Understanding Waveplates

Terminology | **Fabrication** | **The Right Waveplate** | **Applications**

Waveplates, also known as retarders, transmit light and modify its polarization state without attenuating, deviating, or displacing the beam. They do this by retarding (or delaying) one component of polarization with respect to its orthogonal component. In unpolarized light, **waveplates** are equivalent to windows – they are both flat optical components through which light passes. Understanding waveplates as they pertain to polarized light is a bit more complex. To simplify the process, consider key terminology and specifications, fabrication, common types, and application examples.

WAVEPLATE TERMINOLOGY AND SPECIFICATIONS

Birefringence - Waveplates are made from birefringent materials, most commonly crystal quartz. Birefringent materials have slightly different indices of refraction for light polarized in different orientations. As such, they separate incident unpolarized light into its parallel and orthogonal components (Figure 1).
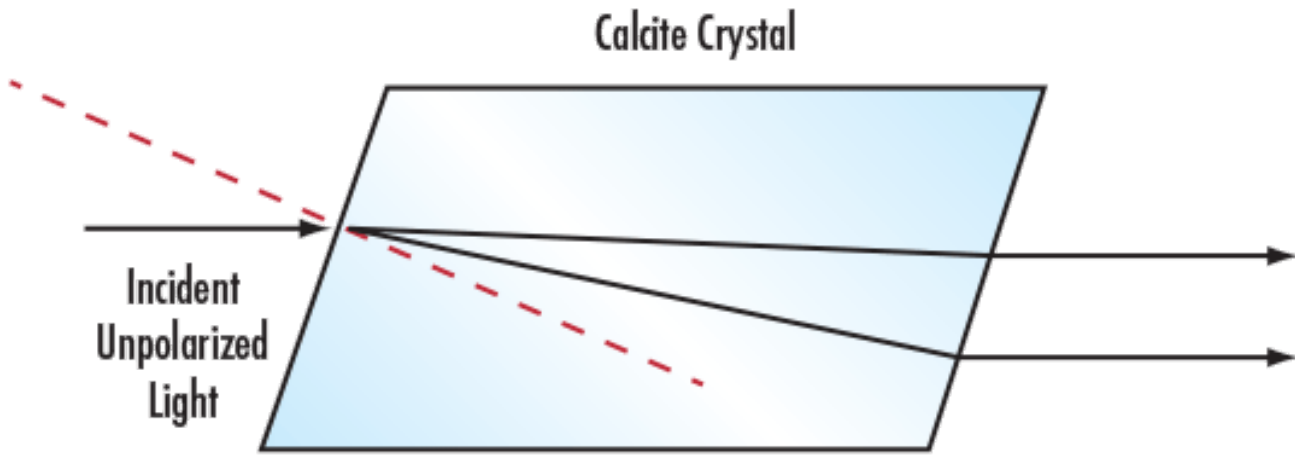
Figure 1: *Birefringent Calcite Crystal Separating Unpolarized Light*

Fast Axis and Slow Axis - Light polarized along the fast axis encounters a lower index of refraction and travels faster through waveplates than light polarized along the slow axis. The fast axis is indicated by a small flat spot or dot on the fast axis diameter of an unmounted waveplate, or a mark on the cell mount of a mounted waveplate.

Retardation – Retardation describes the phase shift between the polarization component projected along the fast axis and the component projected along the slow axis. Retardation is specified in units of degrees, waves, or nanometers. One full wave of retardation is equivalent to 360°, or the number of nanometers at the wavelength of interest. Tolerance on retardation is typically stated in degrees, natural or decimal fractions of a full wave, or nanometers. Examples of typical retardation specifications and tolerances are:
λ/4 ± λ/300
λ/2 ± 0.003λ
λ/2 ± 1°
430nm ± 2nm

The most popular retardation values are λ/4, λ/2, and 1λ, but other values can be useful in certain applications. For example, internal reflection from a prism causes a phase shift between components that may be troublesome; a compensating waveplate can restore the desired polarization.

Multiple Order – In multiple order waveplates, the total retardation is the desired retardation plus an integer. The excess integer portion has no effect on the performance, in the same way that a clock showing noon today looks the same as one showing noon a week later – although time has been added, it still appears the same.

Although multiple order waveplates are designed with only a single birefringent material, they can be relatively thick, which eases handling and system integration. The high thickness, though, makes multiple order waveplates more susceptible to retardation shifts caused by wavelength shift or ambient temperature changes.

Zero Order – In zero order waveplates, the total retardation is the desired value without excess. For example, **Quartz Zero Order Waveplates** consist of two multiple order quartz waveplates with their axes crossed so that the effective retardation is the difference between them.

The standard zero order waveplate, also known as a compound zero order waveplate, consists of multiple waveplates of the same birefringent material that have been positioned so that they are perpendicular to the optical axis. Layering multiple waveplates counterbalances the retardation shifts that occur in the individual waveplates, improving retardation stability to wavelength shifts and ambient temperature changes. Standard zero order waveplates do not improve retardation shift caused by a different angle of incidence.

True zero order waveplates, such as polymer waveplates, are comprised of a single birefringent material that has been processed into an ultra-thin plate that may be only a few microns thick in order to achieve a specific level of retardation at zero order. While the thinness of the plate may make handling or mounting the waveplate more difficult, true zero order waveplates offer superior retardation stability to wavelength shift, ambient temperature change, and a different angle of incidence than other waveplates.

