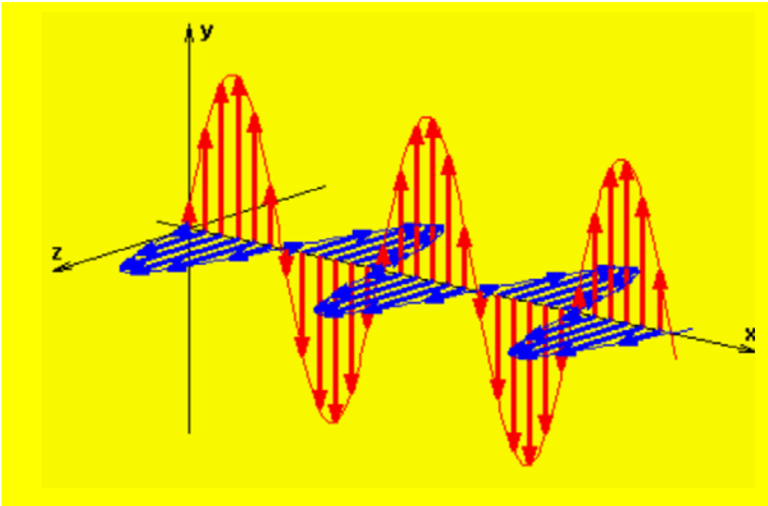
College of Optical Sciences
THE UNIVERSITY OF ARIZONA

OPTI 380A
Intermediate Optics Lab 6: Linear Polarization

Tom Milster
Professor, College of Optical Sciences,
University of Arizona
milster@arizona.edu

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

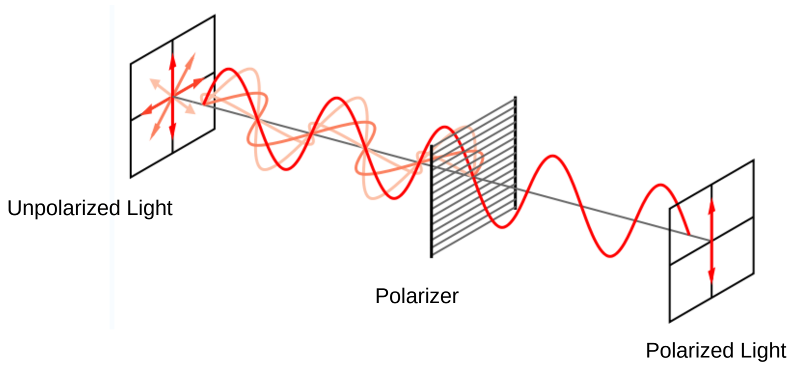
Linearly Polarized EM Wave



College of Optical Sciences

Polarizers

- A polarizer transmits only one orientation of polarization. That is, only one direction of electric field vibration is allowed to pass through the polarizer material.

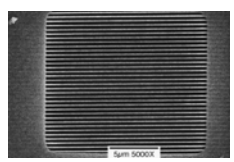


(Figure credit: http://en.wikipedia.org/wiki/File:Wire-grid-polarizer.svg)

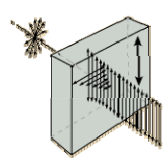
College of Optical Sciences

Absorptive Polarizers

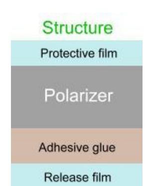
- Wire-grid: parallel metallic wires



- Crystals: dichroism (two colored), preferential absorption of light polarized in one direction

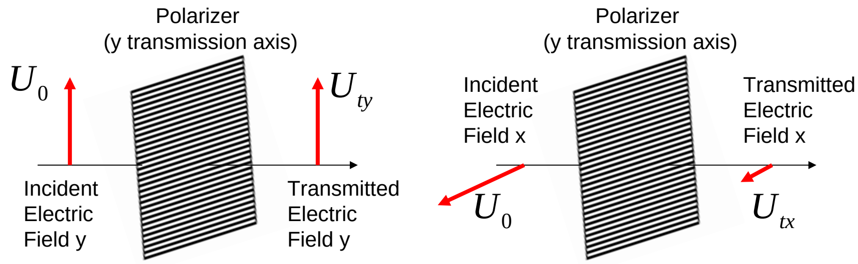


- Polaroid film: polyvinyl alcohol (PVA) plastic with iodine doping, align PVA by stretching (common in sunglasses, camera filters, LC displays)
- Corning Polarcor glass: elongated silver particles



Polarizer Extinction Ratio

- A polarizer's *extinction ratio* is the ratio of the power transmitted when the incident polarization is aligned with the transmission axis of the polarizer to the power transmitted when the incident polarization is orthogonal to the transmission axis.



$$\text{Extinction Ratio} = \left|\frac{U_{ty}}{U_{tx}}\right|^2$$

Polarizer Specifications

Typical Polarcor Performance

The table below shows typical performance for nominal wavelengths of (633 – 2100) nm.

