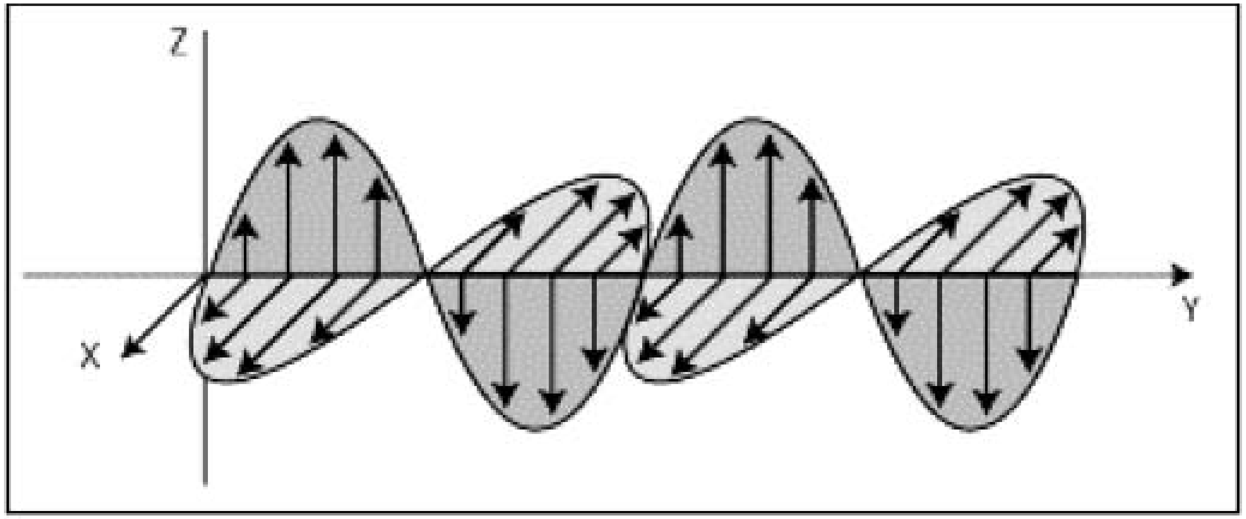
Polarization and Waveplates

- Polarization states
- Linear polarizers
- Free space Waveplates
- Fiber waveleplates
- Optical isolators

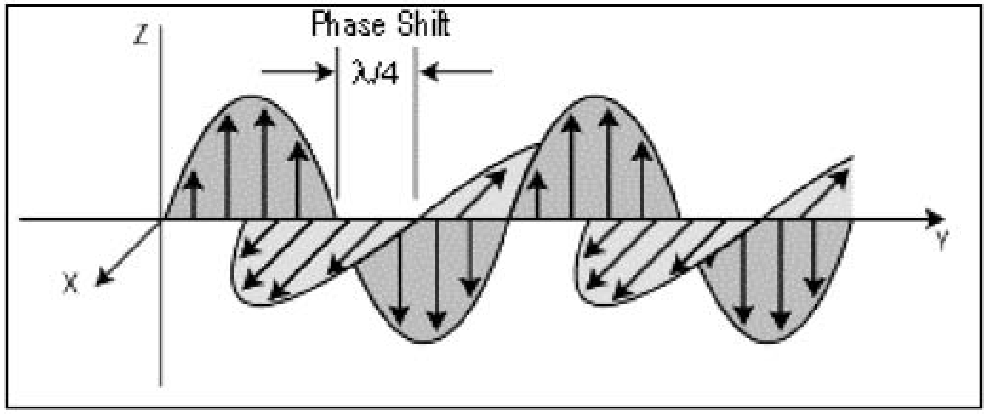
Linearly Polarized Light



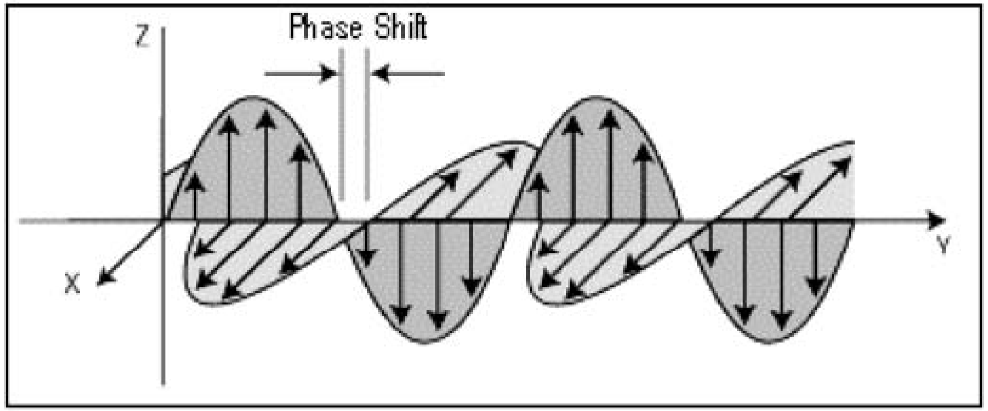
B. Linearly Polarized Light at 45 Degrees