Achromatic – Achromatic waveplates consist of two different materials that practically eliminate chromatic dispersion. Standard achromatic lenses are made from two types of glass, which are matched to achieve a desired focal length while minimizing or removing chromatic aberration. Achromatic waveplates operate on the same basic priniciple. For example, **Achromatic Waveplates** are made from crystal quartz and magnesium fluoride to achieve nearly constant retardation across a broad spectral band.

FABRICATION AND CONSTRUCTION

Fabrication

Waveplates are particularly challenging optical components to manufacture. They are made of crystalline materials that must be cut with their axes oriented within a few arcminutes. Then, they must be polished to a laser-quality finish, arcsecond parallelism, and <λ/10 wavefront. There is no room for correction, as their thickness tolerance is a small fraction of a micron. To verify retardation tolerances, specially-trained optical technicians use purpose-built test gear. After anti-reflective coating, zero order and achromatic waveplates are matched in pairs and accurately aligned to each other within their cell mounts.

Quartz waveplates are ideal for applications requiring high damage thresholds and retardation stability over temperature change, such as for use with lasers or infrared light sources.

Polymer waveplates consist of thin polymer sheets laminated between two glass plates, and provide many of the benefits of zero order designs including excellent angular field-of-view and lower sensitivity to incidence angles than comparable quartz waveplates. While the glass plates increase durability and ease handling, many polymer waveplates contain adhesive layers and are therefore not recommended for high power laser or high temperature applications.

Construction

Multiple order waveplates consist of a single plate, either unmounted or edge mounted to an aluminum cell. Two common construction methods exist for **Precision Zero Order Waveplates** and **Achromatic Waveplates**. The first method utilizes an air gap where the two plates, coated on all faces, are mounted on opposite sides of a spacer and then placed within a cell. Typical beam deviation is <0.5 arcseconds. It is important to note that power handling, especially for pulsed lasers, is highly suggested when using waveplates constructed with air gaps. The second method involves cementing achromatic lenses together with a transparent layer of optical cement across their full diameters. Then, an anti-reflection coating is applied to only their outer surfaces. Transmitted wavefront is <λ/4 at 633nm; beam deviation is <1 arcminute.

CHOOSING THE RIGHT WAVEPLATES

Multiple Order Waveplates

Consisting of a single plate of crystal quartz (nominally 0.5mm in thickness), multiple order waveplates are the least expensive of the three types. Their retardation changes versus temperature (Figure 2), and changes substantially versus wavelength (Figure 3). They are a good choice for use with monochromatic light in a climate-controlled environment. They are typically coupled with a **laser** in a laboratory. In contrast, applications such as mineralogy exploit the chromatic shift (retardance versus wavelength change) inherent in multiple order **waveplates**.

Multiple Order Waveplate: Retardance vs. Temperature
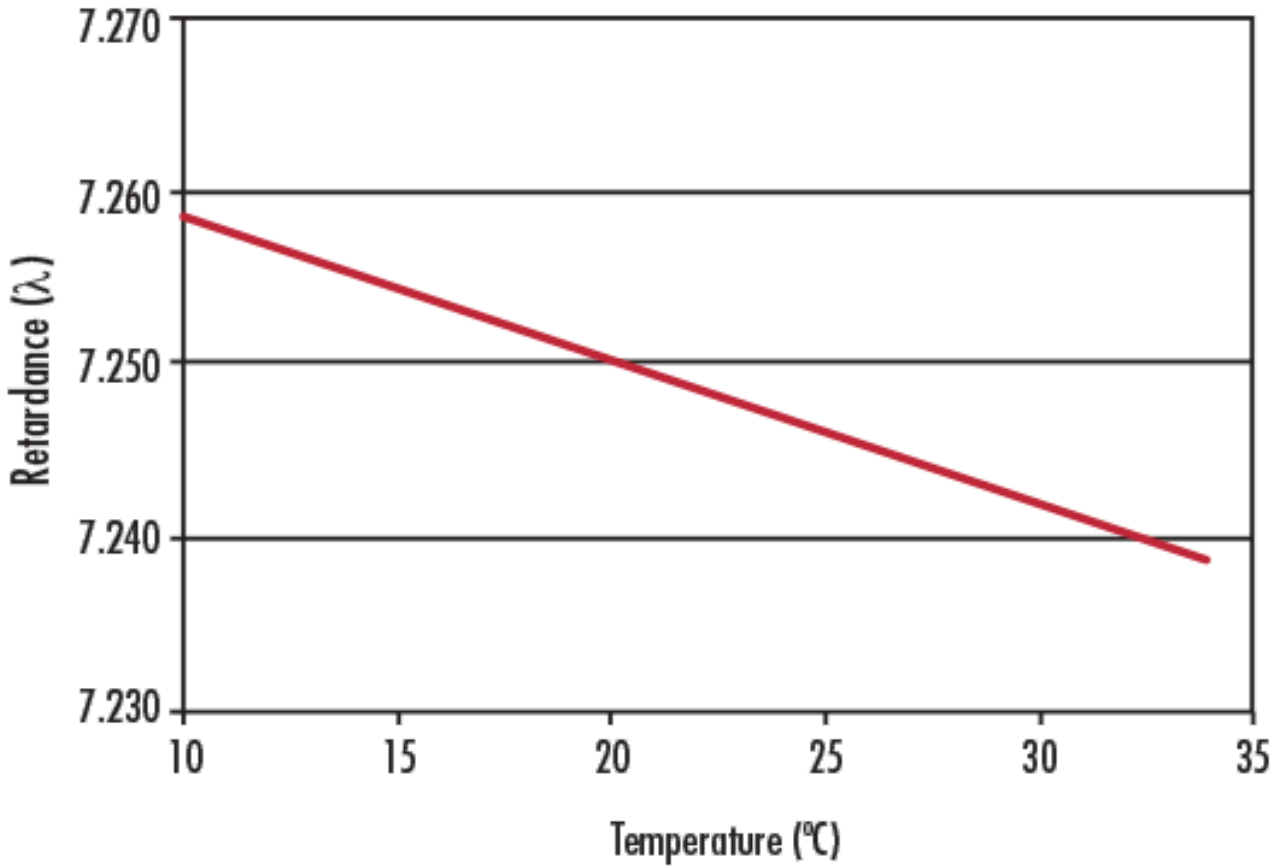
Figure 2: Retardance vs. Temperature for a 7.25λ Multiple Order Waveplate at 632.8nm

