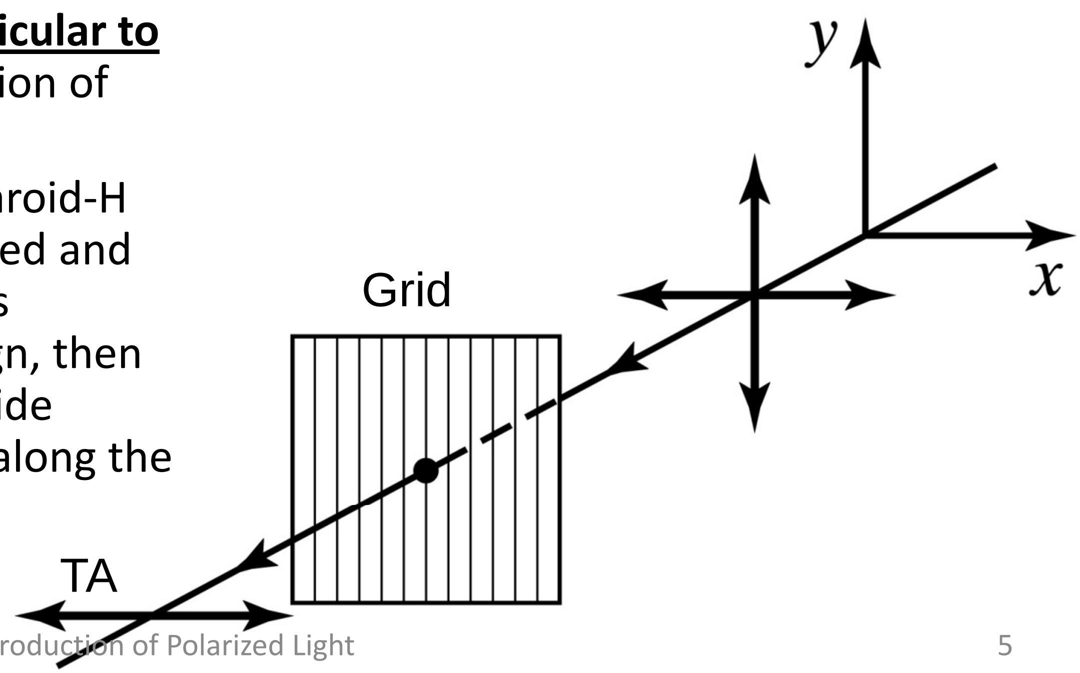




Mechanism of dichroic polarizers



- (**Wrong**) Radio waves produced by antennas are usually polarized along the antenna length.
- Electric field of the incident light accelerates the electrons along the wire. The accelerated charges emit EM waves in all directions but the direction of motion of the electrons.
- No absorption perpendicular to the wires happens so the waves pass.
- The net result is an E field **perpendicular to the direction of the grid** and direction of propagation.
- Edwin H. Land (1938) invented Polaroid-H sheet. When polyvinyl alcohol heated and stretched along a given direction its hydrocarbon molecules tend to align, then doped with iodine atoms that provide conduction electrons transporting along the molecules we have a polarizer.



Efficiency of a polaroid

Light from an incandescent lamp is un-polarized due to the random orientation of the molecules that produce the light.

Dichroism: selective absorption of light based on direction of the oscillation of E field.

There is always loss associated with polarization process.

Ideal polarizer is the one that passes 100% of the originally polarized light.

As the wave advances through the polarizer, there is gradual dissipation.

Efficiency of dichroic absorber is proportional to its thickness x: $\boxed{I = I_0 e^{-\alpha x}}$

Where α is the absorbtivity or absorption coefficient

Good dichroic filters' absorption is independent of wavelength.

In reality the Polaroid H-sheets pass some of the blue light that is why they appear bluish.

Polarization by reflection; Brewster angle

Light incident of a dielectric medium causes electrons oscillate along the E field. That leads to emission of EM waves in all directions but the direction of oscillation. The net result is a wave with propagation direction perpendicular to the E field of the original field.

When polarized light is incident on a dielectric medium, two cases are recognized:

TE the result is reflected and refracted waves both TE

TM only small fractions of the TM beam is reflected it is mostly transmitted (electric field is mostly along the reflected beam direction so $I \propto \sin^2\theta$)

Most of dipole emission is in the direction perpendicular to it.

If we have misture of TE and TM arriving at the dielectric surface:

the reflected beam will be rich in TE or E_s and refracted beam will be rich in TM or E_p

When the reflected beam is perpendicular to the refractd beam, the reflected beam has only E_S and the refracted beam has only E_P. Both of them are linearly polarized.

From the Snell's law we can find this angle so called **Polarization Angle** or **Brewster Angle**:

$$\left.\begin{aligned} n_1 \sin\theta_P &= n_2 \sin\theta_t \\ \theta_P + \theta_t &= 90^0 \end{aligned}\right\} \boxed{\theta_P = \tan^{-1}\left(\frac{n_2}{n_1}\right)}$$

θ_{Pe} for externl reflection $\left(n_2 > n_1\right)$ for example from air to glass $n_1 = 1,\ n_2 = 1.5,\ \theta_{Pe} = 56.30^0$

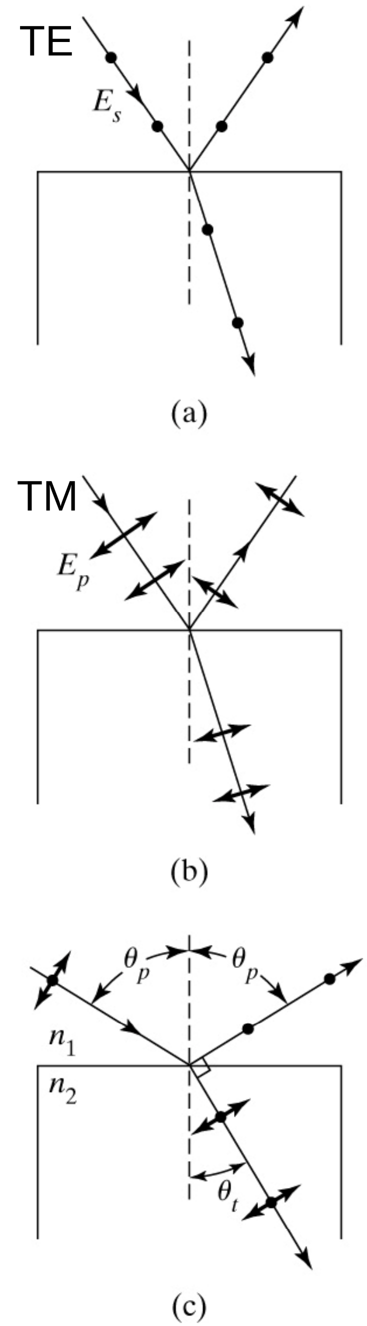
θ_{Pi} for internal reflection $\left(n_2 < n_1\right)$ for example from glass to air $n_1 = 1.5,\ n_2 = 1,\ \theta_{Pi} = 33.70^0$

