The Standard in Optical Filters for Biotech & Analytical Instrumentation

Optical Filters
Polarization and Filters

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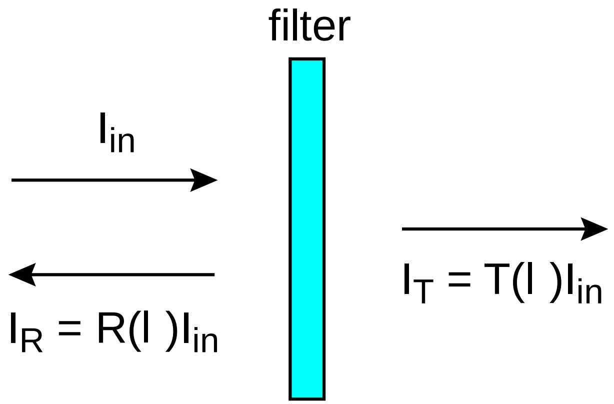
Sometimes polarization does not matter

- Often we can sufficiently characterize the spectral performance of an optical filter by determining simply the amount of light intensity (I) it transmits (T(λ)) and it reflects (R(λ))
- T and R are called the “intensity transmission” and “intensity reflection” coefficients
- At normal incidence, polarization does not matter



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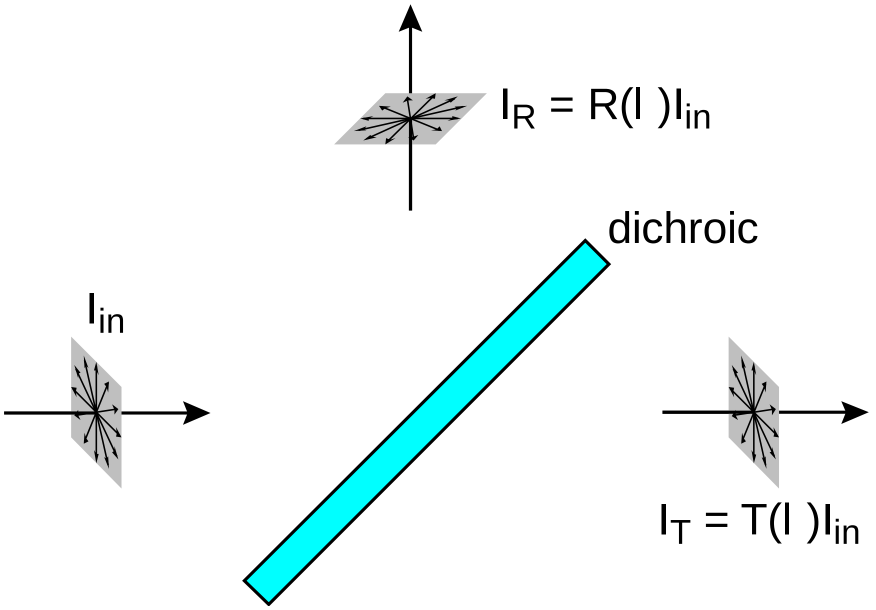
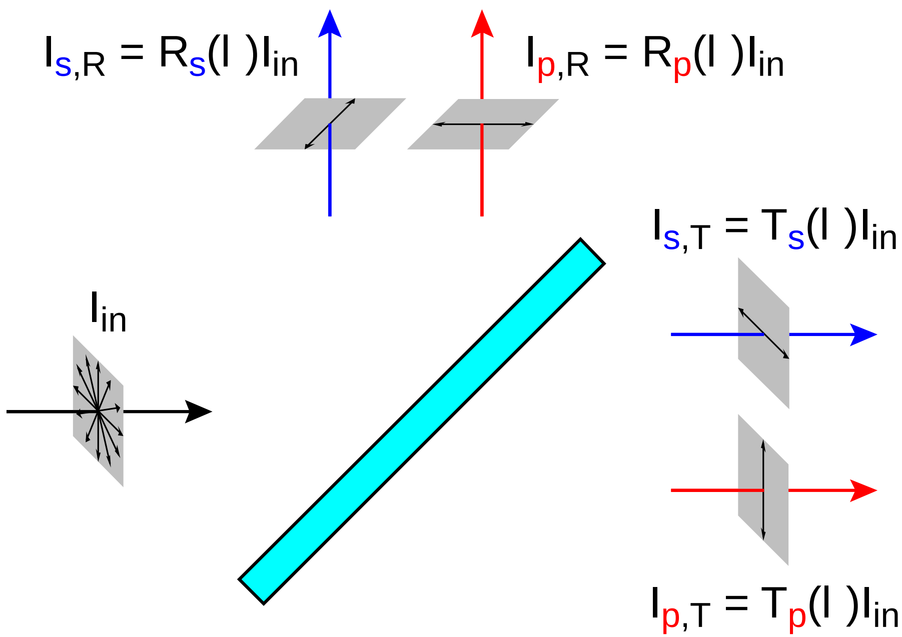
Polarization matters sometimes