Multiple Order Waveplate: Retardance vs. Wavelength
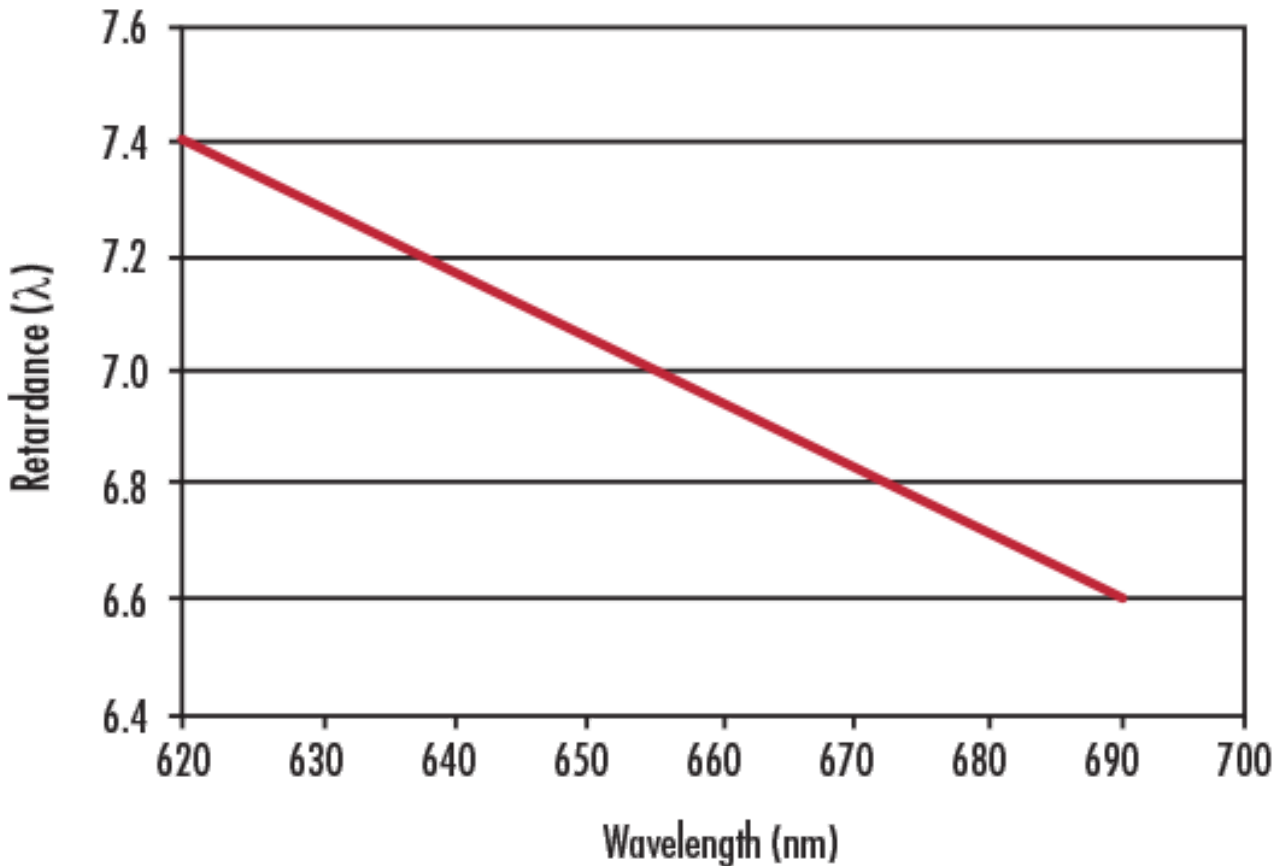

Figure 3: *Retardance vs. Wavelength for a 7.25λ Multiple Order Waveplate at 632.8nm*

Zero Order Waveplates

As their total retardation is a small percentage of the multiple order type, the retardation for zero order waveplates is far more constant with respect to temperature (Figure 4) and wavelength variations (Figure 5). In situations requiring greater stability or requiring greater temperature excursions, zero order waveplates are the ideal choice. Application examples include observing a broadened spectral wavelength, or taking measurements with an instrument used in the field.