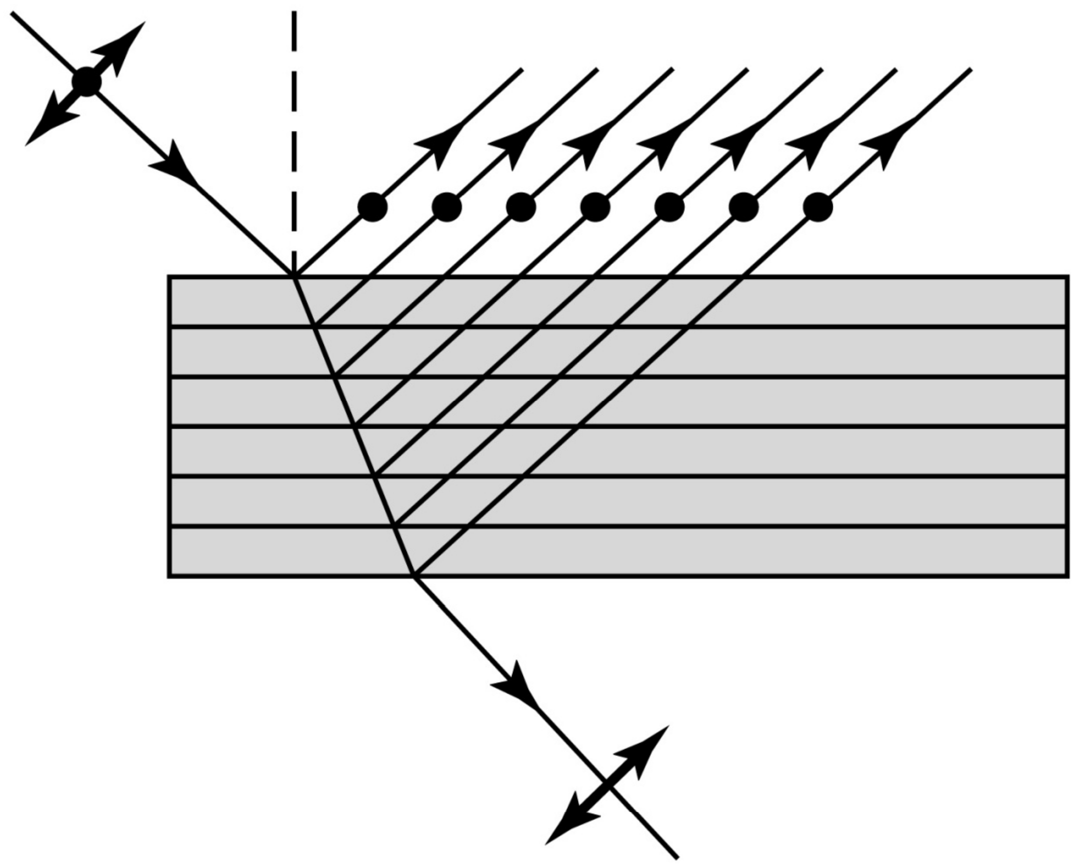
$$\boxed{\theta_{Pi} + \theta_{Pe} = 90^0}$$

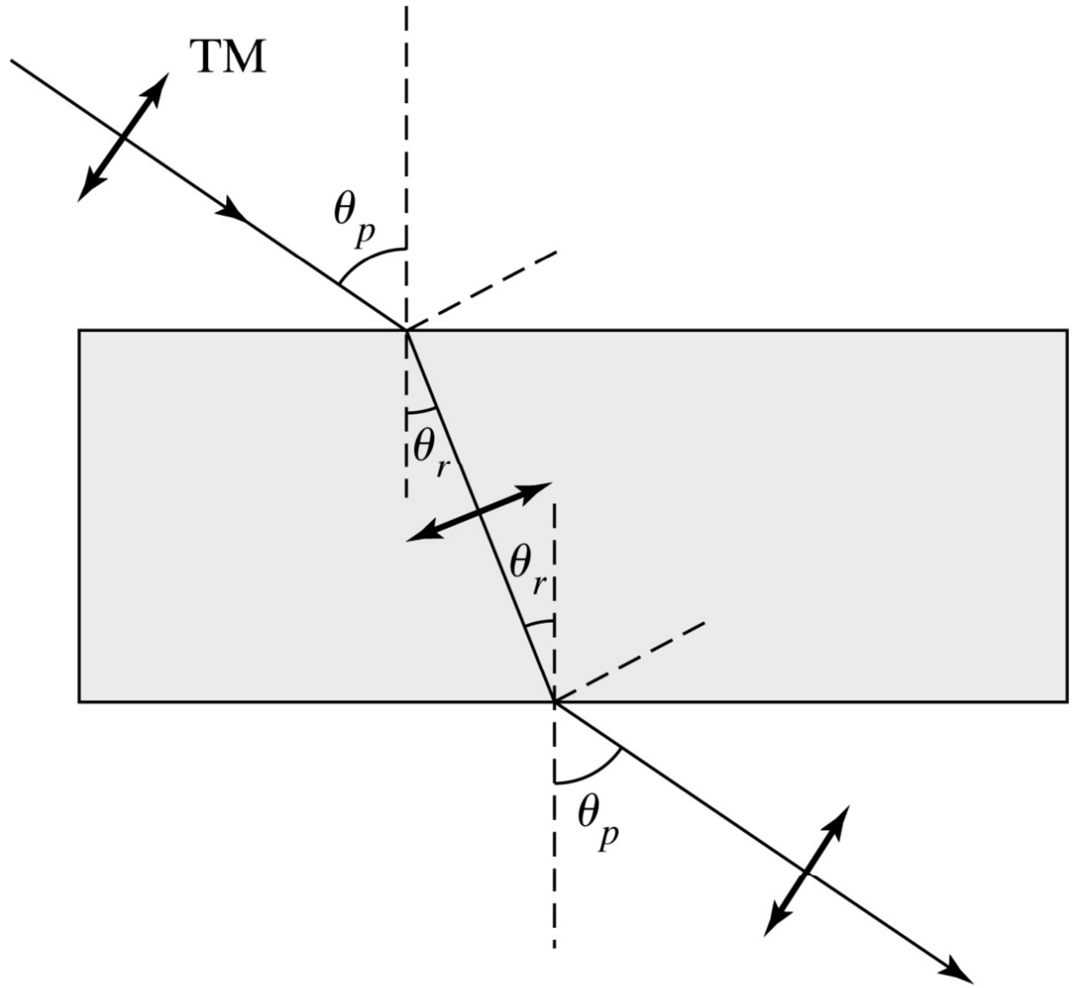
The efficiency of this method is low. In this case only 15% of the reflected light is E_s.

Pile-of -plates polarizer is a stack of parallle plates that purifies the reflected beem to have high percentage of E_s

Brewster Window: a perfect windoe for TM polarized light.






TM
θ_p
θ_r
θ_r
θ_p

Polarization by scattering

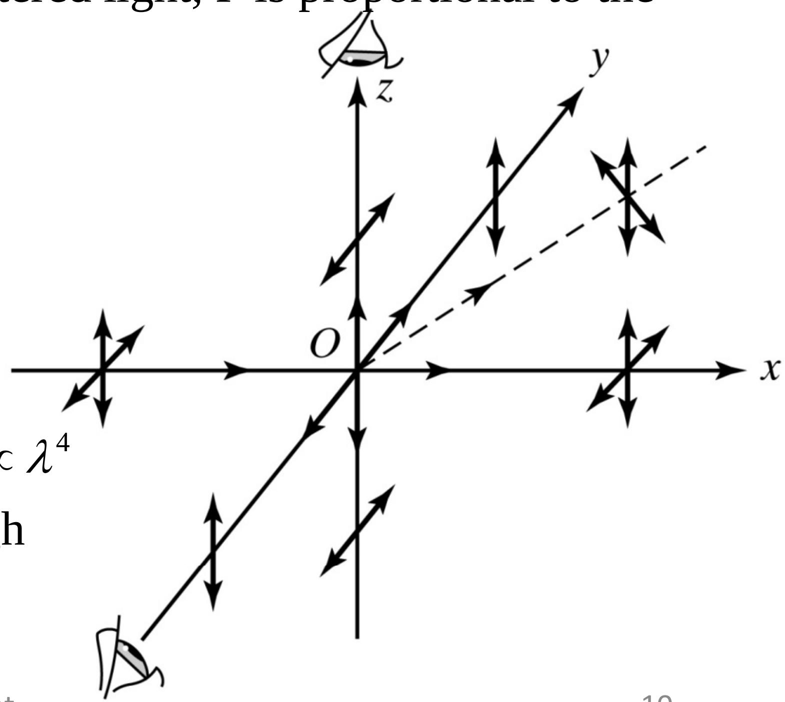
Scattering: removing energy from the original wave by means of absorption and then re-emitting it in other directions.

