Polarization of Light

- Polarization states
- Stokes Vectors
- Mueller Matrices
- Jones Matrices
- Components
- Examples
Polarization states

Linear states of polarization

Linear x polarized
\[ |E_x| \neq 0 , \quad |E_y| = 0 \]

Linear y polarized
\[ |E_x| = 0 , \quad |E_y| \neq 0 \]

Linear -45° polarized
\[ |E_x| = |E_y| , \quad \phi_y - \phi_x = \pi \]

Linear θ polarized
\[ |E_x| \neq |E_y| , \quad \phi_y - \phi_x = 0 , \pi \]

\textit{O’Shea 1.6, Saleh & Teich 6}
Polarization states

Elliptical states of polarization

Right-hand circular

\[ |E_x| = |E_y|, \phi_y - \phi_x = \frac{\pi}{2} \]

Left-hand circular

\[ |E_x| = |E_y|, \phi_y - \phi_x = -\frac{\pi}{2} \]

Elliptical

\[ |E_x| \neq |E_y|, \quad \text{and/or} \]

\[ \phi_y - \phi_x \neq \pm \frac{\pi}{2} \]
Stokes vectors
Complete description of polarization state

Perform 6 \underline{irradiance} measurements with \underline{ideal} polarizers:

\begin{align*}
E_x & \quad \text{Horizontal linear} \\
E_y & \quad \text{Vertical linear} \\
E_{45} & \quad 45^\circ \text{ linear} \\
E_{135} & \quad 135^\circ \text{ linear} \\
E_R & \quad \text{Right circular} \\
E_L & \quad \text{Left circular}
\end{align*}

\[
\vec{S} = \begin{bmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{bmatrix} = \begin{bmatrix}
E_H + E_V \\
E_H - E_V \\
E_{45} - E_{135} \\
E_R - E_L
\end{bmatrix}
\]
Stokes vectors
Complete description of polarization state

\[ H = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 0 \end{bmatrix} \]

\[ 45 = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \]

\[ R = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} \]

\[ \begin{bmatrix} 1 \\ 0 \\ .8 \\ .6 \end{bmatrix} \]

\[ V = \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} \]

\[ 135 = \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix} \]

\[ L = \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix} \]
Poincarè sphere

Useful visualization of Stokes parameters

\[ S_{i} \cdot S_{j} = S_{i1} S_{j1} + S_{i2} S_{j2} + S_{i3} S_{j3} \]

- Surface is polarized, center is unpolarized
- Equator is linear polarized
- North hemisphere is right elliptical, south is left elliptical
- Orthogonal polarizations are on opposite points of sphere
Stokes vectors

Degree of polarization

\[ DoCP = \frac{S_3}{S_0} \]

Degree of circular polarization

\[ DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \]

Degree of linear polarization

\[ DoP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \]

Degree of polarization

Stokes vectors are polychromatic on addition:

\[ \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 0 \end{bmatrix} \]

H + V at different frequencies give Lissagous figure with no average polarization state

\[ \begin{bmatrix} 2 \\ 2 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \\ 0 \\ 0 \end{bmatrix} \]

2H + V = H polarized DoP = 1/3
Mueller Matrics
Complete polarization modeling

4x4 matrix of real values describing transformation of polarizations. Can describe de-polarizing elements. Eigenvectors are eigenpolarization of system (unchanged).

E.g. Linear polarizer

\[
\begin{bmatrix}
\frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\begin{bmatrix}
1 \\
1
\end{bmatrix}
= \begin{bmatrix}
1 \\
0
\end{bmatrix}
\]

Moral: We are going to use Jones vectors/matrices to do designs, but you should know their limitations. Jones vectors deal only with systems with perfect temporal and spatial coherence. Systems with finite coherence can be partially polarized and then you must use Mueller matrices and Stokes parameters.
Jones vectors
Simplified for fully polarized systems

\[ \bar{J} \equiv \begin{bmatrix} A_x \\ A_y \end{bmatrix} \]
where \( A_x \) and \( A_y \) are the complex amplitudes of the x and y polarized electric fields.