- Filters are used at non-normal incidence to separate light into two paths – for example, a dichroic beamsplitter sends different wavelength bands into different directions
- Often, especially when the light is incoherent or randomly polarized for other reasons, the intensity transmission and reflection coefficients are sufficient to characterize the spectral performance of the filter



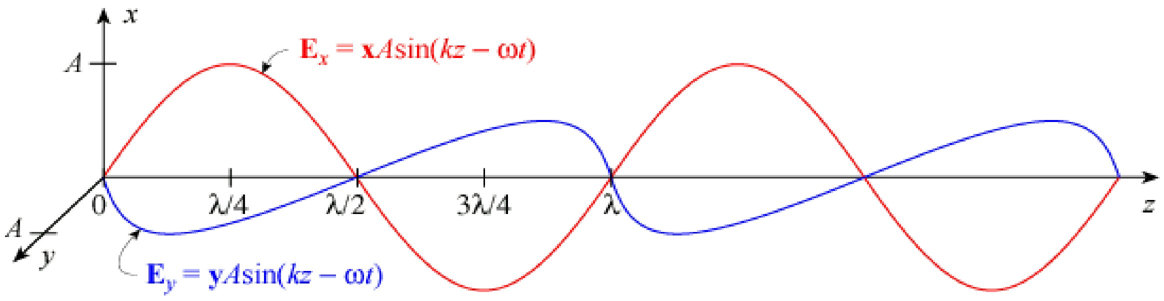
Polarization matters sometimes

- However, if the intensity coefficients T and R are very different for the two states of polarization (s and p) **AND** if the polarization of the output light matters (often it doesn't), then the transmission and reflection should be analyzed separately for each state of polarization



Polarization – linear polarization

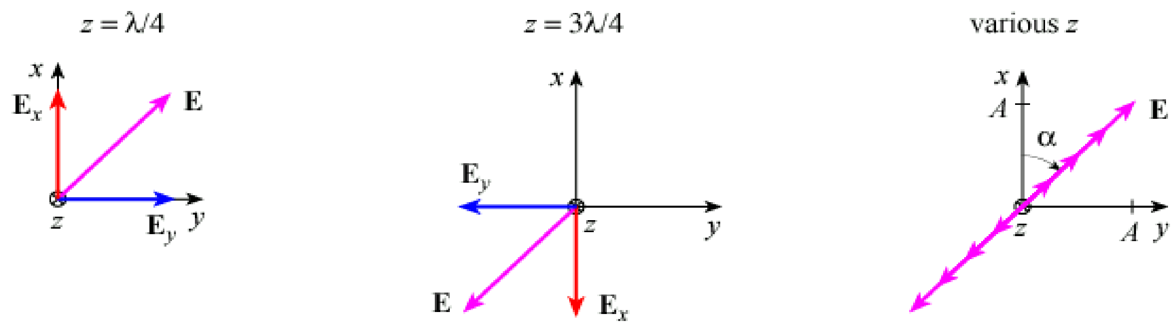
- Since light is a transverse wave, there are two distinct directions transverse to the propagation direction in which it may oscillate
  - We can view a light wave at a "**fixed time**" (say $t = 0$):



  - The total electric field is the sum of the two orthogonally polarized components:

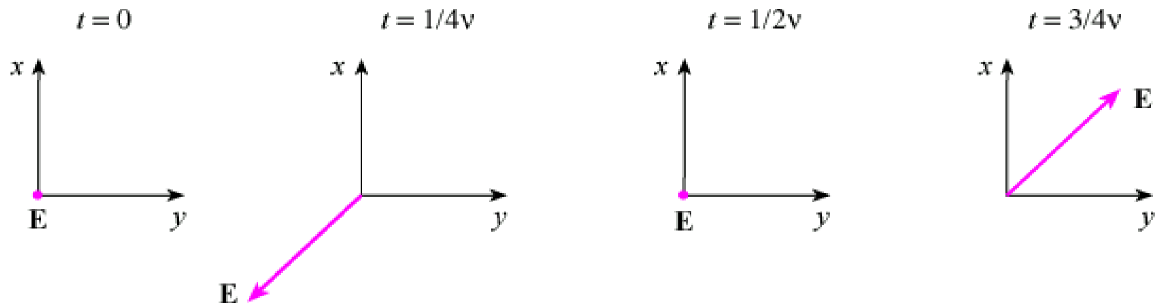
$$\mathbf{E} = \mathbf{E}_x + \mathbf{E}_y = (\mathbf{x} + \mathbf{y})A\sin(kz - \omega t)$$

  - Looking down the z axis (in the $+z$ direction) and at $t = 0$, the total field $\mathbf{E}$ traces out a line in the x-y plane – hence the name "**linear polarization**"