Rayleigh scattering: dimension of scattering centers is small compared to the wavelength of the incident light.

In Rayleigh scattering the well-separated centers act incoherently and the intensities add up not the amplitudes.

Rayleigh scattering law : power of the Rayleigh-scattered light, P is proportional to the 4th power of the frequency.

$$P = \frac{e^2 \omega^4 r_0^2}{12\pi\varepsilon_0 c^2}$$



Oscillating dipoles radiate more energy in the shorter wavelength than longer. Why the sky is blue?

Why the sunsets are redish?

Coherent scattering from clouds and water particles $\propto \lambda^4$

That cancels the frequency dependence of the Rayleigh scattering and that is why clouds appear white.

Birefringence: polarization with two refractive indices

Anisotropy in bonnding of the molecules gives rise to Birefringence (two index) property in material.

$\frac{dn}{d\omega}$ is anomalus or negative for certain frequency band around the resonant frequency of the molecules.

$\frac{dn}{d\omega} < 0$ corresponds to absorption band usually in UV

Anisotropy leads to different dispersion curves for xa nd y direction leading to different n_x and n_y

The index is complx $\tilde{n} = n + ik \begin{cases} \text{Dichroic } n_x = n_y \text{ and } k_x \neq k_y \\ \text{Birefingence } n_x \neq n_y \text{ and } k_x = k_y \end{cases}$

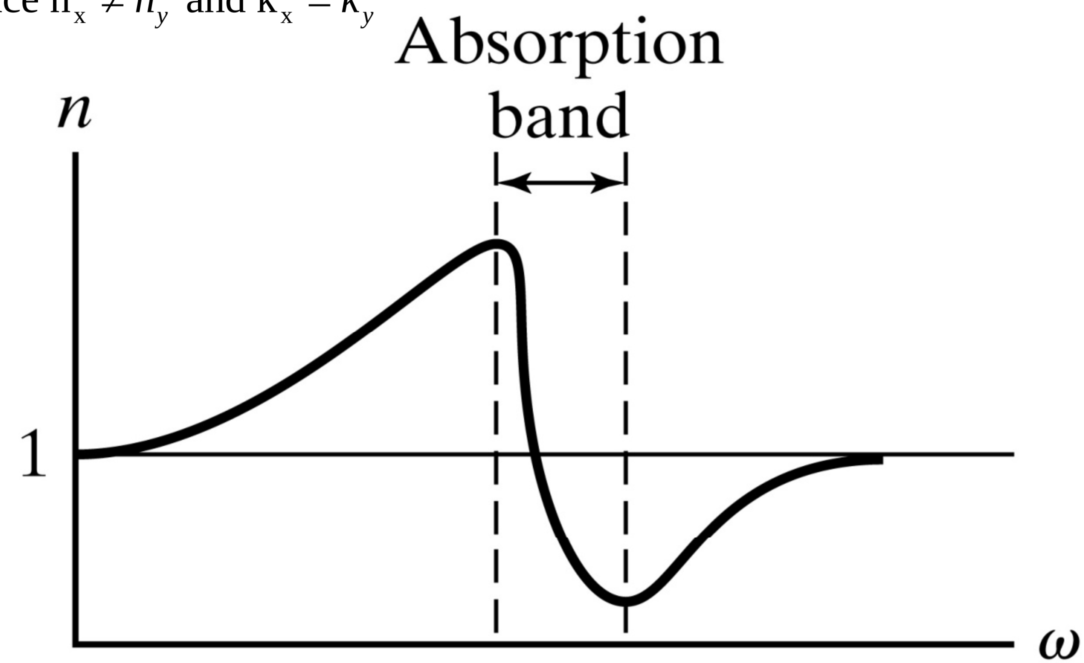
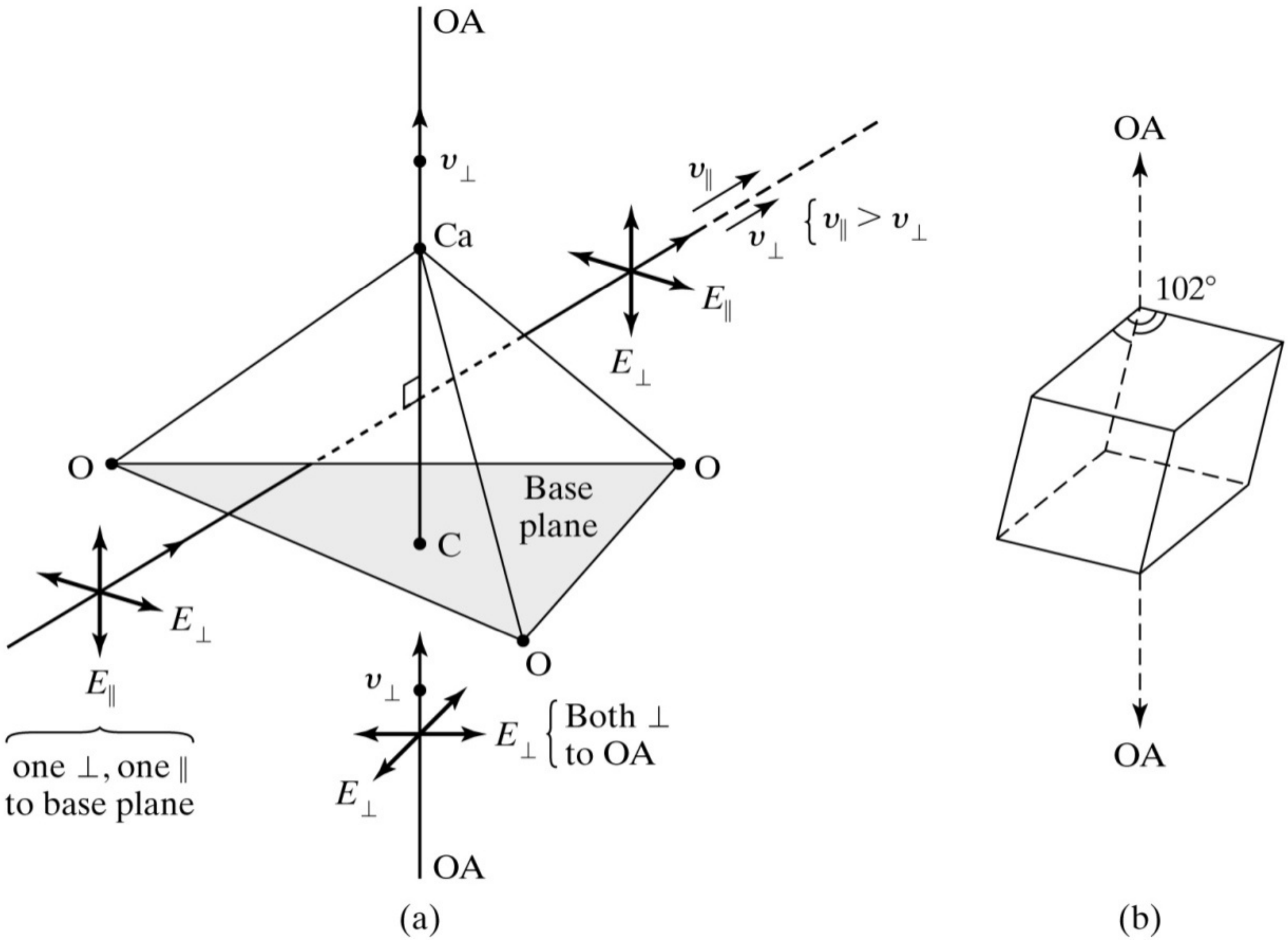
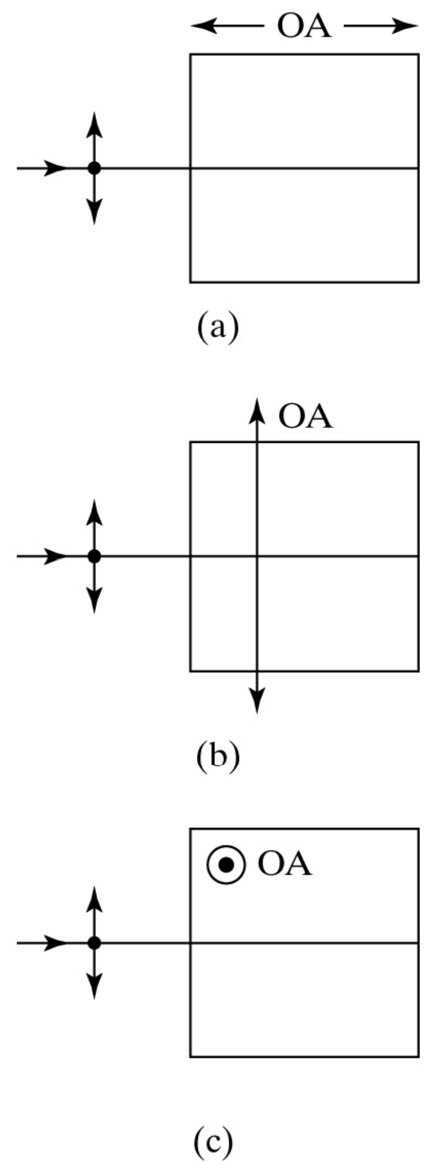
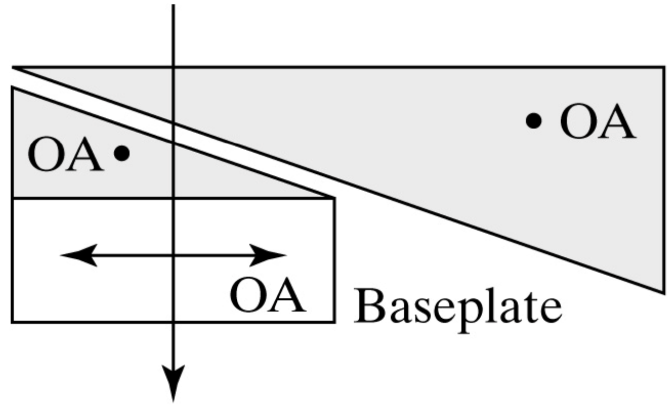