Zero Order Waveplate:
Retardance vs. Temperature
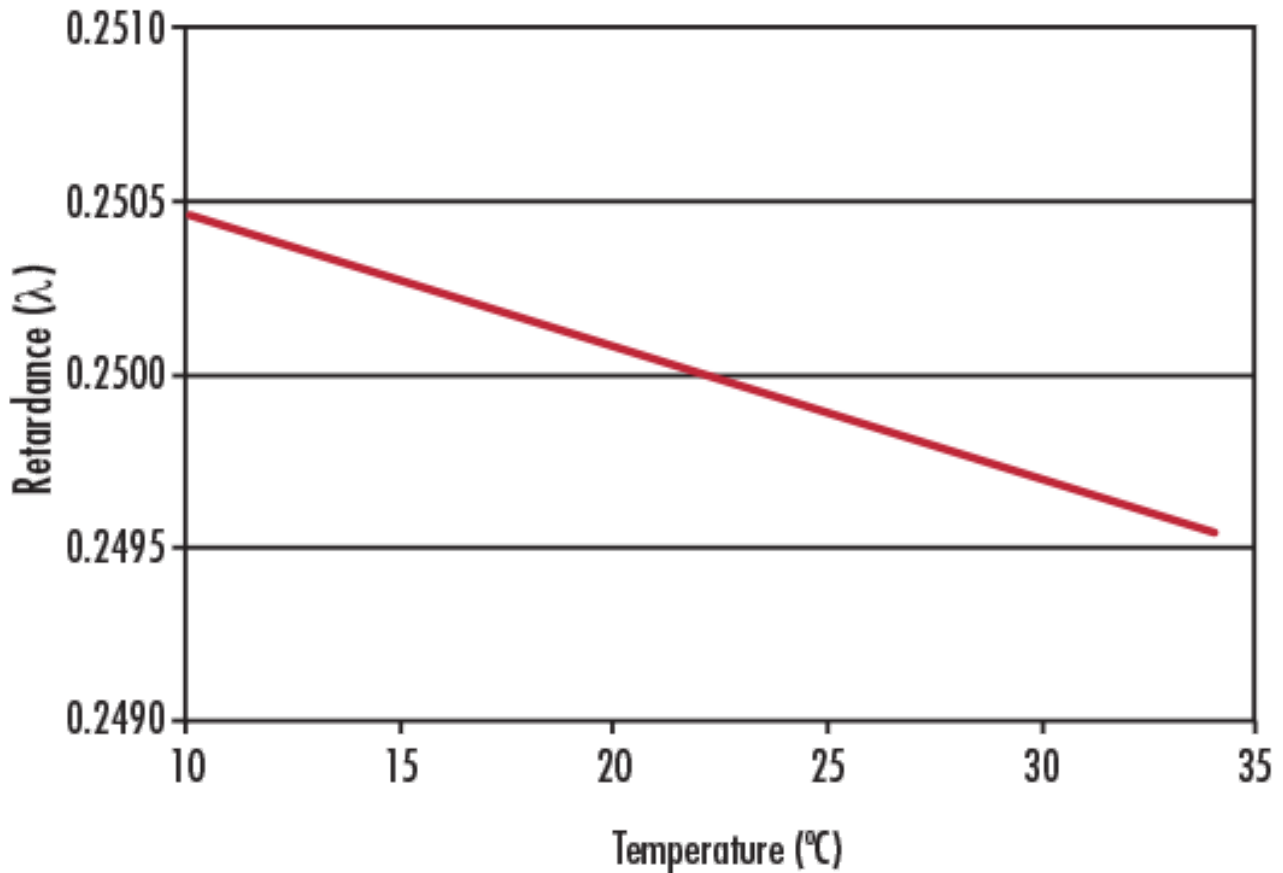
Figure 4: *Retardance vs. Temperature for a λ/4 Zero Order Waveplate at 632.8nm*
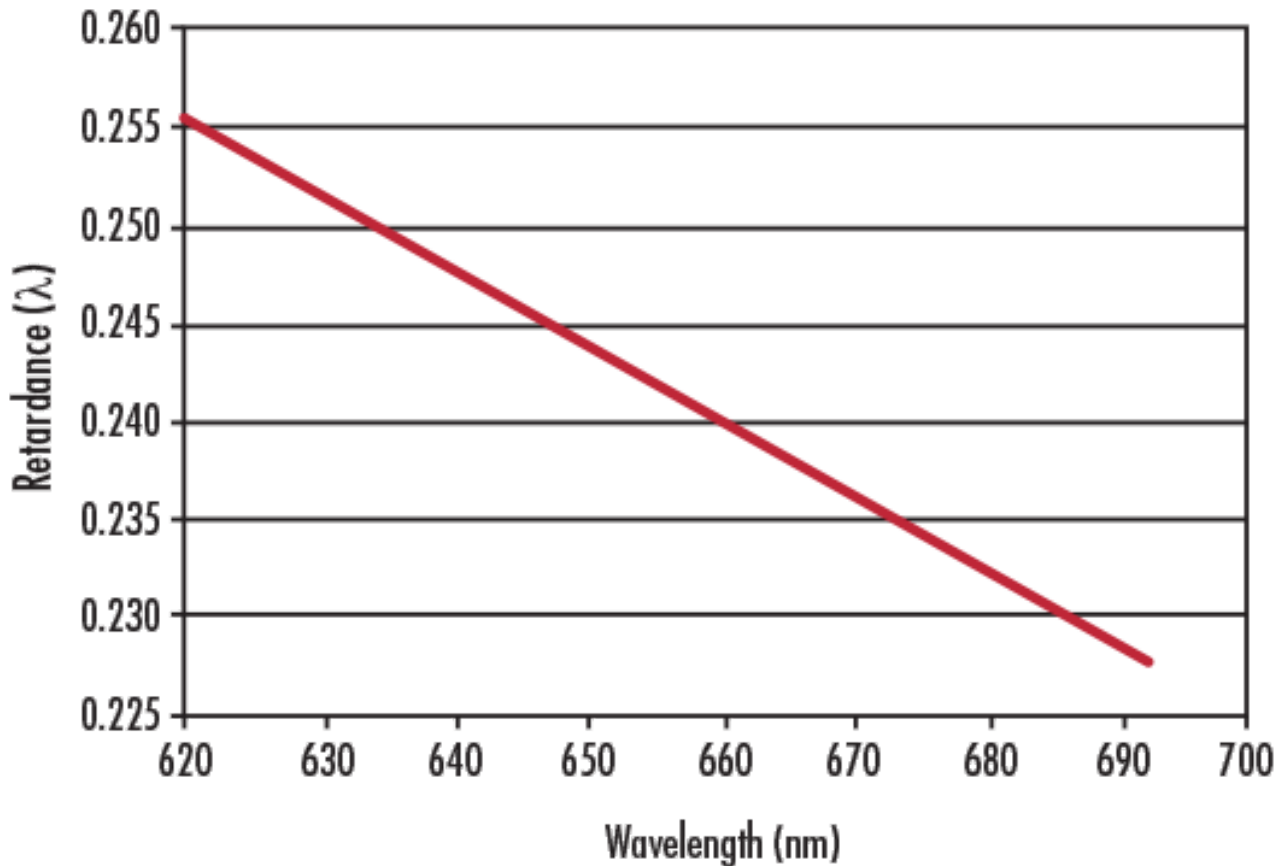
Zero Order Waveplate: Retardance vs. Wavelength