- Axes determined by optical components, or by definition
- $\boldsymbol{E_x}$ and $\boldsymbol{E_z}$ in phase

Polarization States



C. Circularly Polarized Light



D. Elliptically Polarized Light

- $\boldsymbol{E_x}$ and $\boldsymbol{E_z}$ equal amplitude
- $\boldsymbol{E_x}$ and $\boldsymbol{E_z}$ 90° out of phase
- Field rotates about propagation axis
- $\boldsymbol{E_x}$ and $\boldsymbol{E_z}$ arbitrary but fixed amplitude and phase

Stokes Vector

$$\begin{aligned} E_x &= E_{0x}\cos[(kz-\omega t)+\delta_x] \\ E_y &= E_{0y}\cos[(kz-\omega t)+\delta_y] \end{aligned}$$

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

$$\begin{aligned} S_0 &= \langle {E_{0_x}}^2 \rangle + \langle {E_{0_y}}^2 \rangle \\ S_1 &= \langle {E_{0_x}}^2 \rangle - \langle {E_{0_y}}^2 \rangle \\ S_2 &= \langle 2E_{0_x}E_{0_y}\cos\delta \rangle \\ S_3 &= \langle 2E_{0_x}E_{0_y}\sin\delta \rangle\,, \end{aligned}$$

$S_{out} = \mathbf{M}s_{in}$

M = Mueller Matrix for polarization component

Mueller Matrices

optical element	Mueller matrix
linear horizontal polarizer	$\frac{1}{2}\begin{bmatrix}1 & 1 & 0 & 0\\ 1 & 1 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$
linear vertical polarizer	$\frac{1}{2}\begin{bmatrix}1 & -1 & 0 & 0\\ -1 & 1 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$
linear polarizer at $+45°$	$\frac{1}{2}\begin{bmatrix}1 & 0 & 1 & 0\\ 0 & 0 & 0 & 0\\ 1 & 0 & 1 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$
linear polarizer at -45°	$\frac{1}{2}\begin{bmatrix}1 & 0 & -1 & 0\\ 0 & 0 & 0 & 0\\ -1 & 0 & 1 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$

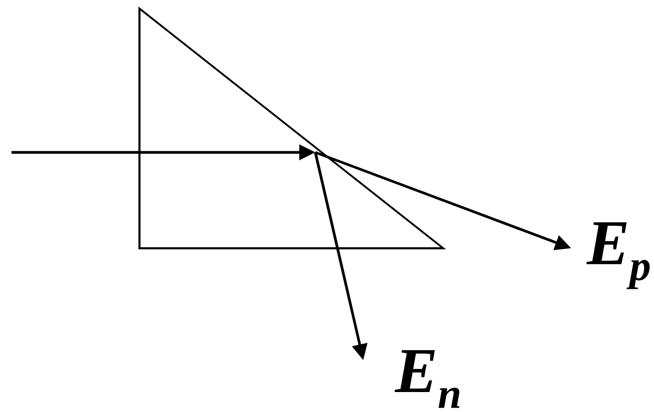
quarter-wave plate, fast axis vertical	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & -1\\ 0 & 0 & 1 & 0\end{bmatrix}$
quarter-wave plate, fast axis horizontal	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & -1 & 0\end{bmatrix}$
circular polarizer, right-handed	$\frac{1}{2}\begin{bmatrix}1 & 0 & 0 & 1\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 1 & 0 & 0 & 1\end{bmatrix}$

Polarizers

- Birefringent
  - Polarization- dependent refractive index
  - Redirects one polarization component
- Dichroic
  - Polarization-dependent absorption
  - Absorbs one polarization component

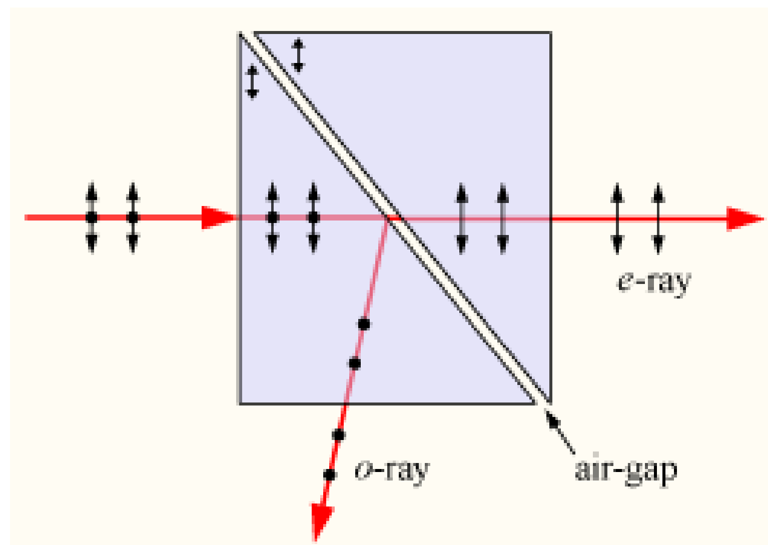
Birefringent Polarizers

E_n undergoes total internal reflection, E_p does not.