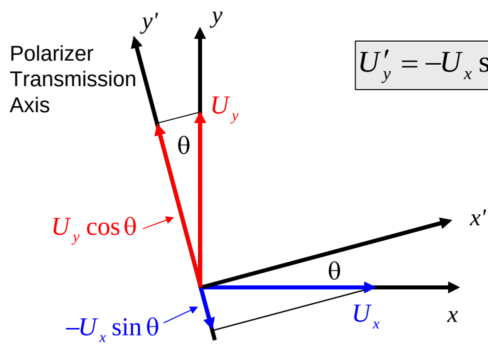
$\lambda_{Nominal}$(nm)	633	800	900	1060	1310	1480	1550	2100
Polarization Bandwidth (nm)	630 – 700	740 – 860	840 – 960	960 – 1160	1275 – 1345	1460 – 1500	1510 – 1590	2000 – 2300
Contrast Extinction Ratio (dB)	>10,000:1 > 40	> 10,000:1 > 40	> 10,000:1 > 40	> 10,000:1 > 40	> 100,000:1 > 50	> 100,000:1 > 50	> 100,000:1 > 50	> 10,000:1 > 40
Transmittance (%) Insertion Loss (dB) without AR-Coating	> 76.5 < 1.16	> 84.0 < 0.76	> 87.0 < 0.60	> 88.5 < 0.53	> 90.5 < 0.43	> 90.5 < 0.43	> 90.5 < 0.43	> 90.5 < 0.43
Transmittance (%) Insertion Loss (dB) (for 2-sides AR-Coated)	> 83.9 < 0.76	> 91.3 < 0.39	> 94.3 < 0.25	95.7 < 0.19	> 98.5 < 0.06	> 98.5 < 0.06	> 98.5 < 0.06	–
Refractive Index @ $\lambda_{Nominal}$	1.5210	1.5161	1.5138	1.5123	1.5088	1.5061	1.5051	1.5020
Reflectance R (%) per each side*	< 0.4	< 0.4	< 0.4	< 0.4	< 0.25	< 0.25	< 0.25	–
Thickness (mm)	0.50	0.50	0.50	0.50	0.50 & 0.20	0.50 & 0.20	0.50, 0.20 & 0.15	0.50
Thickness Tolerances (mm)	± 0.05 mm for product with 0.5 mm thickness and +0.03 mm /-0.05 mm for products with 0.2 mm and 0.15 mm thickness.							

$$dB = 10\log_{10}\left(\frac{P_1}{P_2}\right),$$ -10dB = 10%, -20dB = 1% etc…

Rotated Polarizer

If a polarizer is rotated by angle θ, the effect on the transmitted light is to project *x* and *y* components of the incident polarization onto the rotated axis. In the example below, the transmission of the polarizer is in the *y′* direction.

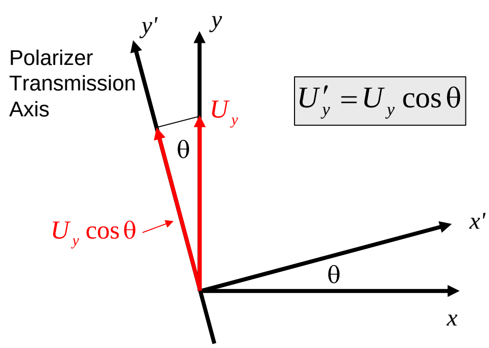
Vector Diagram:



$$U'_y = -U_x \sin\theta + U_y \cos\theta$$

Law of Malus

- Let the incident polarization be in the y direction, then



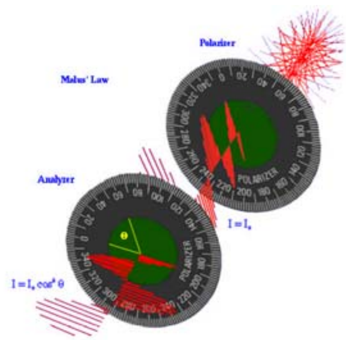
$$U'_y = U_y \cos\theta$$

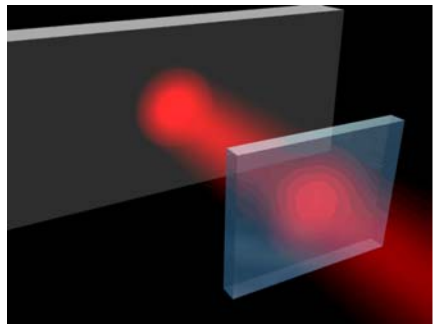
Etienne-Louis Malus

- Transmitted power is: $P_{\text{transmitted}} \propto P_{\text{incident}} \cos^2\theta$