Figure 5: *Retardance vs. Wavelength for a λ/4 Zero Order Waveplate at 632.8nm*

Achromatic Waveplates

Due to the compensation of two materials, achromatic waveplates are far more constant than even zero order waveplates (Figure 6). If the situation covers several spectral wavelengths or an entire band (from violet to red, for example), achromatic waveplates are the ideal choices.

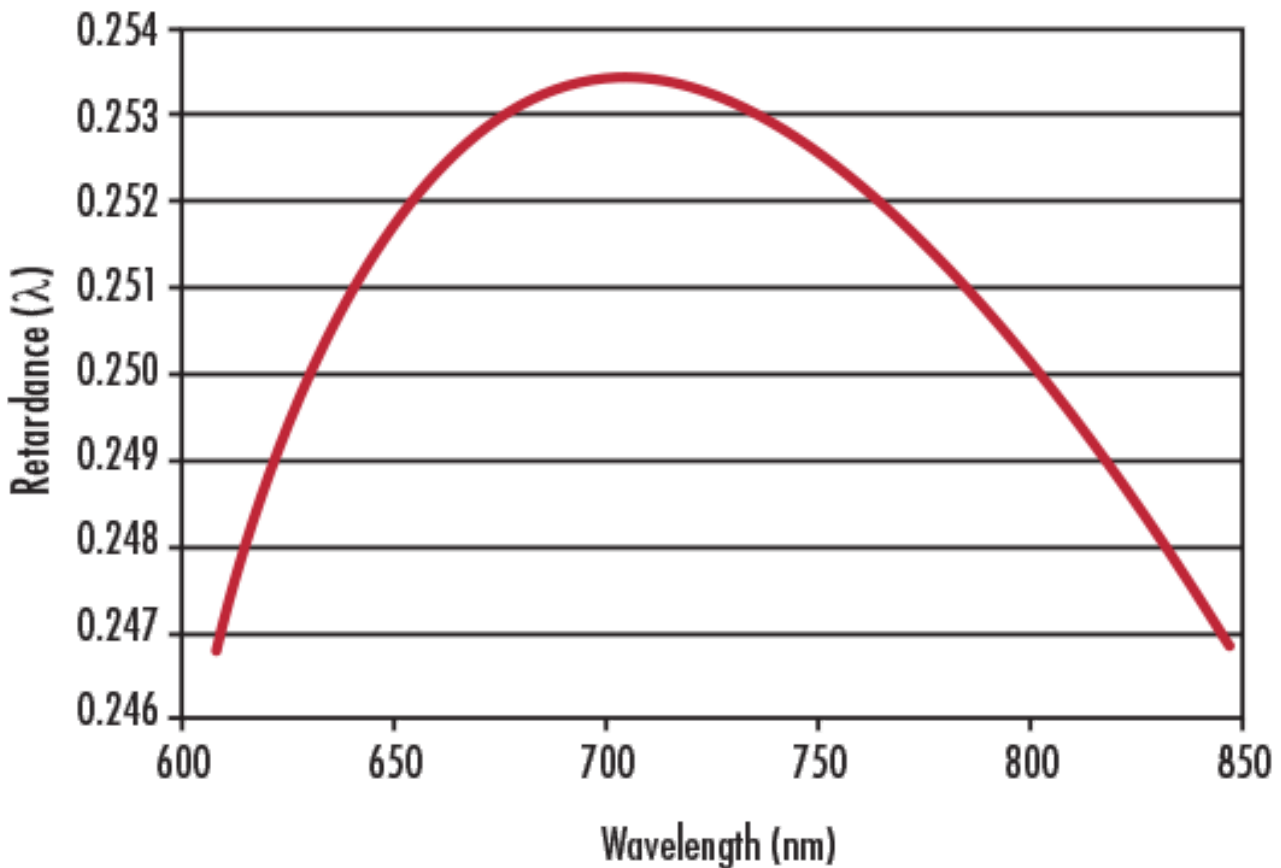## Achromatic Waveplate: Retardance vs. Wavelength

Figure 6: *Retardance vs. Wavelength for a 610 – 850nm Achromatic Waveplate*

APPLICATION EXAMPLES

Rotating Linear Polarization

It is sometimes necessary to alter the existing polarization of an optical system. For example, lasers are typically horizontally polarized. If the system calls for laser light to reflect off a metallic surface, then this can be a problem because mirrors work best with vertically polarized light. What is the solution? A λ/2 **waveplate** with its axes oriented at 45° will rotate the polarization to vertical.