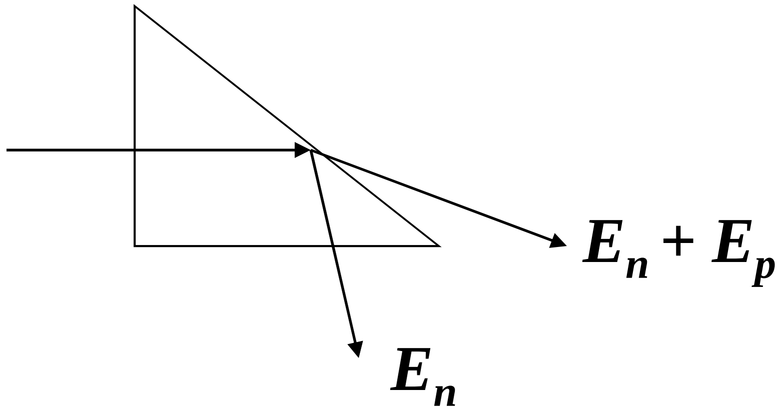
Glan Taylor Polarizer

2nd prism straightens beam



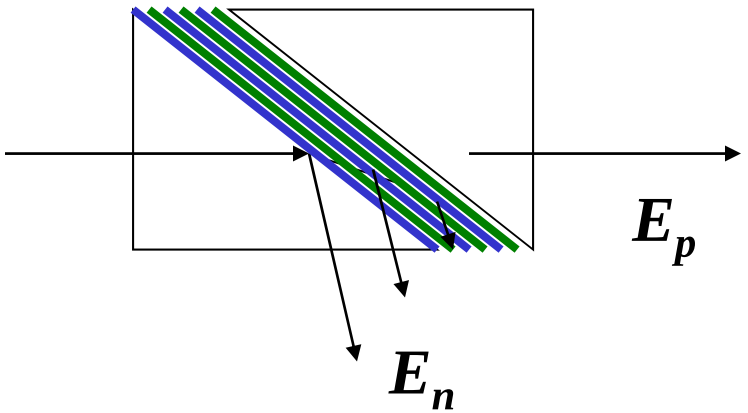
Reflection Polarizers

Brewster's angle: $R_p = 0$

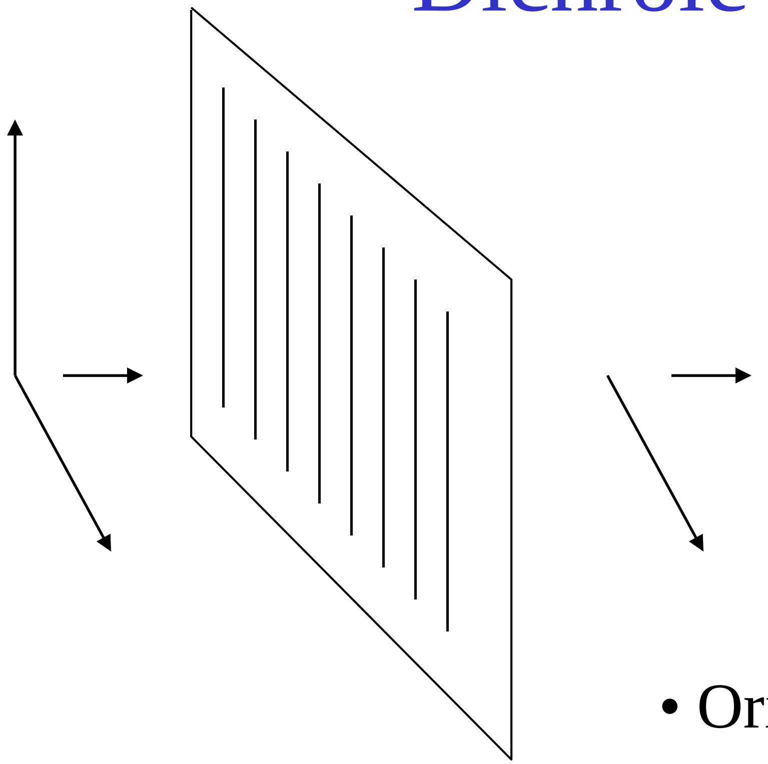


Dielectric stack

Polarizing beamsplitter cube

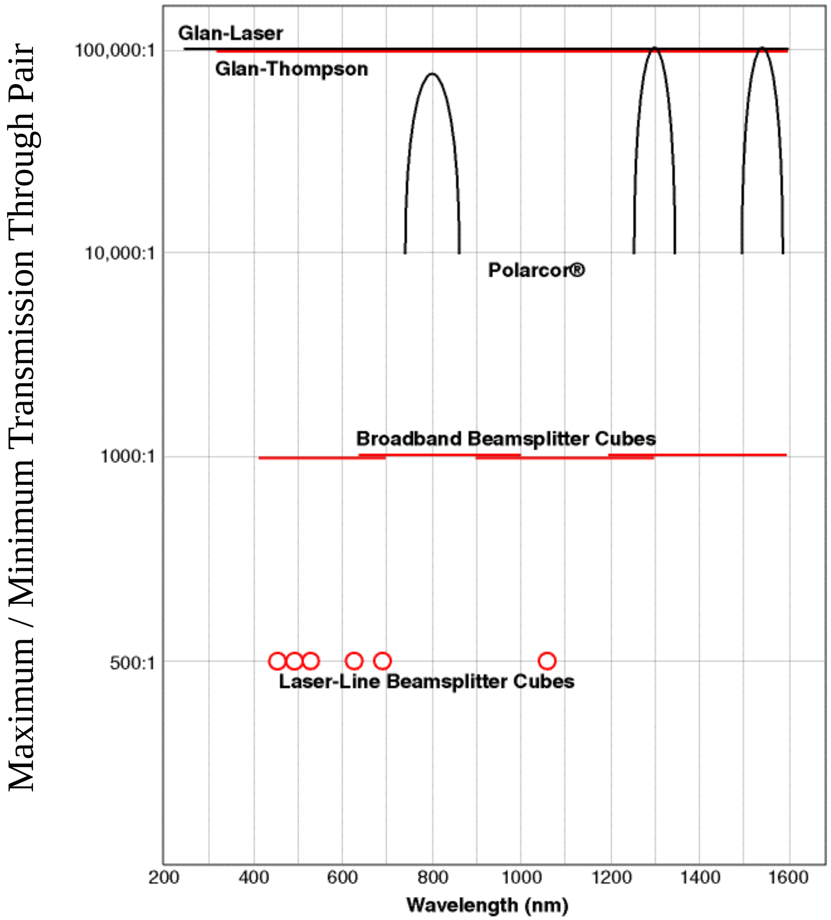


Dichroic Polarizers



- Oriented molecules or nanoparticles
- Absorption depends on field direction
- Example: polaroid lenses

Extinction Ratio



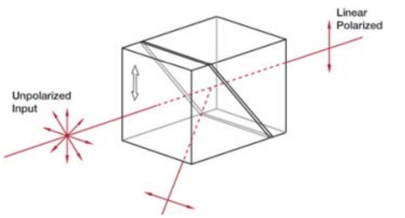
Extinction ratio measured with pair of polarizers aligned for max. then min. transmission