TABLE 15-1 REFRACTIVE INDICES FOR SEVERAL MATERIALS MEASURED AT SODIUM WAVELENGTH OF 589.3 nm

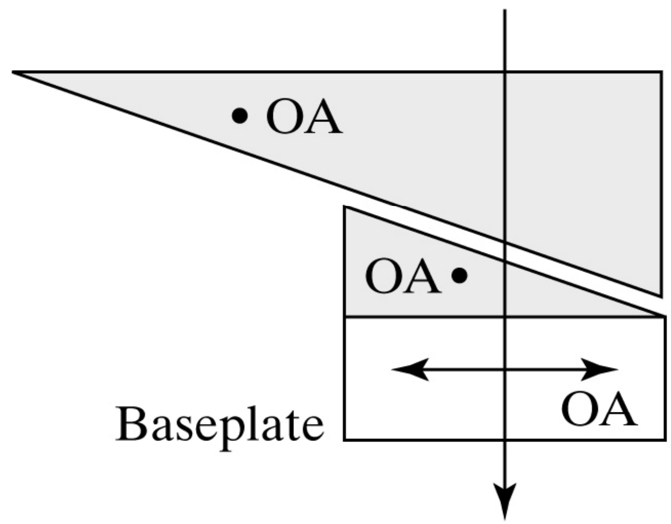
Isotropic (cubic)	Sodium chloride		1.544	
	Diamond		2.417	
	Fluorite		1.392	
Uniaxial (trigonal, tetragonal, hexagonal)	**Positive** $n_\parallel > n_\perp$**:**	$n_\parallel$	$n_\perp$	
	Ice	1.313	1.309	
	Quartz (SiO_2)	1.5534	1.5443	
	Zircon ($ZrSiO_4$)	1.968	1.923	
	Rutile (TiO_2)	2.903	2.616	
	Negative $n_\parallel < n_\perp$**:**			
	Calcite ($CaCO_3$)	1.4864	1.6584	
	Tourmaline	1.638	1.669	
	Sodium Nitrate	1.3369	1.5854	
	Beryl ($Be_3Al_2(SiO_3)_6$)	1.590	1.598	
Biaxial (triclinic, monoclinic, orthorhombic)		n_1	n_2	n_3
	Gypsum ($CaSO_4(2\,H_2O)$)	1.520	1.523	1.530
	Feldspar	1.522	1.526	1.530
	Mica	1.552	1.582	1.588
	Topaz	1.619	1.620	1.627


OA
$v_\perp$
$v_\parallel$
Ca
$\{v_\parallel > v_\perp$
$E_\parallel$
$E_\perp$
O
O
Base plane
C
$E_\perp$
$E_\parallel$
O
$v_\perp$
$E_\perp$ {Both ⊥ to OA
$E_\perp$
one ⊥, one ∥ to base plane
OA
(a)
OA
102°
OA
(b)


OA
(a)
OA
(b)
OA
(c)