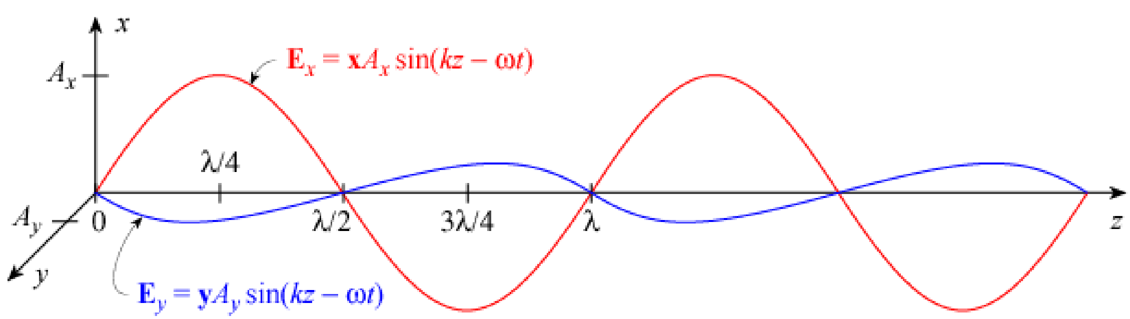


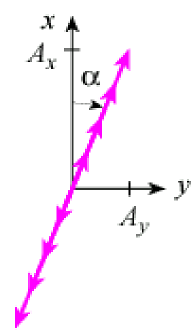
Polarization – linear polarization

- Another way of looking at the electric field is to sit at a "**fixed position**" and observe the evolution of the total field vector $\mathbf{E}$ in time
  - At $z = 0$ we see the total field can be written: $\mathbf{E} = \mathbf{E}_x + \mathbf{E}_y = -(\mathbf{x} + \mathbf{y}) A \sin(2\pi \nu t)$



- When the two components $\mathbf{E}_x$ and $\mathbf{E}_y$ have **unequal amplitudes**, we still find linear polarization, but the line traced by $\mathbf{E}$ is at angle α with respect to x

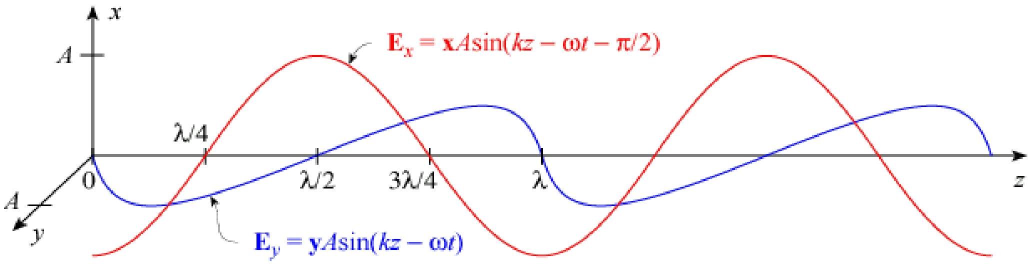




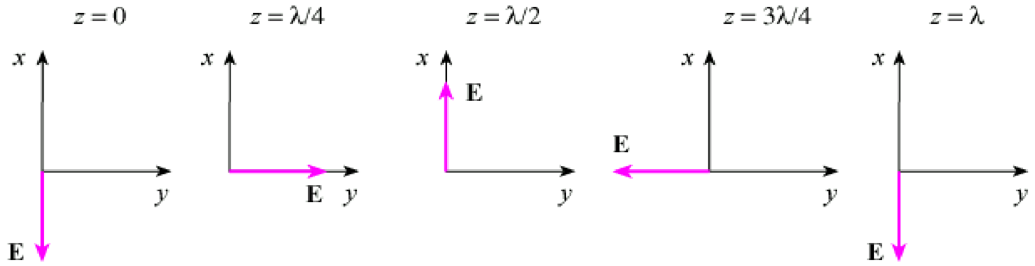
$$\tan \alpha = \frac{A_y}{A_x}$$

Polarization – circular polarization

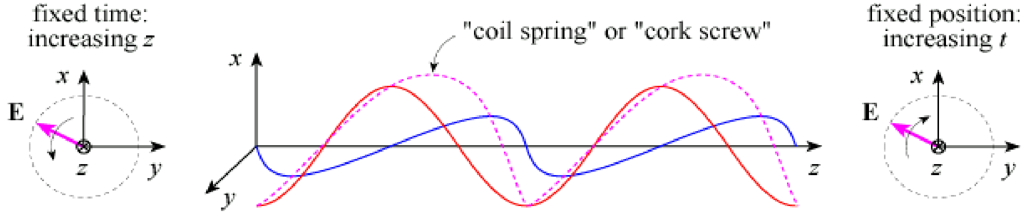
- If the two components have equal amplitude, but are out of phase by $\pi/2$, the total field $\mathbf{E}$ traces out a **circle**



  - In the "fixed time" picture, the total field at various locations looks like:



  - The field also traces out a circle in time at a "fixed position"