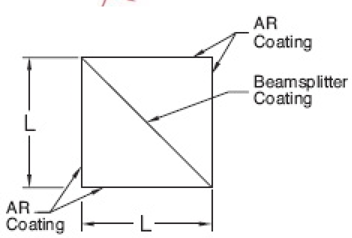
Malus' Law:
$I = I_0 \cos^2\theta$

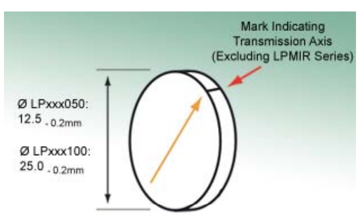
where θ is angle between polarizers

Various Polarizers

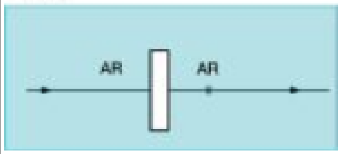
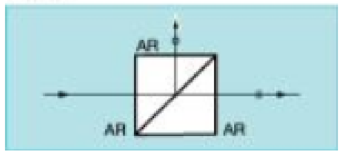
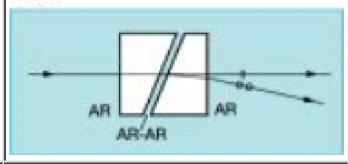
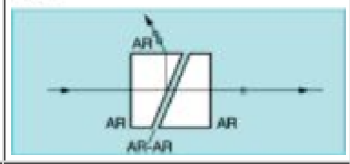
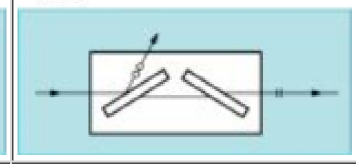
Type	Spectral Width nm	Extinction Ratio	Minimum Field of View, deg
Birefringent Prism	2000	10^5	3
Dielectric Stack Cube	300-400	10^2 - 10^3	No spec ~5
Dichroic	30-1000	10^4-10^5	±20