Another example is when it is desirable to adjust the polarization axis to any other orientation. Rotating the waveplate axis an angle of θ from the incident polarization will rotate the exiting polarization by 2θ. Since waveplates are highly parallel, inserting or rotating a λ/2 waveplate can reconfigure an entire optical setup with no realignment.

Transforming between Linear and Circular Polarization

Linearly polarized light can be transformed into circularly polarized light, and vice versa, by orienting a linear polarizer and λ/4 waveplate in a certain way. For example, a λ/4 waveplate with its axes oriented at 45° to linear polarization produces circular polarization. Circular polarization, which is of indeterminate orientation, passing through a λ/4 waveplate produces linear polarization at 45° to the waveplate's axis. Additionally, if linearly polarized light enters a λ/4 waveplate at any angle besides 45°, it becomes elliptically polarized.

Optical Isolation with a Linear Polarizer

A linear polarizer plus a λ/4 waveplate creates an optical isolation system where light polarized by the linear polarizer passes through the λ/4 waveplate without attenuation but is transformed to circular polarization. If reflected from a mirror, the circularly polarized light encounters the waveplate again and is returned to linear polarization, but rotated 90° (Figure 7). Note: Two passes of a λ/4 are equivalent to one pass of a λ/2. The reoriented light is rejected by the linear polarizer. This system uses a double pass technique to remove feedback.
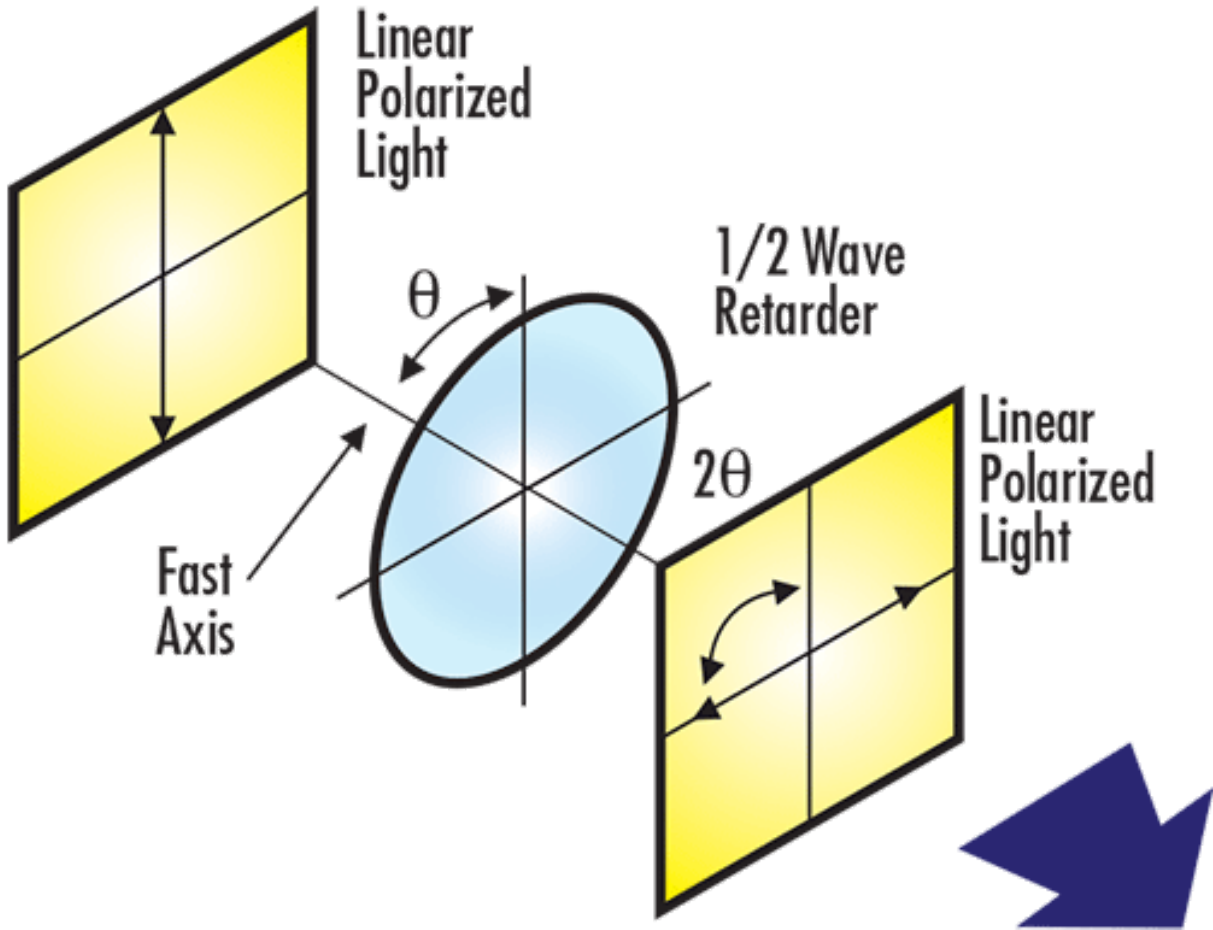
Figure 7: *Rotating Linear Polarization with a λ/2 Waveplate*