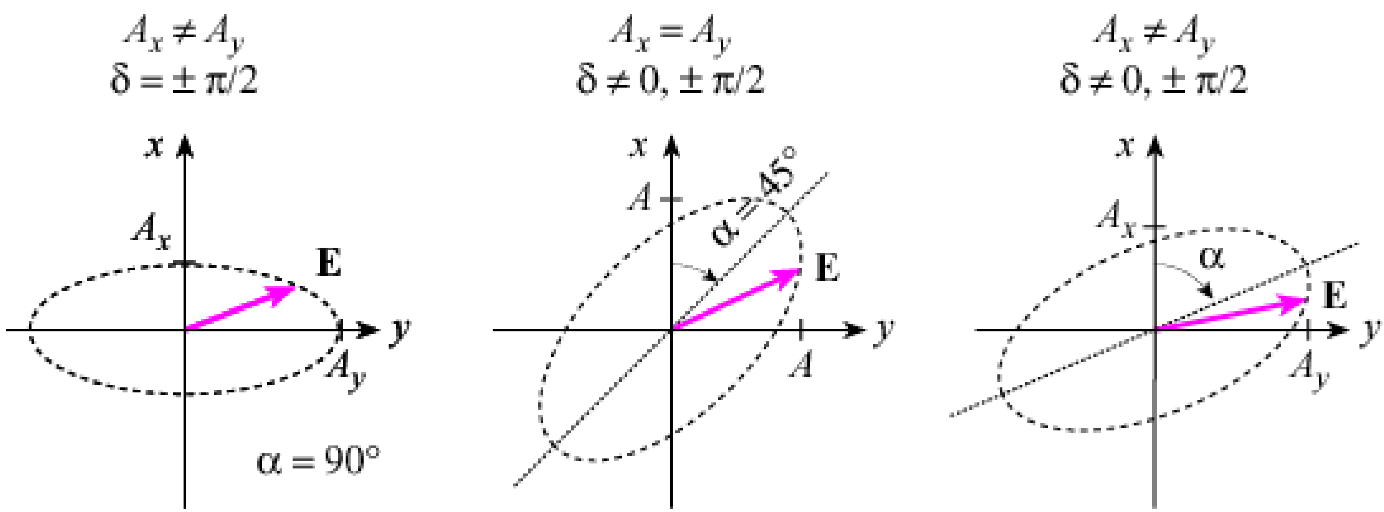


Polarization – elliptical polarization

- In the most general case the two components do not have equal amplitude ($A_x \neq A_y$) and they are out of phase ($\delta \neq 0$). Because the tip of the electric field vector traces out an ellipse, this state is called "**elliptical polarization**"

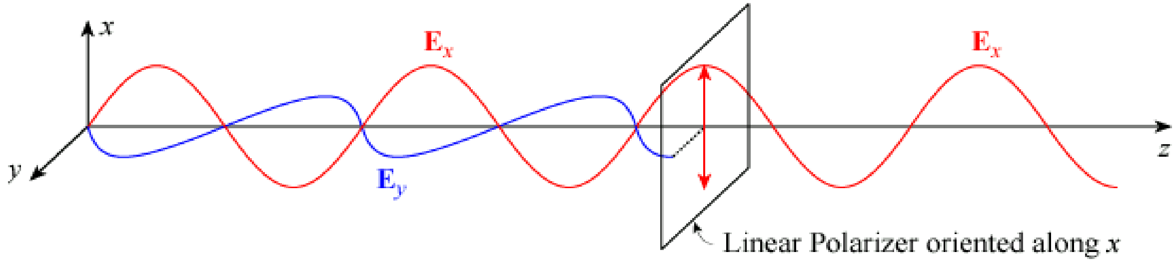
$$\mathbf{E}_x = \mathbf{x}A_x \sin(kz - \omega t) \qquad \mathbf{E}_y = \mathbf{y}A_y \sin(kz - \omega t - \delta) \qquad \mathbf{E} = \mathbf{E}_x + \mathbf{E}_y$$

  - Some examples of more general states of elliptical polarization are shown below

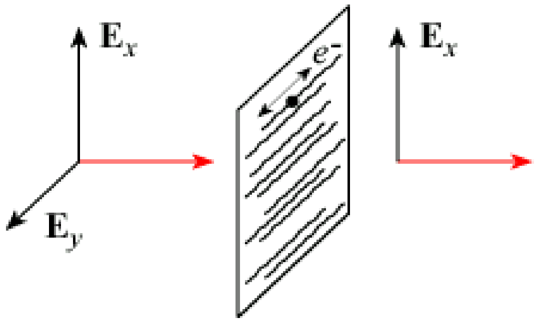


Polarization – polarizers

- A simple polarizer transmits only a single orientation of linear polarization, and blocks the rest of the light



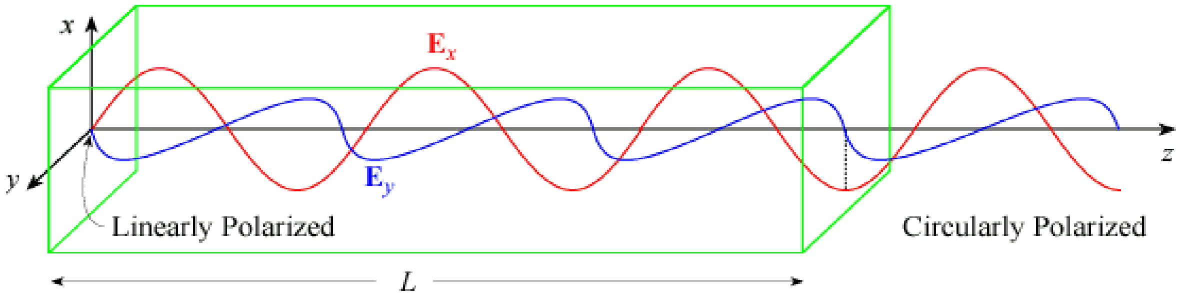
  - There are many different types of polarizers, but most are based on the same physical principle: the polarizing material allows charges (electrons) to freely move in one direction but not the other