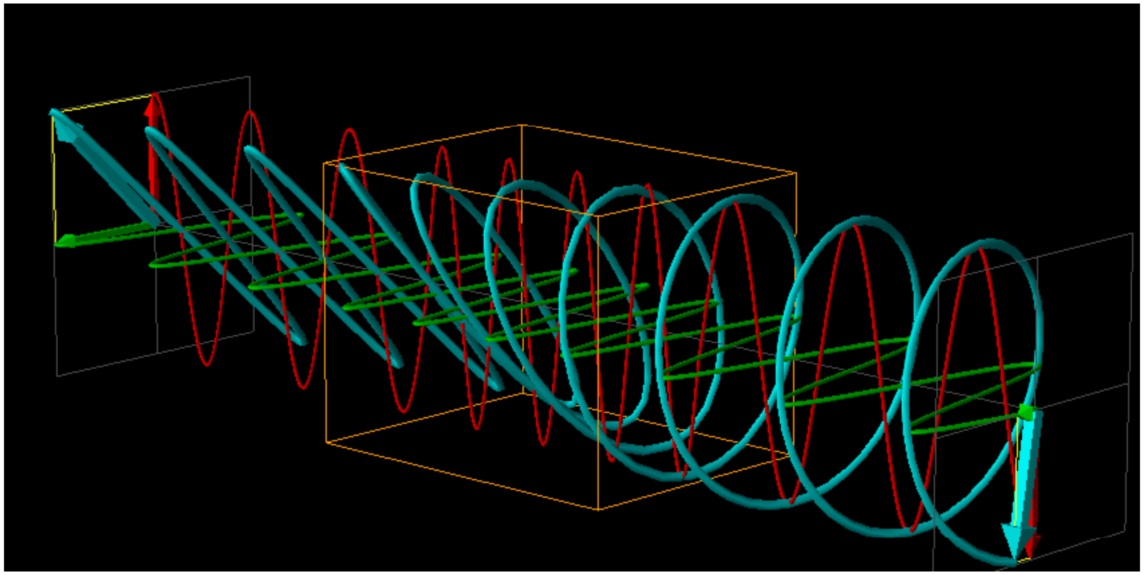




Polarizer Power Handling Limits

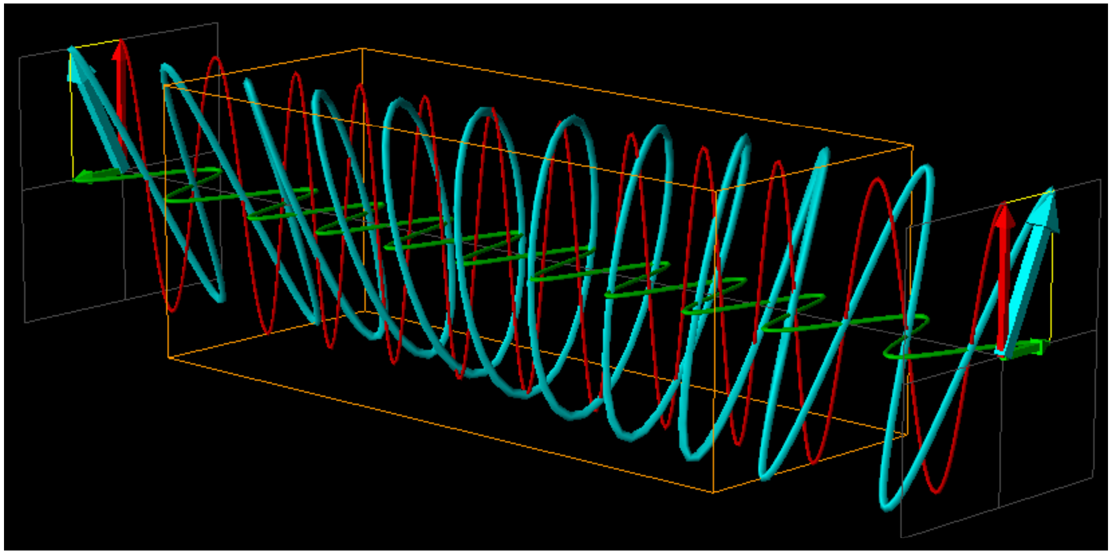
VLP	PBS	LP	HP	VHP
				
Very Low Power absorptive film polarizer. Smallest package and usually least expensive.	Polarizing Beam Splitter cube. Low power applications. Good for injection locking applications.	Low Power Glan-type crystal polarizer. Larger package size but very high transmission.	High Power Glan-type crystal polarizer. Larger package size but very high transmission.	Very High Power Brewster window polarizer. Highest power possible, largest package, narrowband, lower cost than HP.
25 W/cm^2 (CW)	50 W/cm^2 (CW)	250 W/cm^2 (CW)	500 W/cm^2 (CW)	20 kW/cm^2 (CW)
300 kW/cm^2 (Pulsed)	-	25 MW/cm^2 (Pulsed)	200 MW/cm^2 (Pulsed)	1 GW/cm^2 (Pulsed)