Optical Isolation with a Beamsplitter: Efficient Routing

A **polarizing beamsplitter** can be substituted for the linear polarizer in the optical isolation application example from Figure 7. This redirects the returning light into an alternate path without attenuation (Figure 8). By contrast, double pass through a non-polarizing beamsplitter only returns a theoretical maximum of 25% into the desired path and 25% into the other path.
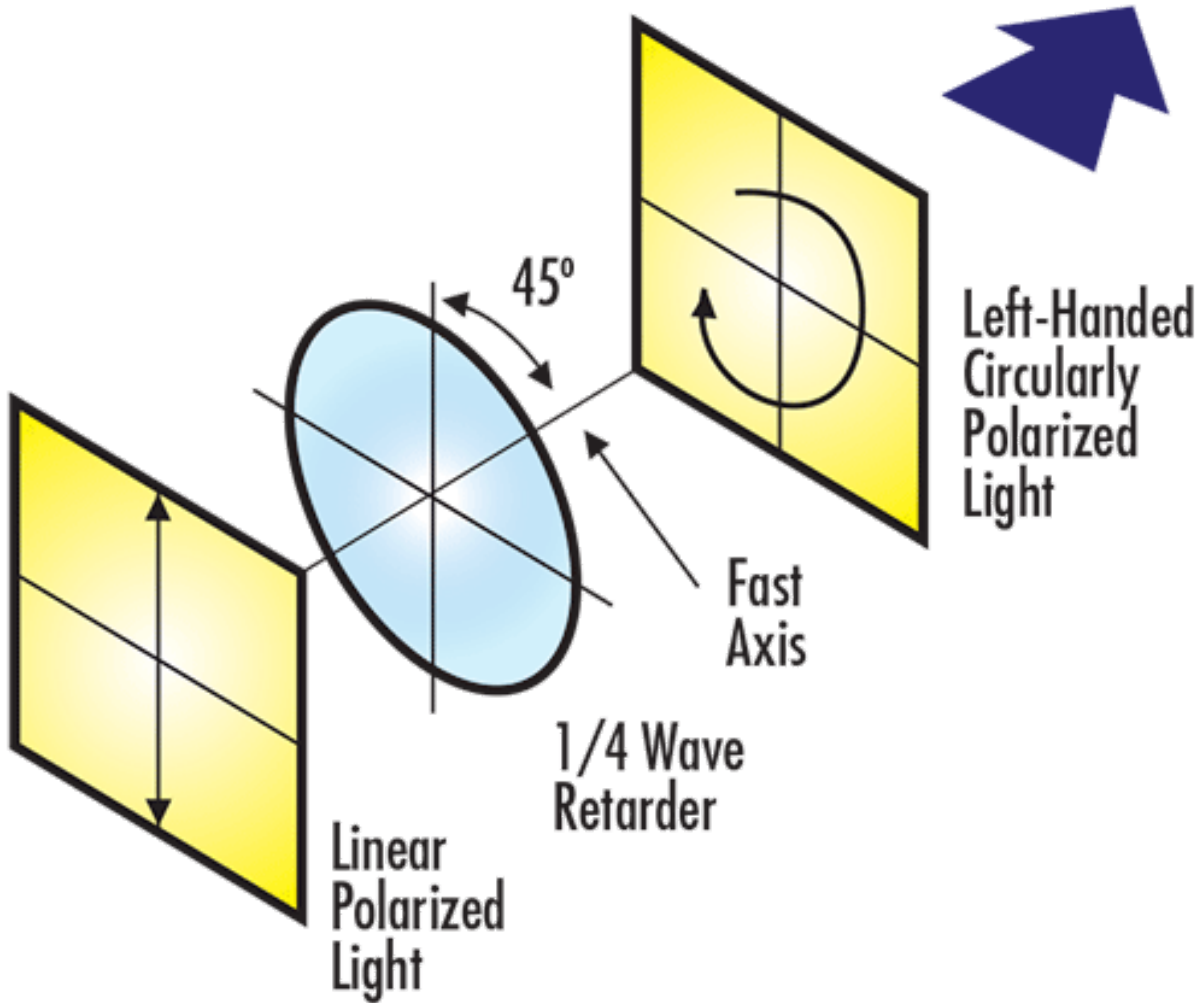
Figure 8: *Circularizing Linear Polarization with a λ/4 Waveplate*