When the electric field of a light wave encounters the polarizer, the component parallel to the direction along which charge flows freely (E_y in the example) causes the charges to oscillate, thereby absorbing energy and preventing that component from being transmitted. Since charges can not respond to the orthogonal component, that component is passed

Polarization – birefringence

- A material that has different indexes of refraction for light polarized along different orientations is said to be "**birefringent**"
  - For example, suppose linearly polarized light with $\alpha = 45°$ is transmitted through a material of index n_x for light polarized along $\mathbf{x}$ and n_y for light polarized along $\mathbf{y}$



  - In general the light emerges in a different state of elliptical polarization

$$\mathbf{E}_x = \mathbf{x} A \sin(k n_x z - \omega t) \quad \mathbf{E}_y = \mathbf{y} A \sin(k n_y z - \omega t) \quad \Rightarrow \quad \phi_x = k n_x L \quad \phi_y = k n_y L$$

  - If the length is chosen such that

$$\phi_y - \phi_x = k(n_y - n_x)L = k\,\Delta n\,L = \pi/2 \qquad \text{or} \qquad \boxed{\Delta n\,L = \lambda/4}$$

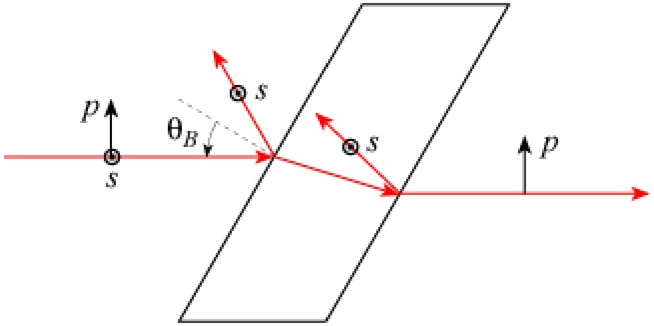
the light emerges circularly polarized! This is called a "**quarter-wave plate**"

Polarization – Brewster's angle

- *s*-polarized light is always more highly reflected than *p*-polarized light; at the special angle called "**Brewster's angle**," θ_B, *p*-polarized light experiences no reflection (complete transmission)

$$\tan\theta_B = \frac{n_t}{n_i}$$

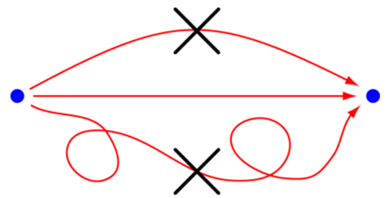
  - Instead of using an Anti-Reflection (AR) coating, a perfectly transmitting window can be made by orienting a parallel plate at Brewster's angle; this configuration is widely used in laser cavities, in which losses must be kept extremely low and polarized light is acceptable



The *p*-polarized light is completely transmitted through the window

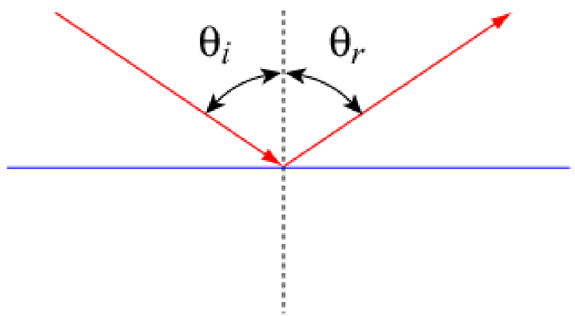
Light at an interface between two media

- **Definition of a Ray**: The path along which light energy is transmitted from one point to another.
  - **Fermat's Principle of Least Time**: when light travels between two points, it takes the path that is traversed in the least time.



The Law of Reflection:

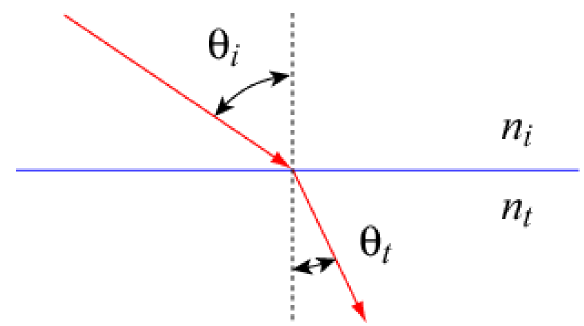
When a ray is reflected off of an interface, the angle of reflection is equal to the angle of incidence.



$$\theta_i = \theta_r$$

The Law of Refraction:

When a ray is transmitted across an interface between two media with different refractive indexes, the product of the index and the sine of the ray angle is equal on both sides.