\[ J_1 \cdot J_2 \equiv A_{1x} A_{2x}^* + A_{1y} A_{2y}^* \]
Inner product

\[ H \equiv \begin{bmatrix} 1 \\ 0 \end{bmatrix} \]
\[ V \equiv \begin{bmatrix} -1 \\ 1 \end{bmatrix} \]

\[ 45 \equiv \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \]
\[ 135 \equiv \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} \]

\[ R \equiv \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ j \end{bmatrix} \]
\[ L \equiv \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -j \end{bmatrix} \]
### Table of Jones and Mueller matrices

<table>
<thead>
<tr>
<th>Linear optical element</th>
<th>Jones matrix</th>
<th>Mueller matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal linear polarizer</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; 1 &amp; 0 &amp; 0 \ 1 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Vertical linear polarizer</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 1 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; -1 &amp; 0 &amp; 0 \ -1 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Linear polarizer at $+45^\circ$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; 1 \ 1 &amp; 1 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Linear polarizer at $-45^\circ$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; -1 \ -1 &amp; 1 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; 0 &amp; -1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ -1 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Quarter-wave plate, fast axis vertical $e^{i\pi/4}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; -i \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>Quarter-wave plate, fast axis horizontal $e^{i\pi/4}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; i \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>Homogeneous circular polarizer right $\bigcirc$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; i \ -i &amp; 1 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; 1 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 1 &amp; 0 &amp; 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>Homogeneous circular polarizer left $\bigcirc$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; -i \ i &amp; 1 \end{bmatrix}$</td>
<td>$\frac{1}{2} \begin{bmatrix} 1 &amp; 0 &amp; 0 &amp; -1 \ 0 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 \ -1 &amp; 0 &amp; 0 &amp; 1 \end{bmatrix}$</td>
</tr>
</tbody>
</table>
Rotation matrices
Components not aligned with x or y

\[ \vec{J}' = R(\theta)\vec{J} \]

\[ R(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \]

\[ T' = R(\theta)T R(-\theta) \]

Transform for Jones Vectors
Coordinate Transform Matrix
Transform for Jones Matrices
Three types of physics

1. Diattenuation (polarization dependent loss)
   - Transmission is polarization dependent
   - “Polarizers”
   - A.k.a.: polarization dependent loss (PDL), dichroism

2. Retardance
   - Optical path length is polarization dependent.
   - “Wave plates”, optical activity, electro-optic
   - A.k.a.: polarization mode dispersion (PMD)
   - Poincarè sphere geometry

3. Depolarization
   - The degree of polarization may decrease depending on input polarization
   - A.k.a.: polarization scrambling
Polarizers

\[ P_x \equiv \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \]

Jones matrix of linear polarizer passing H

Power transmission of analyzer and arbitrary linear polarization:

\[ J_{Out} = P_x L(\theta) = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} = \begin{bmatrix} \cos \theta \\ 0 \end{bmatrix} \]

\[ T = J_{Out} \cdot J_{Out} = \cos^2 \theta \quad \text{Malus’ Law} \]

Dichroism: polarization dependent absorption

\[ P_x \equiv \begin{bmatrix} e^{-\alpha z} & 0 \\ 0 & e^{-\beta z} \end{bmatrix} \]

E.g.: Sheet polarizer, polarizing sunglasses, Polarcor\textsuperscript{TM}, wire-grid

Reflective polarizers: Brewster’s angle, thin-film coatings

Crystal polarizers

E.g.: Wollaston, Rochon, Sénarmont

E.g.: Glan-Focault
Jones matrix example
Cascaded polarizers

Crossed polarizers:

\[ E_1 = A_y A_x E_0 \]

\[
A_y A_x = \begin{bmatrix}
0 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 0
\end{bmatrix}
= \begin{bmatrix}
0 & 0 \\
0 & 0
\end{bmatrix}
\]

so no light leaks through.