Law of Malus

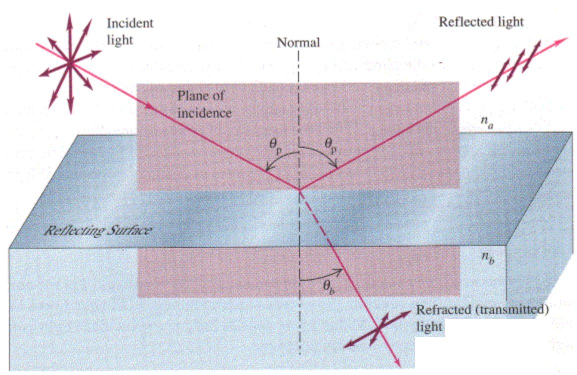
- Experimentally, we can use one polarizer to set the incident polarization
- A second polarizer (called an analyzer) can be rotated to observe Malus's law.





Plane of Incidence

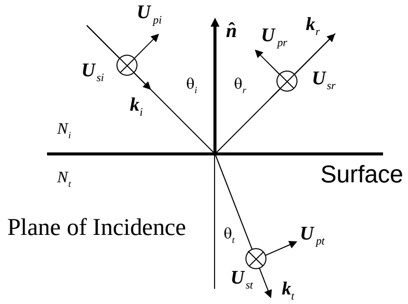
- When polarized light reflects from and transmits through surfaces, the amount of reflection and transmission is defined relative to the *plane of incidence*.



Polarization – Fresnel's Equations

- The s polarization state (⊥ plane of incidence) and p polarization state (in the plane of incidence) define Fresnel's Equations of reflection and transmission.

Polarization Convention



Fresnel's Equations

$$r_s = \frac{N_i \cos\theta_i - N_t \cos\theta_t}{N_i \cos\theta_i + N_t \cos\theta_t} \qquad r_p = \frac{N_t \cos\theta_i - N_i \cos\theta_t}{N_t \cos\theta_i + N_i \cos\theta_t}$$

$$t_s = \frac{2N_i \cos\theta_i}{N_i \cos\theta_i + N_t \cos\theta_t} \qquad t_p = \frac{2N_i \cos\theta_i}{N_t \cos\theta_i + N_i \cos\theta_t}$$

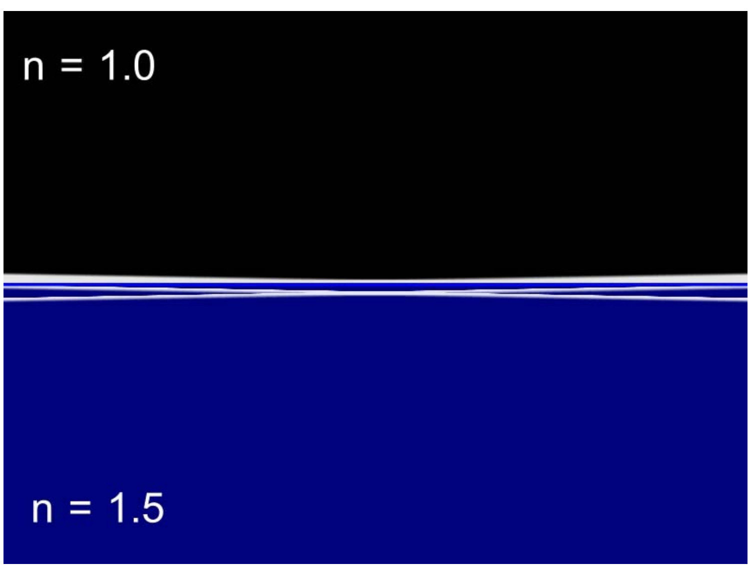
For example, the reflected field amplitude for *p* polarization is:

$$U_{pr} = r_p U_{pi}$$

The reflected power for *p* polarization is:

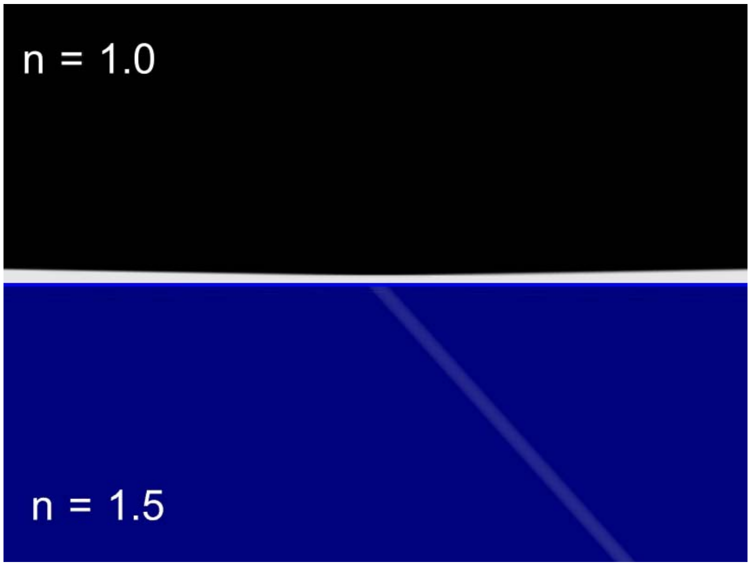
$$P_{pr} = |r_p|^2 P_{pi}$$

Air-to-Glass (s Polarization)



College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Air-to-Glass (p Polarization)



College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Air-to-Glass Reflection

- n_{air} ~ 1 and n_{glass} ~ 1.5
- Total reflection at θ=90 for both polarizations (glancing angle reflection, useful for x-rays)
- Zero reflection for parallel polarization at Brewster's angle (θ_B=56.5)

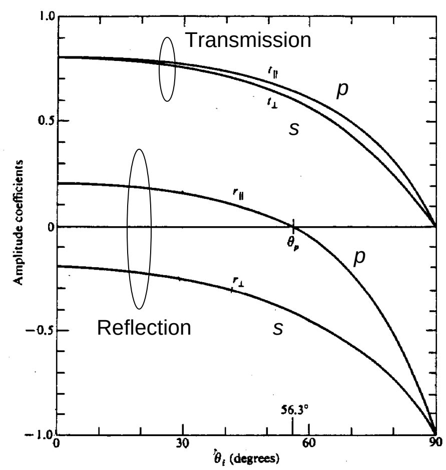
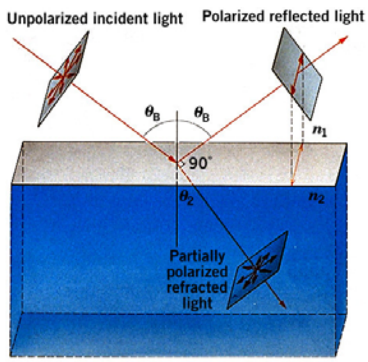


Figure 4.22 The amplitude coefficients of reflection and transmission as a function of incident angle. These correspond to external reflection $n_t > n_i$ at an air–glass interface (n_{ti} = 1.5).

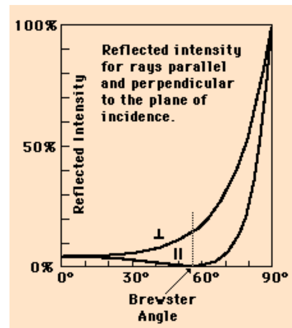
Brewster's Angle

- Sir David Brewster (1781-1868) published about diffraction of light in Philosophical Transactions of London in 1799 at an age of 18.
- When light moves between 2 media, p-polarized light will not be reflected at one incident angle called the Brewster's angle.


Sir David Brewster



$$\theta_B = \tan^{-1}\frac{n_t}{n_i}$$



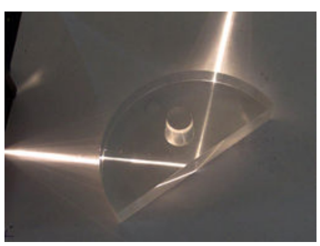
$$R = |r|^2$$

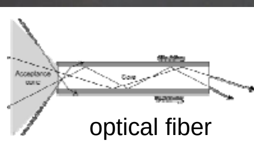
10/3/2009 OPTI380A - Lab 6: Linear Polarization 15