Quarter Wave Retardation



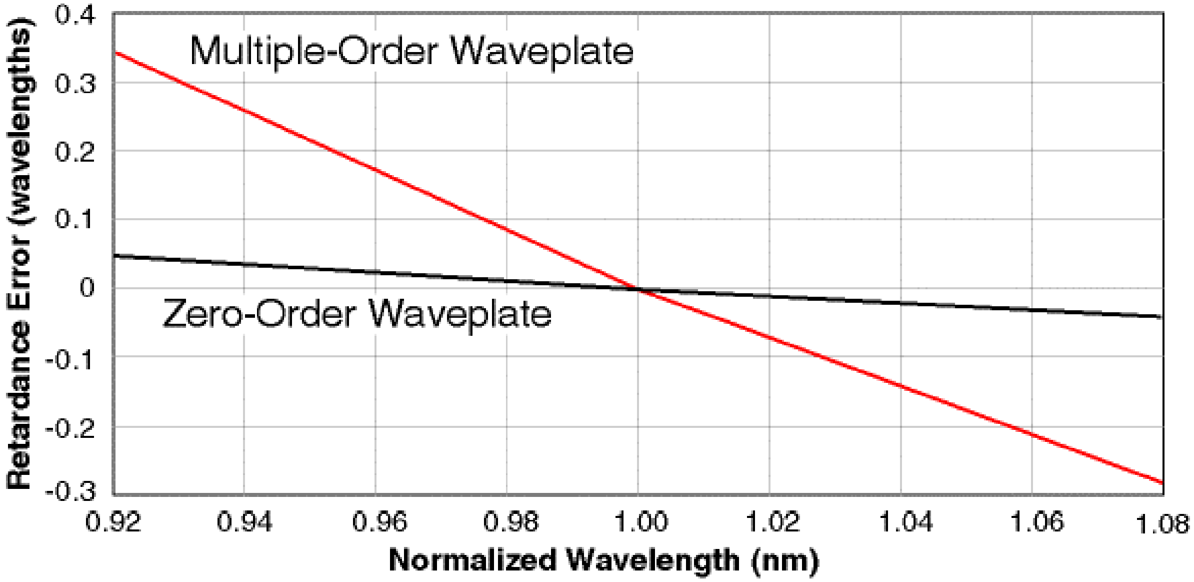
- Linear polarization in, oriented 45º to wave plate fast axis
- Differential delay leads to circular polarization out
- Reciprocity: Circular input produces linear output

Half Wave Retardation



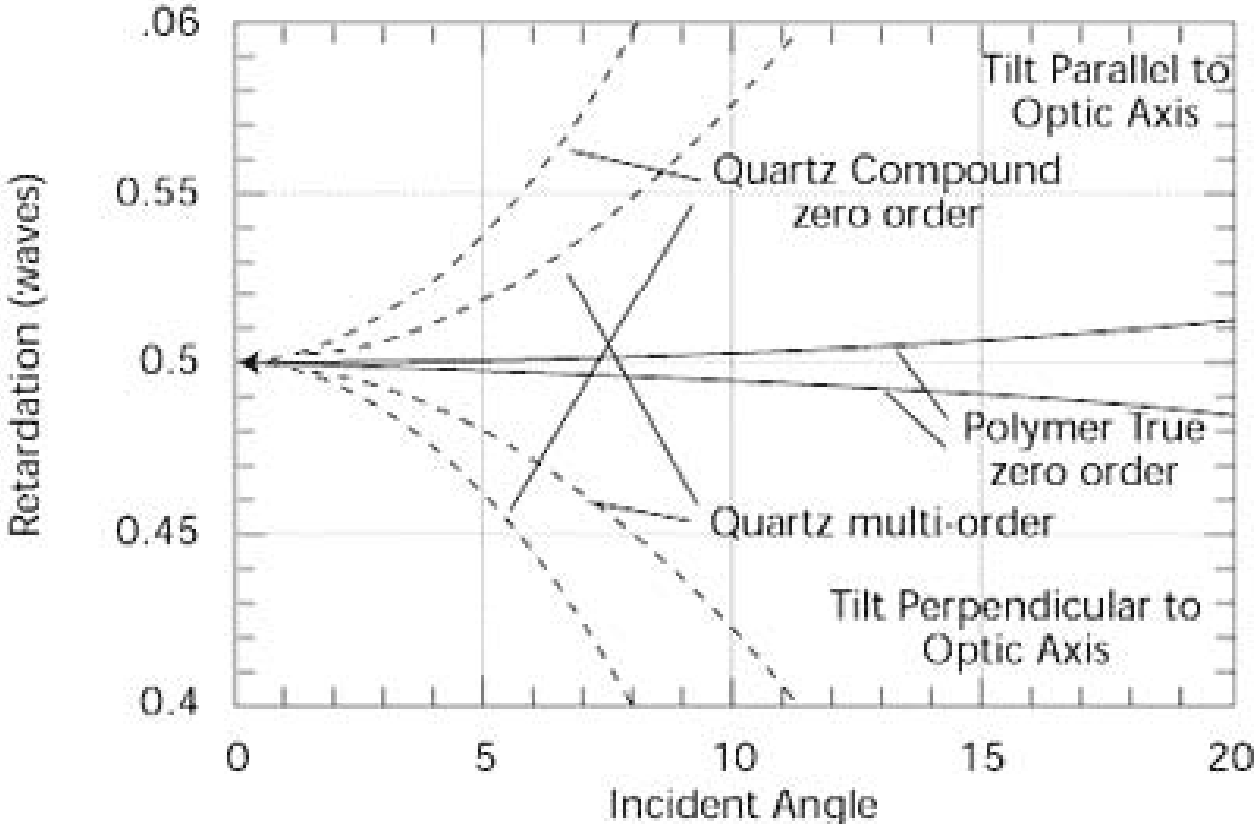
- Linear polarization in, oriented θ to wave plate fast axis
- Differential delay leads to 2θ rotation relative to input angle
- Reciprocity: Backwards propagation reproduces original beam