Rotation tolerance

\[
A_y A_x(\epsilon) = \begin{bmatrix}
0 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \epsilon \\
\epsilon & 0
\end{bmatrix}
= \begin{bmatrix}
0 & 0 \\
\epsilon & 0
\end{bmatrix}
\]

\[
A_y A_x(\epsilon) \begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
= \begin{bmatrix}
0 & 0 \\
\epsilon & 0
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
= \begin{bmatrix}
0 \\
\epsilon E_x
\end{bmatrix}
\]

So \( I_{out} \approx \epsilon^2 I_{in,x} \)
Retarders

\[
R \equiv \begin{bmatrix} 1 & 0 \\ 0 & e^{-j\Gamma} \end{bmatrix}
\]

Jones matrix of retarder with fast axis in x

\[
\Gamma = \frac{2\pi}{4} = \frac{\pi}{2}
\]

\[
\Gamma = \frac{2\pi}{2} = \pi
\]

\[
\frac{1}{n^2(\theta)} = \left\{ \frac{1}{n_o^2}, \frac{\cos^2 \theta}{n_o^2} + \frac{\sin^2 \theta}{n_e^2} \right\}
\]

E.g. Half-wave plate.

\[
\Gamma = \frac{2\pi}{\lambda_o} \left( n_e - n_o \right) L = \pi
\]

\[
L = \frac{\lambda_o}{2 \Delta n}
\]

Quarter-wave plate. Converts linear into circular.

Half-wave plate. Converts linear into linear.

Quartz QWP is only 48 microns thick at 1550 nm.
Crossing plates of differing dispersion can reduce \(\lambda, \theta\) dependence
Power walk-off

Consider a Fourier propagation problem in which the k-surface is a tilted line:

\[ E(x, z) = F_x^{-1} \left\{ F_x^1 \{ E(x,0) \} e^{-j \frac{dk_z}{dk_x} k_x z} \right\} \]

\[ = E \left( x - \frac{dk_z}{dk_x} z, 0 \right) \]

Fourier propagator

Shift theorem

Poynting vector is normal to k surface
Beam displacing polarizer

Separates polarizations with very high isolation (limited only by crystal scatter). Emerging polarizations are parallel to a very high degree since the crystal can be flat to an arc-second.
Beam displacing polarizer

\[ \alpha = \arctan \left[ \frac{n_o^2}{n_e^2} \tan \theta \right] - \theta \quad \text{Walk-off angle vs. crystal cut angle} \]

\[ \theta_{\text{maxBD}} = \arctan \left( \frac{n_e}{n_o} \right) \quad \text{Crystal orientation for maximum walk-off} \]

\[ n_e (\theta_{\text{maxBD}}) = \left[ \frac{\cos^2 \theta}{n_o^2} + \frac{\sin^2 \theta}{n_e^2} \right]^{-1/2} = \sqrt{\frac{n_o^2 + n_e^2}{2}} \quad \text{Phase velocity at this propagation angle} \]

\[ \Delta n = \left( \sqrt{\frac{n_o^2 + n_e^2}{2}} - n_o \right) \]

\[ = \left( \sqrt{\frac{1.9447^2 + 2.1486^2}{2}} - 1.9447 \right) = 0.1045 \quad \text{YVO}_4 \text{ at } 1.55 \mu\text{m} \]
Poincarè and retarders

- Retarders rotate the polarization state on the Poincarè sphere.
- Axis of rotation connects *eigenpolarizations* of the retarder.

**Example 1:** QWP with horizontal axis converts 45° linear into RHC

**Example 2:** Optically active (or Faraday) rotator converts H to 45°
Useful combinations

Circular polarizer

Adjustable linear polarizer

Adjustable transmission

Babinet-Soleil adjustable retarder
Optical activity
Retarders with circular eigenstates

\[
OA \equiv \begin{bmatrix}
\cos \frac{\delta}{2} & \sin \frac{\delta}{2} \\
-\sin \frac{\delta}{2} & \cos \frac{\delta}{2}
\end{bmatrix}
\]
Wollaston

- Wollaston polarizer is made of two birefringent material prisms that are cemented together. The deviations of the ordinary and extraordinary beams are nearly symmetrical about the input beam axis. The separation angle exhibits chromatic dispersion, as shown in the blow. Any separation angle can be designed upon the requirement. Typical separation angle vs wavelength is shown in the plot below for Calcite.