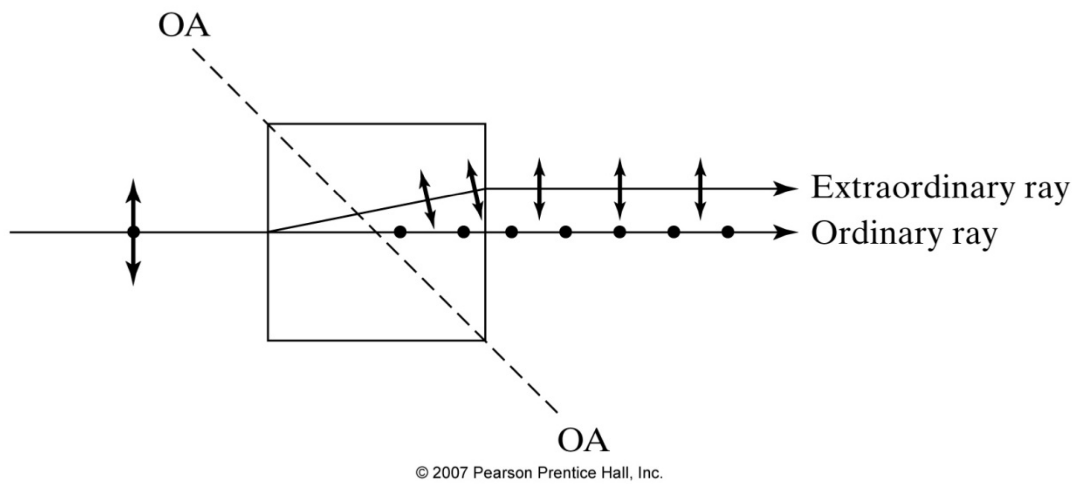


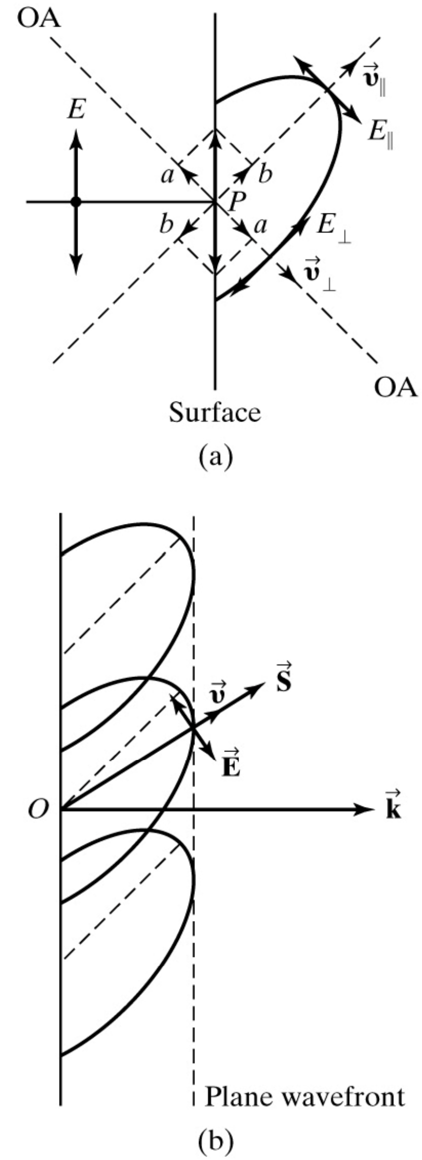
(a)

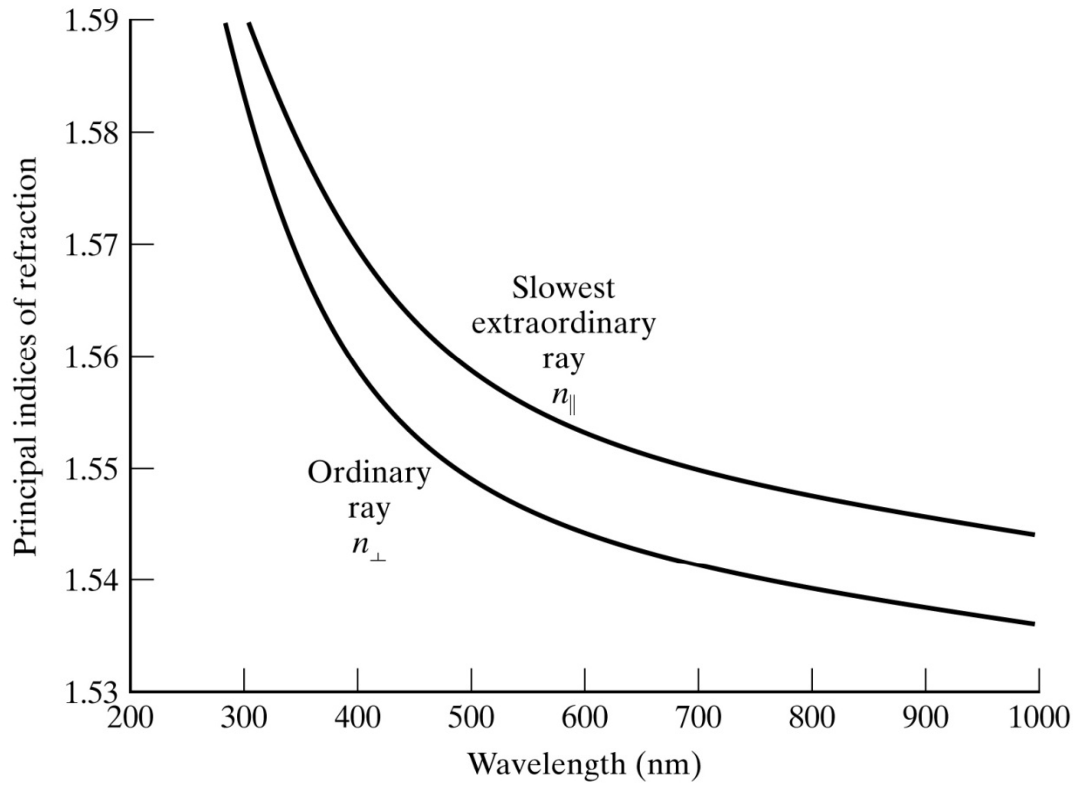


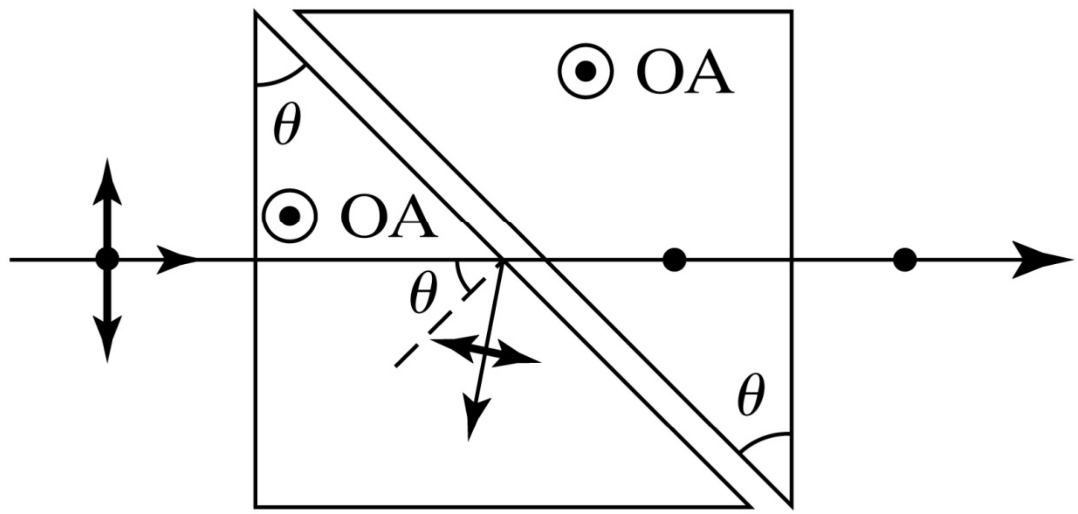
(b)