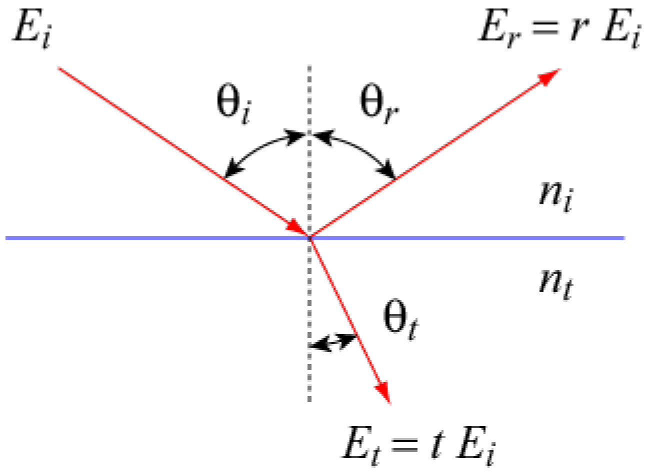


$$n_i \sin\theta_i = n_t \sin\theta_t$$

"Snell's Law"

How much light crosses the interface?

- Reflection and Transmission of Light Rays at an Interface
  - If light is incident in a medium of index n_i at an angle θ_i, so that the transmitted ray in a medium of index n_t is at angle θ_t, then the fraction of the **amplitude** (not power) reflected off of the interface (for parallel polarization) is:



$$r \equiv \frac{E_r}{E_i} = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t}$$

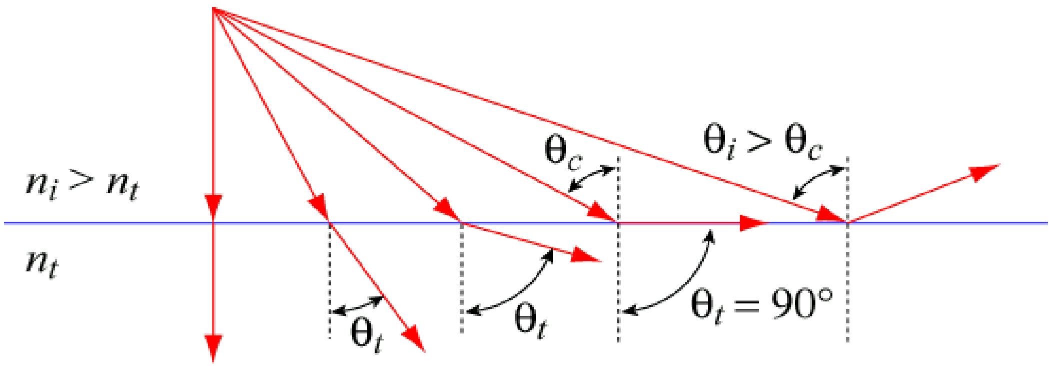
The fraction of the **power** reflected off of and transmitted through the interface is:

$$R = |r|^2$$

$$T = 1 - R$$

Total Internal Reflection at an interface

- **Total Internal Reflection (TIR)** occurs when light is incident from a higher-index medium onto a lower-index medium and the angle of incidence becomes so large that Snell's Law fails.



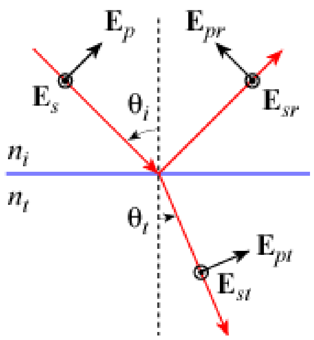
$$\theta_c = \arcsin\left(\frac{n_t}{n_i}\right)$$

for $n_i > n_t$

- The **Critical Angle**, or θ_c, is the angle of incidence that just makes the angle of transmission equal to 90 degrees.
  - For an incident angle greater than the critical angle, **all of the light is reflected**, such that ***R* = |*r*| = 1**

Reflection for different polarizations of light

- When light is not normally incident on an interface, different polarizations are reflected by different amounts – this is called "**Fresnel reflection**"
  - The "**s**" component is perpendicular to and the "**p**" component is parallel to the "**plane of incidence**," or the plane that contains the incident, transmitted, and reflected rays

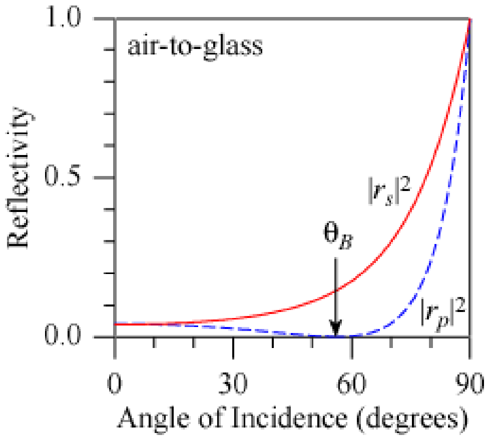


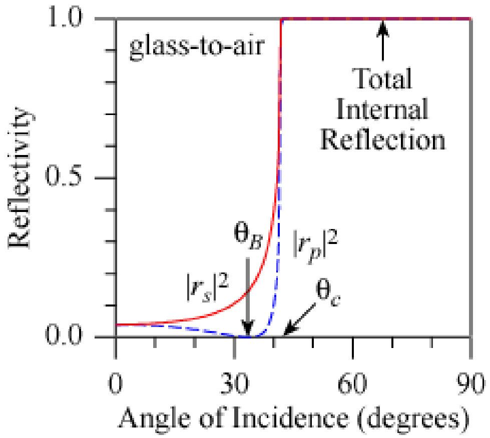
Fresnel (amplitude) reflection coefficients:

$$r_s = \left|\frac{\mathbf{E}_{sr}}{\mathbf{E}_s}\right| = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t}$$

$$r_p = \left|\frac{\mathbf{E}_{pr}}{\mathbf{E}_p}\right| = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_t \cos\theta_i + n_i \cos\theta_t}$$

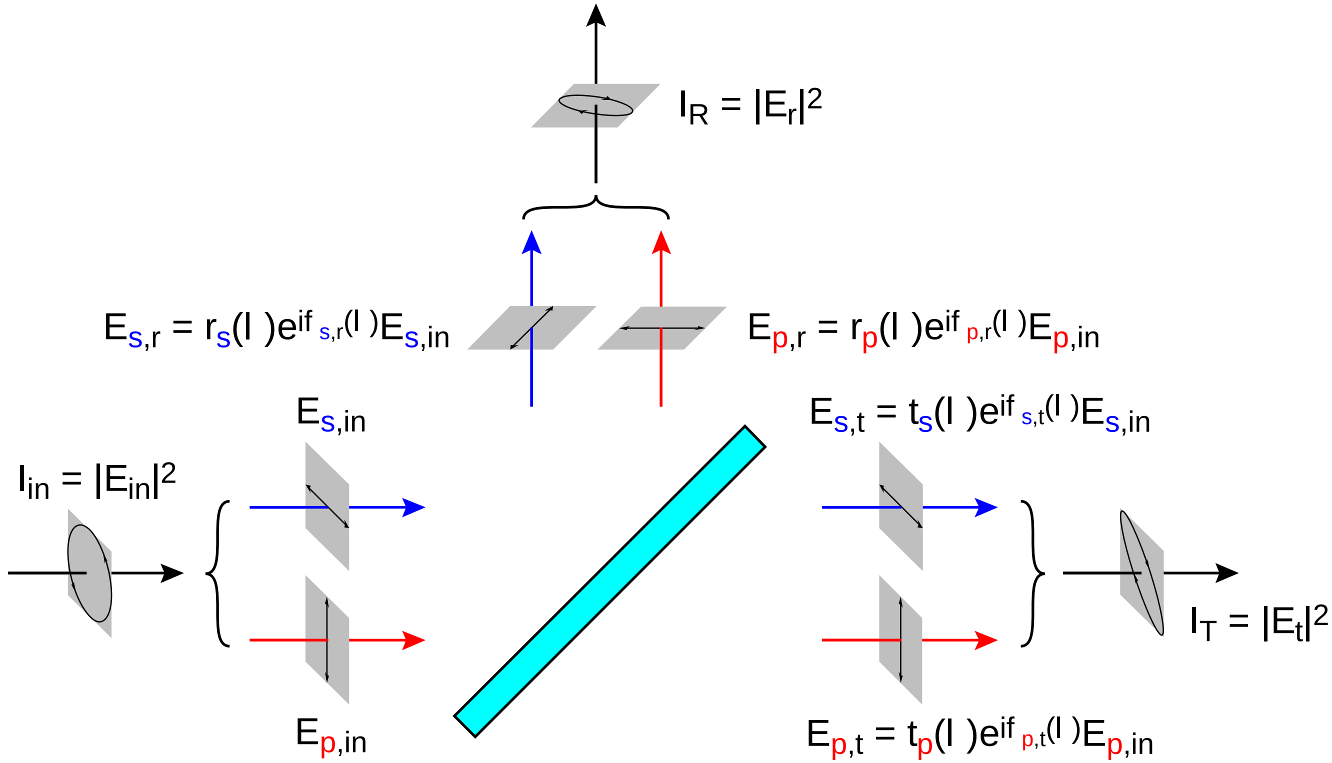
Fresnel (power) reflection coefficients:





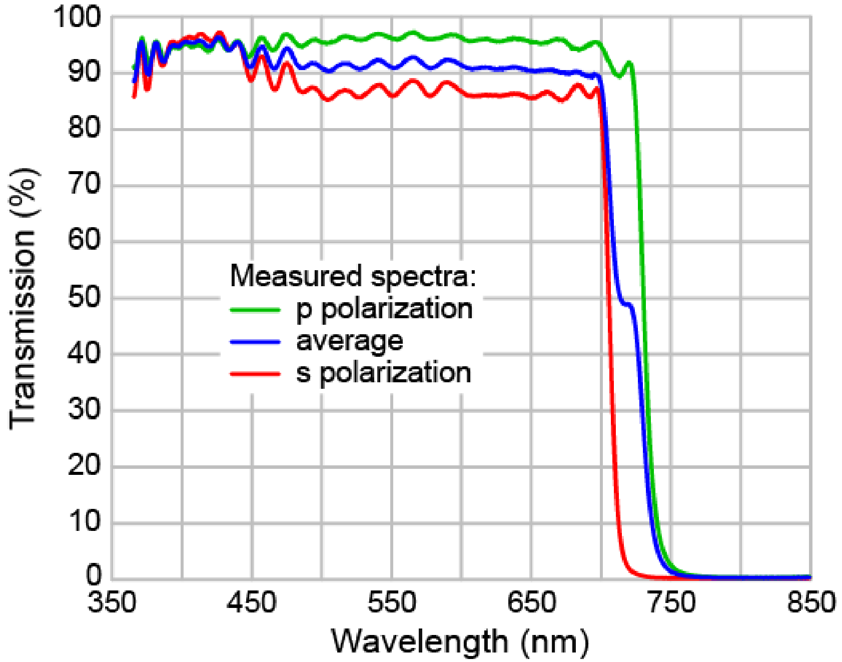
State of polarization changed by a filter

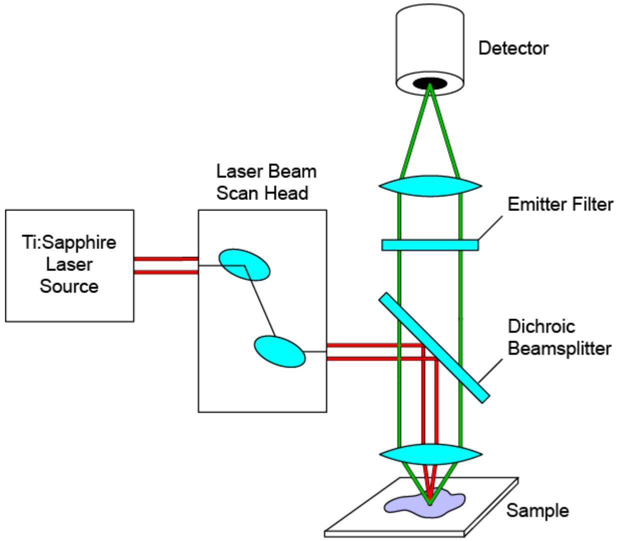
- Now it should be apparent why reflection and transmission can change the state of polarization (when the incident light is polarized)
  - A difference in r_s and r_p (or t_s and t_p) changes the amount of s and p light
  - A difference in φ_s and φ_p acts like birefringence



Short-wave-pass dichroic for "SHG" imaging

- Excellent dispersion and polarization properties make this filter ideal for Second Harmonic Generation (SHG) imaging
- Optimized for excitation at ~ 810 nm and imaging of the nonlinear scattered light (which is not fluorescence!) at ~ 405 nm



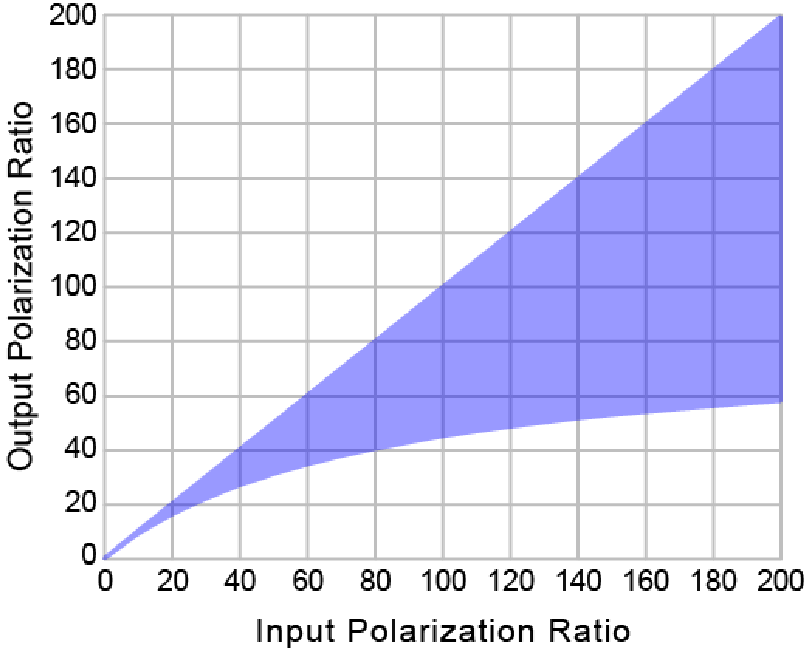


Configuration for using a short-wave-pass dichroic beamsplitter

Short-wave-pass dichroic for "SHG" imaging

- Carefully **controlled polarization dependence** to maintain a high degree of linear polarization for both reflected laser light and transmitted signal light for all polarization orientations

Maintaining linear polarization for light transmitted through FF720-SDi01 at 405 nm



Allows one to vary the polarization state of the laser while measuring a like-polarized signal beam for the utmost in signal-to-noise ratio

Thank you!