Extinction Ratio: $5 \times 10^{-6}$
Beam Separation Angle: 16.7-22.5 at 980nm
Faraday Rotator

- A Faraday rotator is an optical device that rotates the polarization of light due to the Faraday effect, which in turn is based on a magneto-optic effect.
- The Faraday rotator works because one polarization of the input light is in ferromagnetic resonance with the material which causes its phase velocity to be higher than the other.
- The plane of linearly polarized light is rotated when a magnetic field is applied parallel to the propagation direction (permanent magnets). The empirical angle of rotation is given by:

\[ \beta = VBd \]

Where \( \beta \) is the angle of rotation (in radians), \( B \) is the magnetic flux density in the direction of propagation (in teslas), \( d \) is the length of the path (in metres) where the light and magnetic field interact. Then \( V \) is the Verdet constant for the material. This empirical proportionality constant (in units of radians per tesla per metre, \( \text{rad/(T\cdot m)} \)) varies with wavelength and temperature and is tabulated for various materials.
- Note that direction of rotation given by sign of \( B \) Rotation is independent of propagation direction (NOT like waveplate)
- Faraday rotators are used in optical isolators to prevent undesired back propagation of light from disrupting or damaging an optical system.
Polarization Dependent Isolator

- The polarization dependent isolator, or Faraday isolator, is made of three parts, an input polarizer (polarized vertically), a Faraday rotator, and an output polarizer, called an analyzer (polarized at 45 degrees).
- Light traveling in the forward direction becomes polarized vertically by the input polarizer. The Faraday rotator will rotate the polarization by 45 degrees. The analyser then enables the light to be transmitted through the isolator.
- Light traveling in the backward direction becomes polarized at 45 degrees by the analyzer. The Faraday rotator will again rotate the polarization by 45 degrees. This means the light is polarized horizontally (the rotation is insensitive to direction of propagation). Since the polarizer is vertically aligned, the light will be extinguished.
Nonreciprocal optics
aka Faraday rotators

Example: Polarization independent isolator

Similar optics can form a pseudo-circulator:
Design notation for polarization manipulation

View of polarization as if looking into laser. This is the EE convention and yields RHC with thumb pointing into viewers eyes, along with laser. To use the Physics convention, consider view as with laser.
Polarization Independent Isolator
Another example
Spatial phase-shifting interferometer

PBS  HWP @ 22.5°  Vertical beam displacer

Combine  Rotate  Interfere

Height of propagation

Many thanks to Bill Chang for teaching me this notation.
PBS Example

<table>
<thead>
<tr>
<th>Material</th>
<th>SF 2, NSSK grade, precision annealed optical glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavefront Distortion</td>
<td>( \pm \lambda/4 ) at 632.8 nm over the clear aperture</td>
</tr>
<tr>
<td>Clear Aperture</td>
<td>Central diameter, &gt;80% of dimension</td>
</tr>
<tr>
<td>Surface Quality</td>
<td>20-10 scratch-dig</td>
</tr>
<tr>
<td>Efficiency</td>
<td>( T_p &gt;80%, &gt;90% ) average, ( R_s &gt;99.5% ) average</td>
</tr>
<tr>
<td>Extinction Ratio</td>
<td>( T_m/T_s &gt;500:1, 1000:1 ) average</td>
</tr>
<tr>
<td>Transmitted Beam Deviation</td>
<td>( \pm 5 ) arc min</td>
</tr>
<tr>
<td>Reflected Beam Deviation</td>
<td>( 90^\circ \pm 5 ) arc min</td>
</tr>
<tr>
<td>Angle of Incidence</td>
<td>( 0^\circ \pm 5^\circ )</td>
</tr>
<tr>
<td>Dimensions Tolerance</td>
<td>( \pm 0.25 ) mm</td>
</tr>
<tr>
<td>Antirefection Coating</td>
<td>Broadband, multilayer coating, ( R_{ave} &lt;1.0% ) per surface</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-50 °C–90 °C</td>
</tr>
<tr>
<td>Durability</td>
<td>MIL-C-675C</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Non-abrasive method, acetone or isopropyl alcohol on lens tissue recommended (see Care and Cleaning of Optics) Cemented optic, do not immerse in a solvent</td>
</tr>
<tr>
<td>Damage Threshold</td>
<td>2 kW/cm² CW, 1 J/cm² with 10 nsec pulses, typical</td>
</tr>
</tbody>
</table>

NOTE: To avoid damage, beam must enter prism on the side marked with a dot.