Double refraction



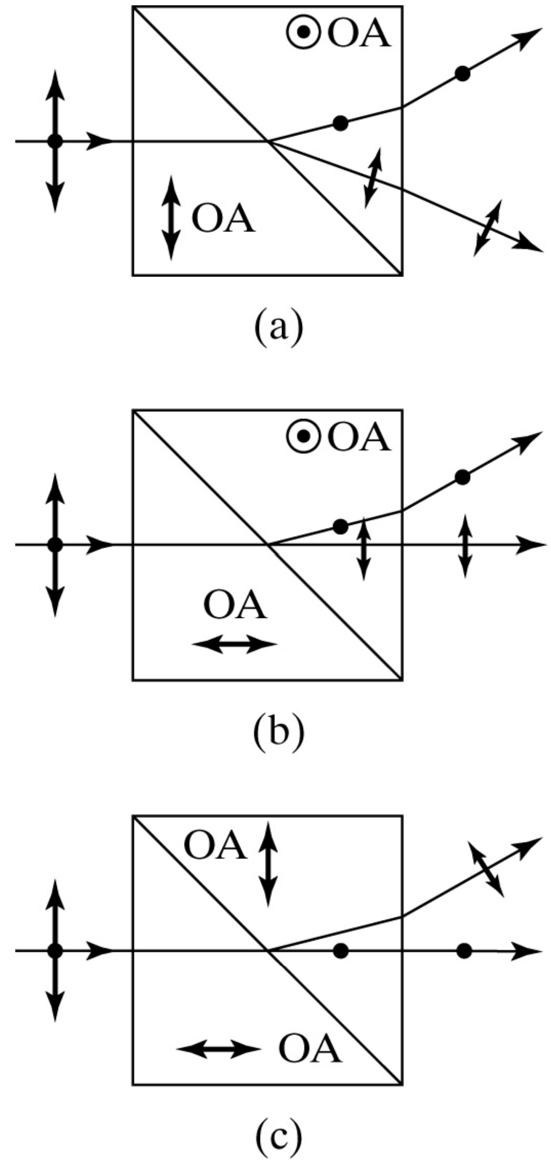

OA
E
a
b
P
b
a
$\vec{v}_{\parallel}$
$E_{\parallel}$
$E_{\perp}$
$\vec{v}_{\perp}$
OA
Surface
(a)
$\vec{S}$
$\vec{v}$
$\vec{E}$
O
$\vec{k}$
Plane wavefront
(b)

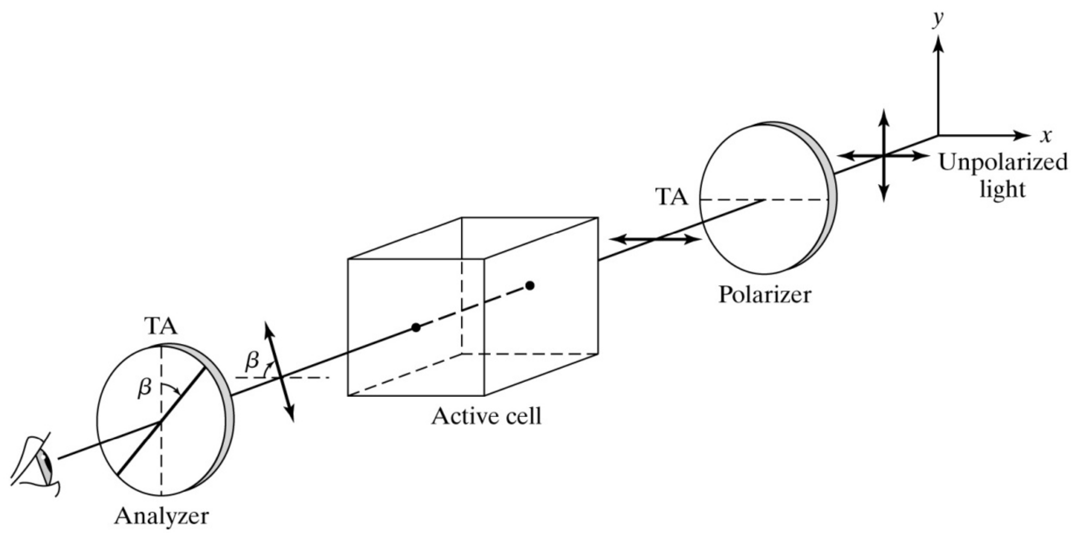

1.59
1.58
1.57
1.56
1.55
1.54
1.53
Principal indices of refraction
Slowest
extraordinary
ray
$n_\parallel$
Ordinary
ray
$n_\perp$
200
300
400
500
600
700
800
900
1000
Wavelength (nm)