A clever routing application used in articulated beam delivery arms takes advantage of the orientation insensitivity of circular polarization: each joint consists of a pair of λ/4 waveplates in fixed orientation before and after a mirror. The first λ/4 waveplate converts the light to S-polarization for efficient reflection from the mirror with no phase shifts. The second waveplate converts the light back to circular polarization, ready for the next joint at arbitrary orientation.
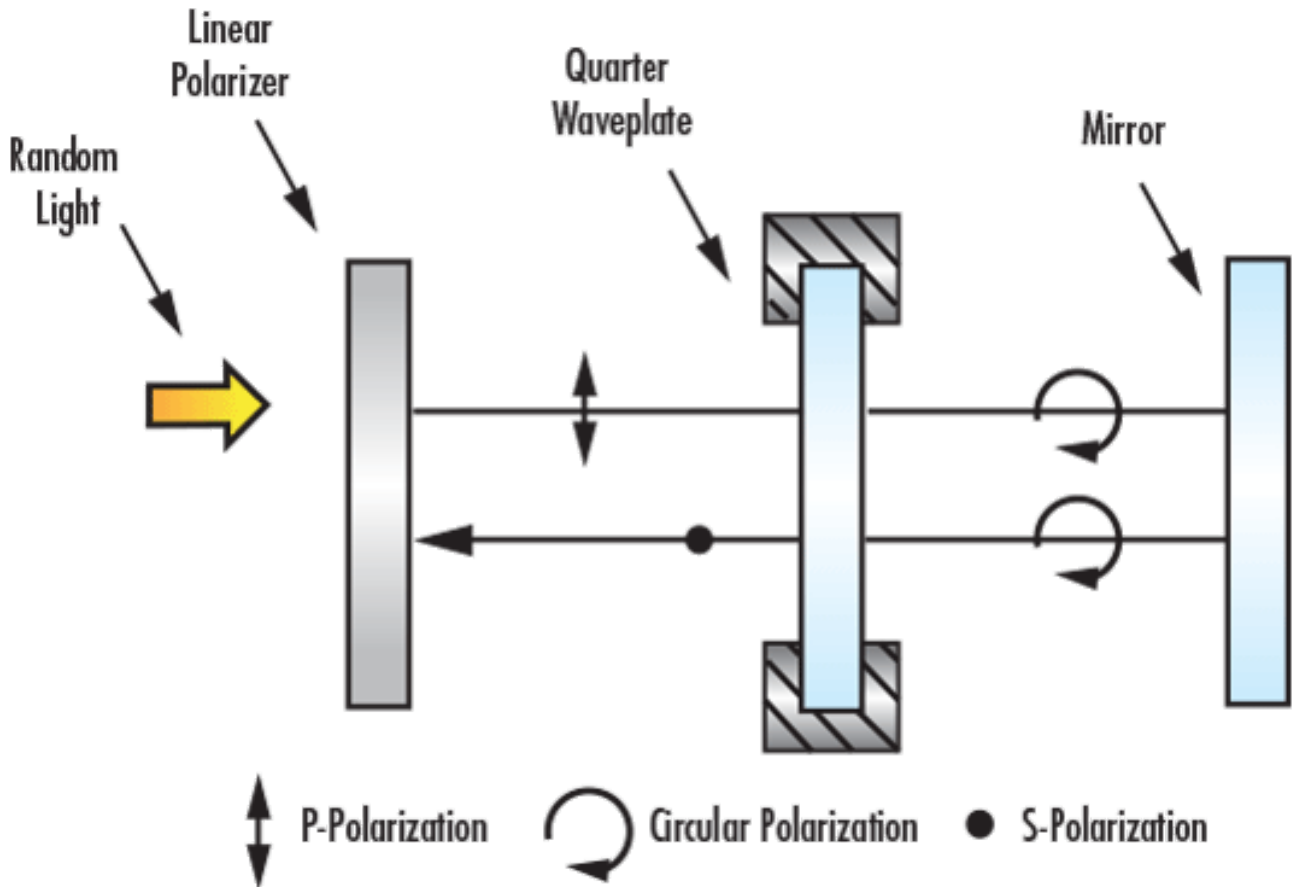
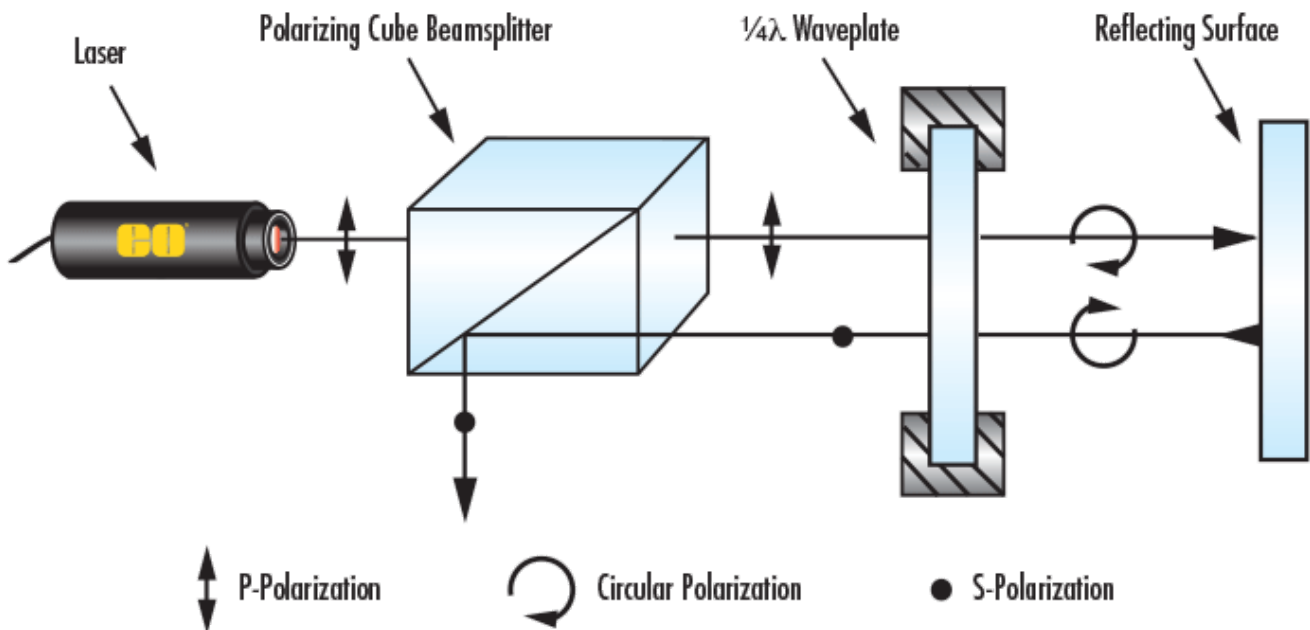**Figure 9:** *Linear Polarizer and λ/4 Waveplate System Illustrating Optical Isolation*

Figure 10: *Polarizing Beamsplitter and λ/4 Waveplate System Illustrating Optical Isolation*

Waveplates are ideal for controlling and analyzing the polarization state of light. They are offered in three main types – zero order, multiple order, and achromatic – each containing unique benefits depending upon the application at hand. A strong understanding of key terminologies and fabrication methods helps in choosing the right waveplate, no matter how simple or complex the optical system.

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