Newport Catalogue
Polarizers

Newport Catalogue
## Zero Order Waveplates

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value/Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retarder Material</td>
<td>Birefringent polymer film stack</td>
</tr>
<tr>
<td>Substrate Material</td>
<td>BK 7, grade A, fine annealed optical glass</td>
</tr>
<tr>
<td>Retardation</td>
<td>$\lambda/4$ or $\lambda/2$</td>
</tr>
<tr>
<td>Retardation Accuracy</td>
<td>$\pm \lambda/100$</td>
</tr>
<tr>
<td>Wavefront Distortion</td>
<td>$\leq \lambda/4$ at 632.8 nm over the full aperture</td>
</tr>
<tr>
<td>Clear Aperture</td>
<td>10.2 mm</td>
</tr>
<tr>
<td>Surface Quality</td>
<td>40-20 scratch-dig</td>
</tr>
<tr>
<td>Transmitted Beam Deviation</td>
<td>$\leq 1$ arc min</td>
</tr>
<tr>
<td>Acceptance Angle</td>
<td>$\pm 7^\circ$</td>
</tr>
<tr>
<td>Thickness</td>
<td>3.56 mm</td>
</tr>
<tr>
<td>Housing Diameter</td>
<td>25.4 ±0.13 mm</td>
</tr>
<tr>
<td>Housing Thickness</td>
<td>6.2 mm</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-20 °C to 50 °C</td>
</tr>
<tr>
<td>Antireflection Coating</td>
<td>Broadband, multilayer coating, $R_{\text{avg}} &lt; 0.5%$</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Non-abrasive method, acetone or isopropyl alcohol</td>
</tr>
<tr>
<td>Damage Threshold</td>
<td>500 W/cm$^2$ CW, 0.3 J/cm$^2$ with 10 nsec pulses, visible</td>
</tr>
<tr>
<td>Housing</td>
<td>Black anodized aluminum</td>
</tr>
</tbody>
</table>

For $\Gamma = \lambda/2$ the plate is called a "0" order half-wave plate. Thickness of the plate is:

$$d = \frac{\lambda}{2(n_e - n_o)}$$
Multiple order Waveplates

Must order for laser line
Incident angles must be close to normal
Multiple nulls with polarizer

<table>
<thead>
<tr>
<th>Material</th>
<th>Quartz, schlieren grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Single plate</td>
</tr>
<tr>
<td>Retardation</td>
<td>( \lambda/4 ) or ( \lambda/2 )</td>
</tr>
<tr>
<td>Retardation Accuracy</td>
<td>( \pm \lambda/300 ) at 20°C ( \pm 1°C )</td>
</tr>
<tr>
<td>Wavefront Distortion</td>
<td>( \pm \lambda/10 ) at 632.8 nm over the full aperture</td>
</tr>
<tr>
<td>Clear Aperture</td>
<td>( \geq ) central 90% of diameter</td>
</tr>
<tr>
<td>Surface Quality</td>
<td>10-5 scratch-dig</td>
</tr>
<tr>
<td>Wedge</td>
<td>( &lt;0.5 ) arc sec</td>
</tr>
<tr>
<td>Diameter Tolerance</td>
<td>( +0/-0.25 ) mm</td>
</tr>
</tbody>
</table>
| Reflectivity per Surface | Single wavelength: \( R <0.5\% \) total, or 0.25\% per surface  
                          | Dual wavelength: \( R_{av} <1.5\% \) |
| Thickness       | Single wavelength: 1 mm, nominal  
                          | Dual wavelength: 0.5–4 mm, nominal |
| Cleaning        | Non-abrasive method, acetone or isopropyl alcohol  
                          | on lens tissue recommended, caution: fragile, thin optic |
| Damage Threshold| 2 MW/cm² CW, 2 J/cm² with 10 nsec pulses |

Newport Catalogue