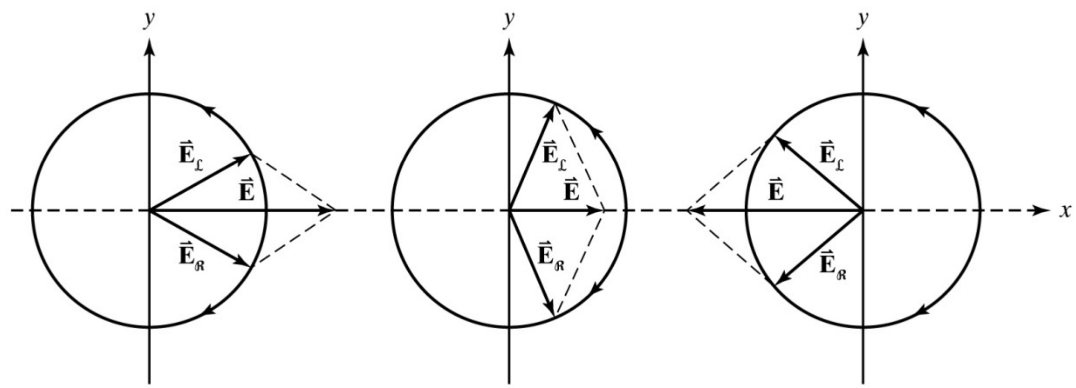


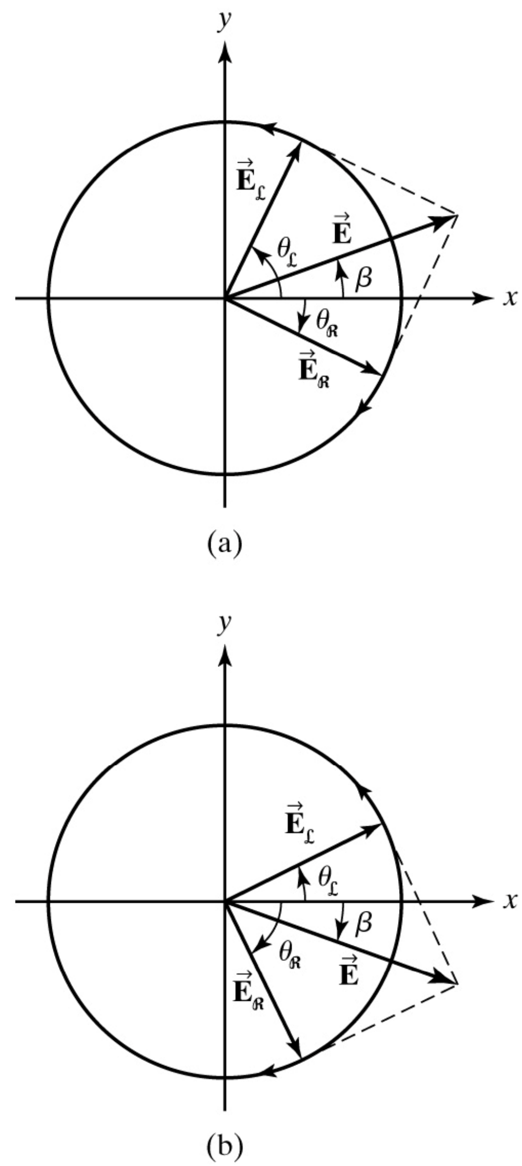
OA
θ
OA
θ
θ

Optical activity



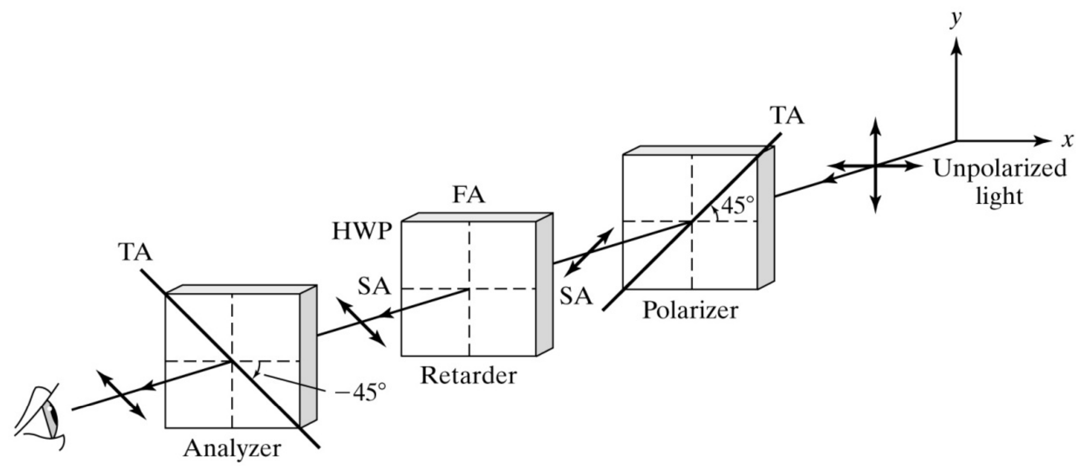

y
x
Unpolarized light
TA
Polarizer
Active cell
TA
β
β
Analyzer

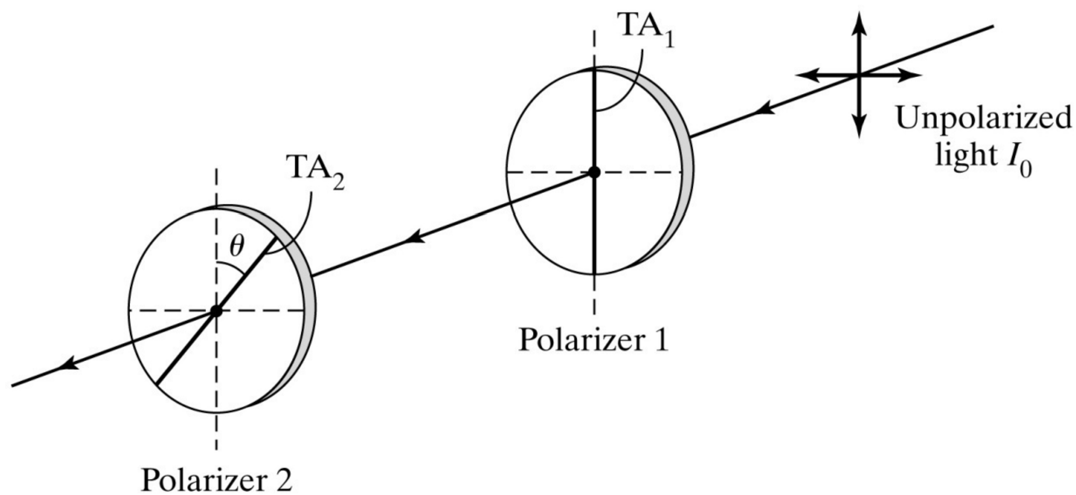

y
y
y
x
$\vec{E}_{\mathfrak{L}}$
$\vec{E}$
$\vec{E}_{\mathfrak{R}}$
$\vec{E}_{\mathfrak{L}}$
$\vec{E}$
$\vec{E}_{\mathfrak{R}}$
$\vec{E}_{\mathfrak{L}}$
$\vec{E}$
$\vec{E}_{\mathfrak{R}}$

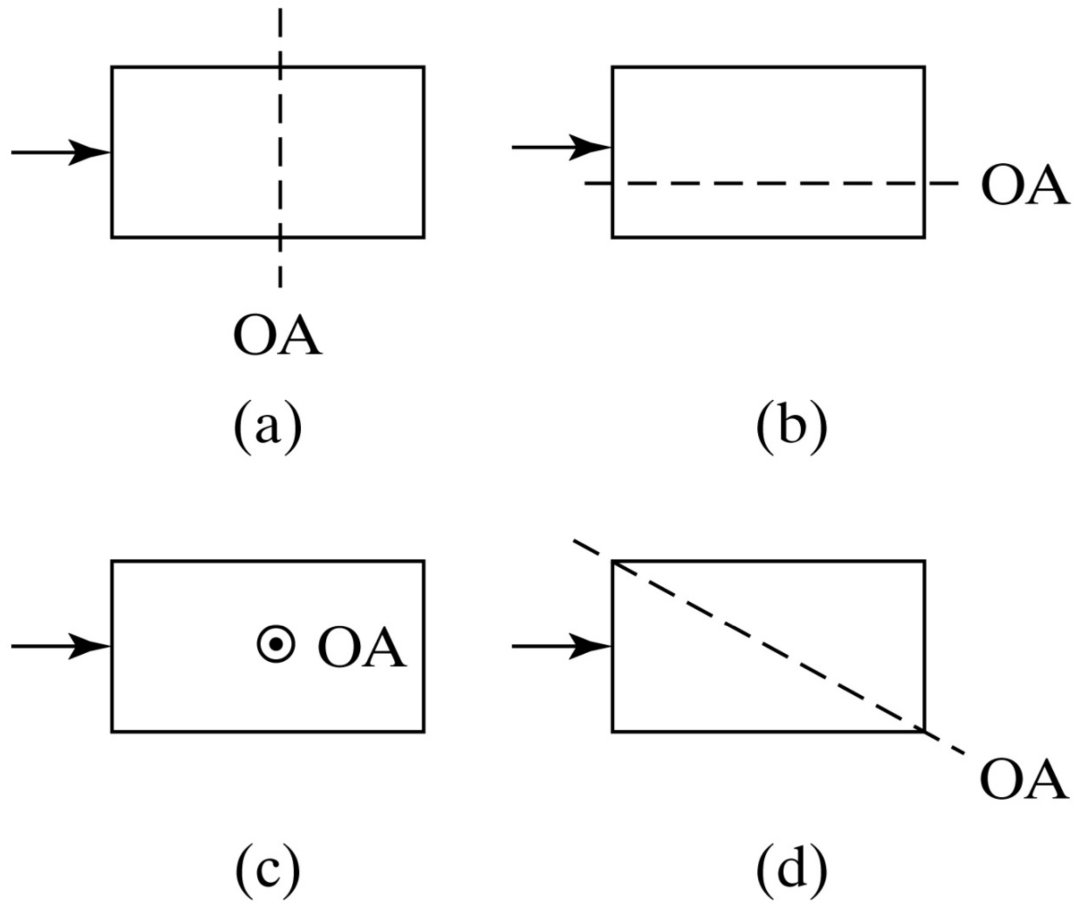


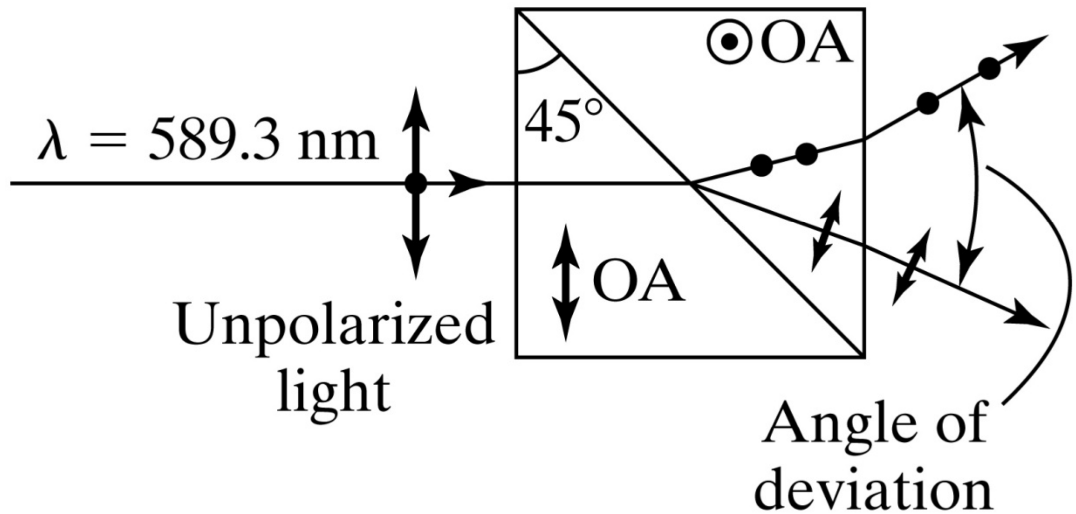
y
x
$\vec{E}_{\mathfrak{L}}$
$\vec{E}$
$\theta_{\mathfrak{L}}$
β
$\theta_{\mathfrak{R}}$
$\vec{E}_{\mathfrak{R}}$
(a)
y
x
$\vec{E}_{\mathfrak{L}}$
$\theta_{\mathfrak{L}}$
β
$\theta_{\mathfrak{R}}$
$\vec{E}$
$\vec{E}_{\mathfrak{R}}$
(b)