Wavelength Sensitivity



Multiple order waveplates eg. $(2m+1)\lambda/4$:Cheaper, more robust, but higher wavelength sensitivity, poorer optical quality

Waveplate Angle Sensitivity



Fiber Polarizers

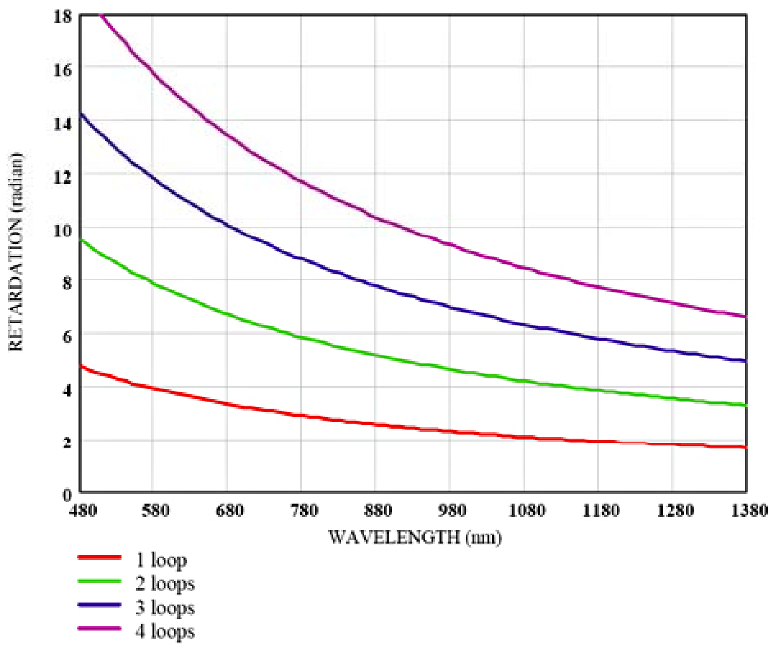


FIGURE C: Retardation vs Wavelength with Ø125 µm Cladding SMF

- Stress induced birefringence
- 1 loop = quarter wave retardation
- Rotate paddle to adjust fast axis
- 1st paddle: makes light linear
- 2d paddle: rotates linear axis
- 3rd paddle: makes light elliptical

Faraday Effect

Rotation of polarization axis due to a magnetic field

$$\theta = \int B(x) V dx$$

θ = Rotation angle

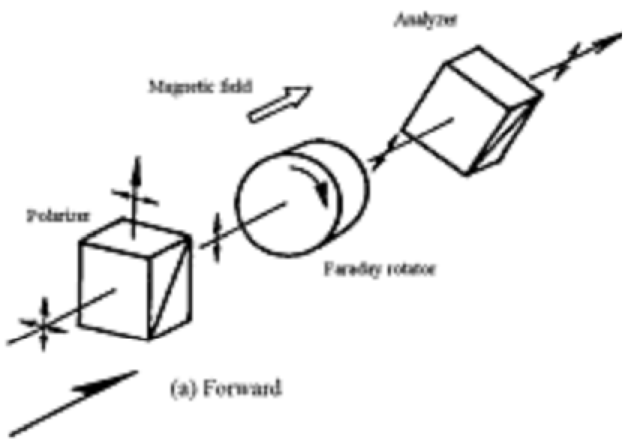
B = magnetic field component parallel to propagation

V = Verdet constant, radians/Tesla-m

dx = infinitesimal path length through rotator

Nonreciprocal: fixed viewer sees clockwise rotation whether light propagates forward or backward

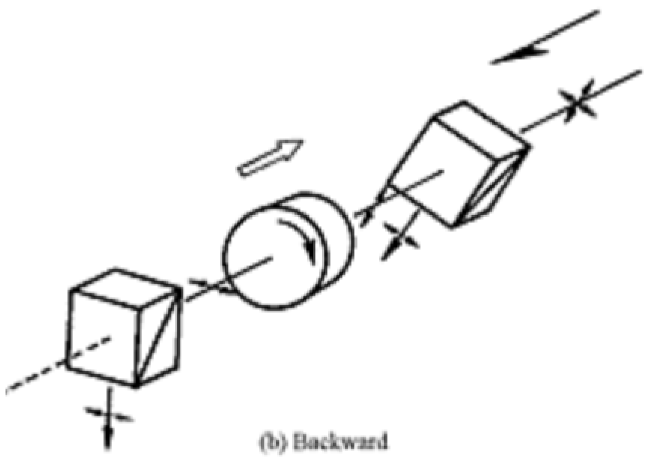
Faraday Isolator Operation



(a) Forward

Forward direction:

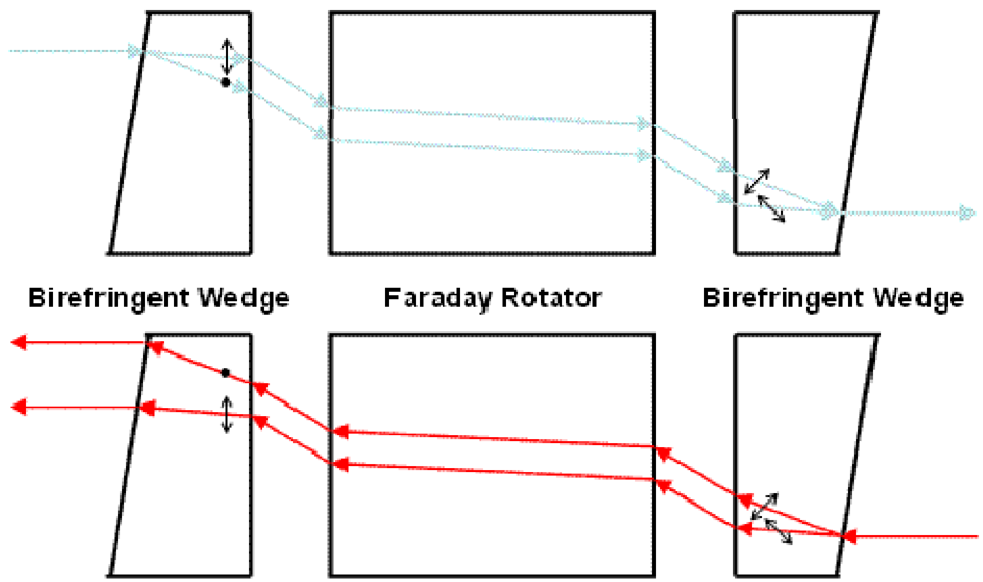
- Input polarizer selects linear component
- Faraday rotator rotates E field 45º
- Output polarizer oriented to pass 45º beam


(b) Backward

Reverse direction:

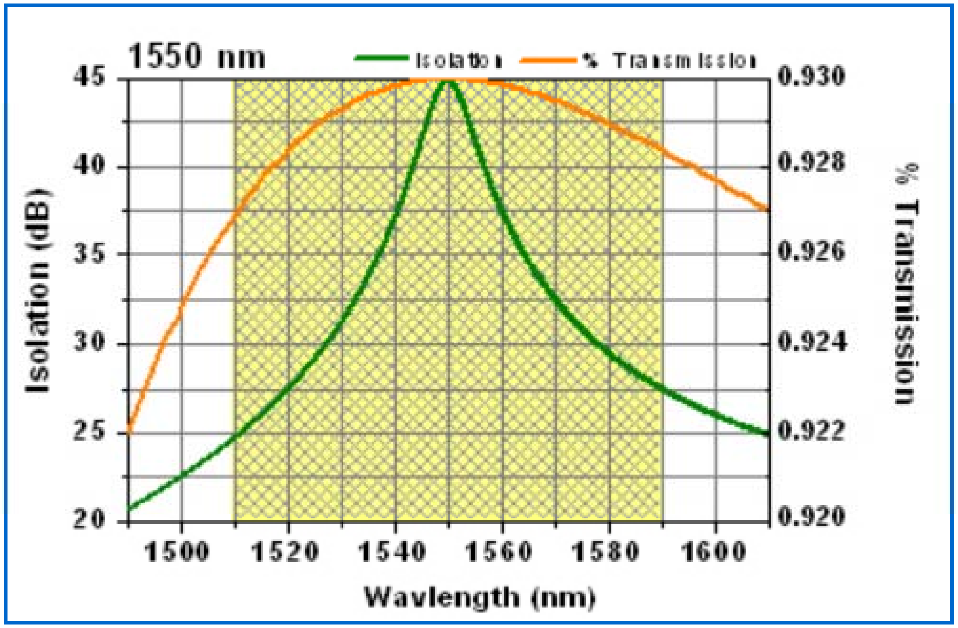
- Output polarizer selects linear component
- Faraday rotator adds <u>additional</u> 45º
- Input polarizer blocks backward transmission

Polarization Independent Isolator



- No power penalty as input polarization drifts
- Forward: Birefringent wedges split then recombine beam
- Reverse: Birefringent wedges split and separate rotated beam

Isolator Performance



- Faraday rotation is dispersive
- Tune via magnetic field
- Compensate with quartz plate

Item#	Wavelength[a]	Max Power	Isolation	Insertion Loss	PDL	PER[b]	Return Loss	Fiber
250 - 300 mW Polarization-Independent Fiber Isolators								
IO-H-1064	1064 +20/-4 nm	250 mW	≥33 dB[c]	1.4 - 2.0 dB	≤0.20 dB	–	>55 dB	HI1060
IO-H-1310	1310 ± 15 nm	300 mW	35 - 40 dB	0.3 - 0.7 dB	≤0.1 dB	–	>55 dB	SMF-28e
IO-H-1550	1550 ± 15 nm	300 mW	35 - 40 dB	0.3 - 0.7 dB	≤0.1 dB	–	>55 dB	SMF-28e

Credits

- www.newport.com/
- www.cvimellesgriot.com
- www.meadowlarkoptics.com
- http://en.wikipedia.org/wiki/Polarizer
- http://en.wikipedia.org/wiki/Optical_isolator
- www.thorlabs.com
- http://www.enzim.hu/~szia/emanim/emanim.htm

- Yariv, A., Optical Electronics
- Hecht and Zajac, Optics