Glass to Air Reflection

- n_{air} ~ 1 and n_{glass} ~ 1.5
- Total internal reflection above a critical angle

$$\theta_{crit} = \arcsin(n_t / n_i)$$




optical fiber

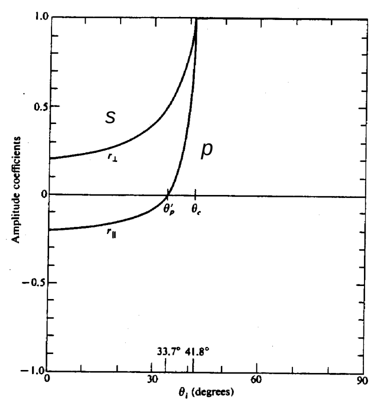
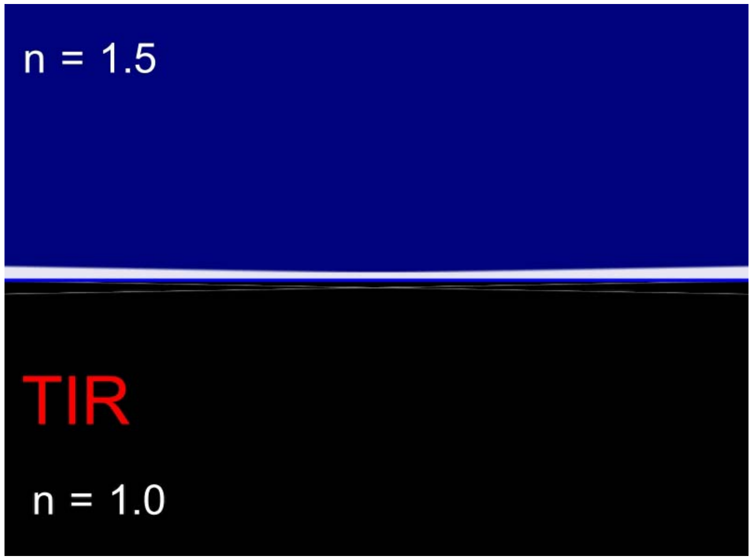


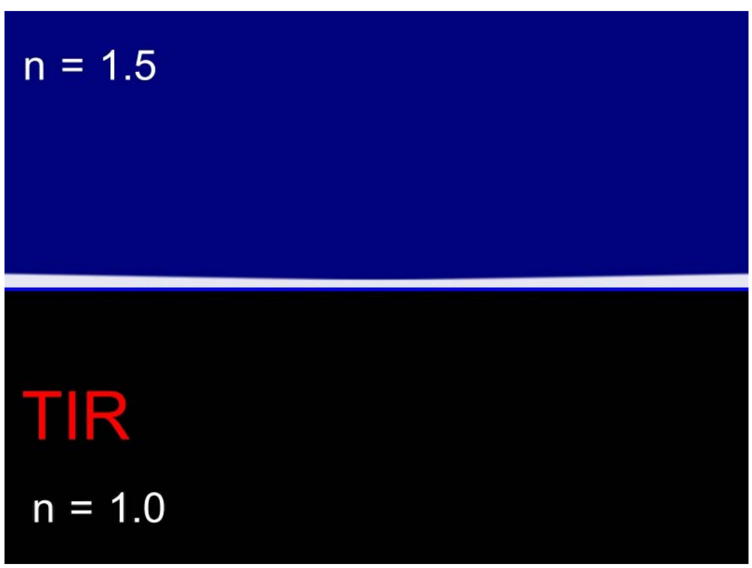
Figure 4.23 The amplitude coefficients of reflection as a function of incident angle. These correspond to internal reflection $n_t < n_i$ at an air–glass interface ($n_{ti} = 1/1.5$).

10/3/2009 OPTI380A - Lab 6: Linear Polarization 16

Glass-to-Air (s Polarization)

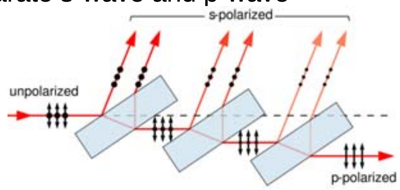


Glass-to-Air (p Polarization)



Beam-Splitting Polarizers

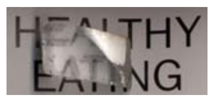
- Polarization by reflection, direct beam at Brewster's angle to separate s-wave and p-wave



For a stack of 10 plates, 20 reflections, about 3% of s-polarized light is transmitted.

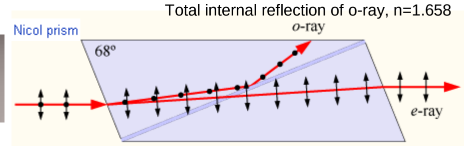
- Birefringent (double refraction) polarizer
  - Refractive index is different for different axis or polarization
  - Quartz and calcite: ordinary (o-ray) or extraordinary (e-ray)

Silica (silicon dioxide, SiO_2)



$CaCO_3$

Total internal reflection of o-ray, n=1.658



Rhombohedral crystal of calcite

e-ray is transmitted, n=1.486