Photoelasticity

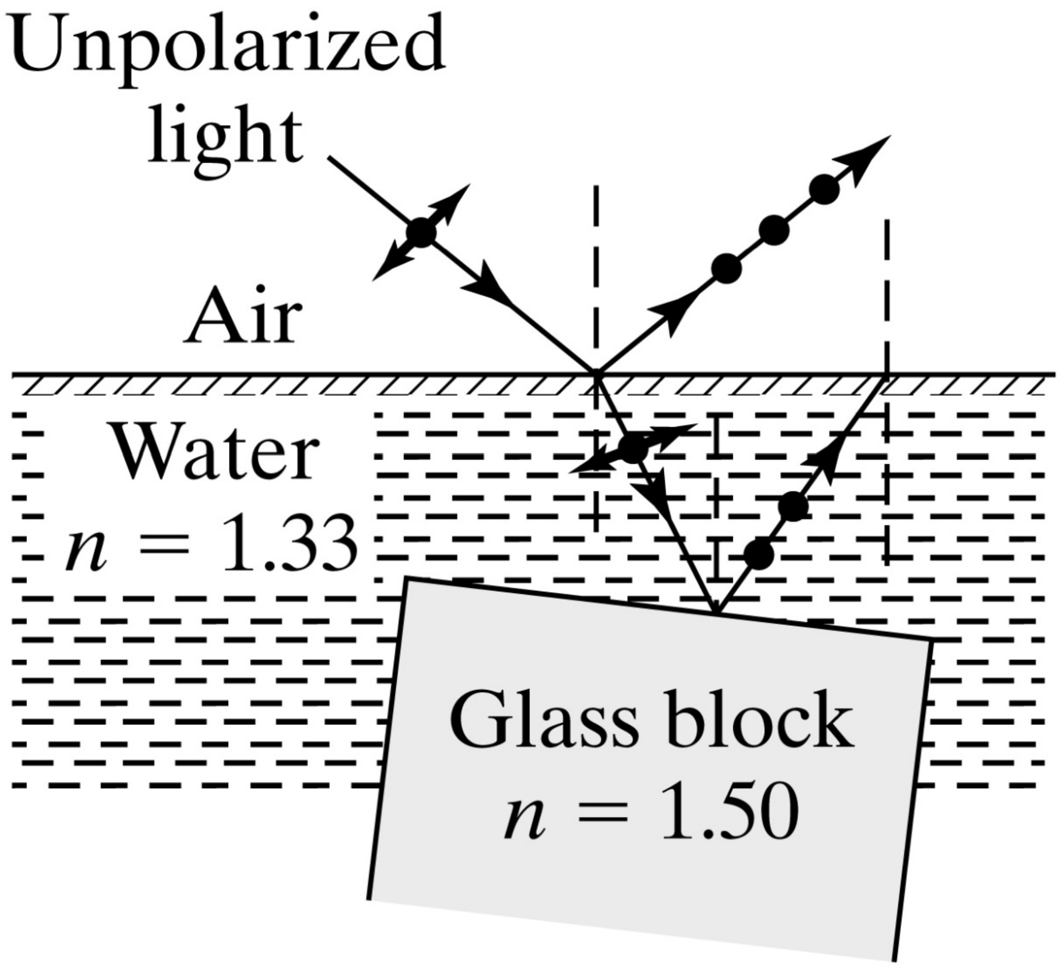



TA$_1$
Unpolarized light I_0
TA$_2$
θ
Polarizer 1
Polarizer 2


OA
(a)
OA
(b)
OA
(c)
OA
(d)



⊙OA
45°
λ = 589.3 nm
OA
Unpolarized
light
Angle of
deviation


Unpolarized
light
Air
Water
$n = 1.33$
Glass block
$n = 1.50$

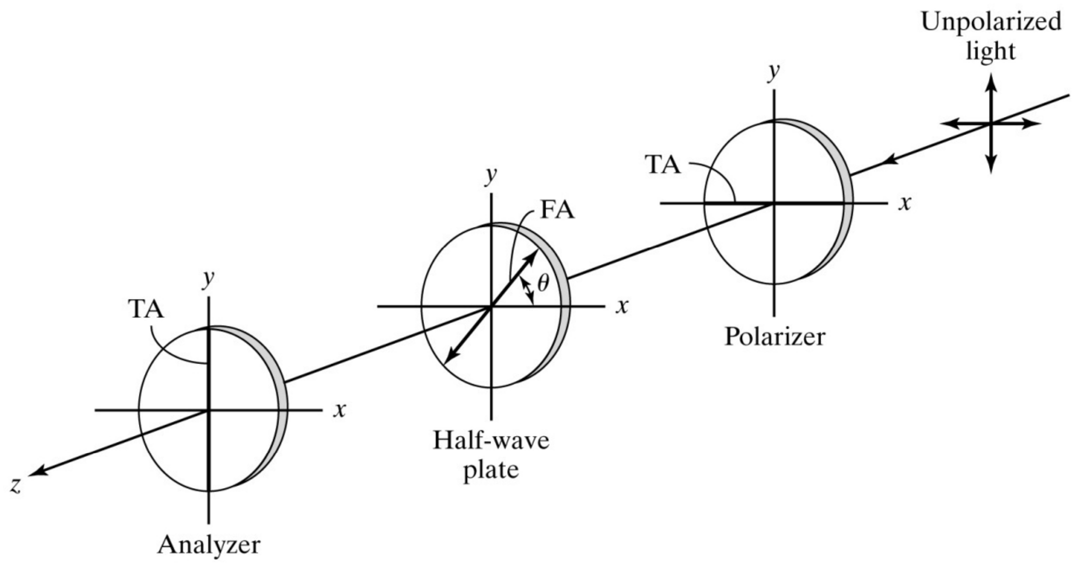

Unpolarized
light
y
TA
x
Polarizer
y
FA
θ
x
Half-wave
plate
y
TA
x
z
Analyzer

TABLE 15-2 SPECIFIC ROTATION OF QUARTZ

λ (nm)	ρ (degrees/mm)
226.503	201.9
404.656	48.945
435.834	41.548
546.072	25.535
589.290	21.724
670.786	16.535

TABLE 15-3 REFRACTIVE INDICES FOR QUARTZ

λ (nm)	$n_{\parallel}$	$n_{\perp}$	$n_{\mathfrak{R}}$	$n_{\mathfrak{L}}$
396.8	1.56771	1.55815	1.55810	1.55821
762.0	1.54811	1.53917	1.53914	1.53920