Introduction to Waveplates

The interaction of light with the atoms or molecules of a material is wavelength dependent. A result of this dependence is the resonant interactions related to material dispersion. Birefringence is another consequence of such resonant interaction, which is the change in refractive index with the polarization of light. The orderly arrangement of atoms in some crystals results in different resonant frequencies for different orientations of the electric vector relative to the crystalline axes. In turn, this results in different refractive indices for different polarizations. Unlike dispersion, birefringence can be avoided by using amorphous materials such as glass, or crystals that have simple symmetries, such as NaCl or GaAs. We can also "use" birefringence to modify the polarization state of light, which is a useful thing to do in many situations. The optical components that do this "trick" are called birefringent waveplates or retardation plates (or just waveplates or retarders, for short).

Waveplates

By taking just the right slice of a crystal with respect to the crystalline axes, it can be arranged so that the minimum index of refraction is exhibited for one polarization of the electric vector of a linearly polarized wave, as shown in Figure 1. The wave is polarized along the fast axis, since its phase velocity will be a maximum.

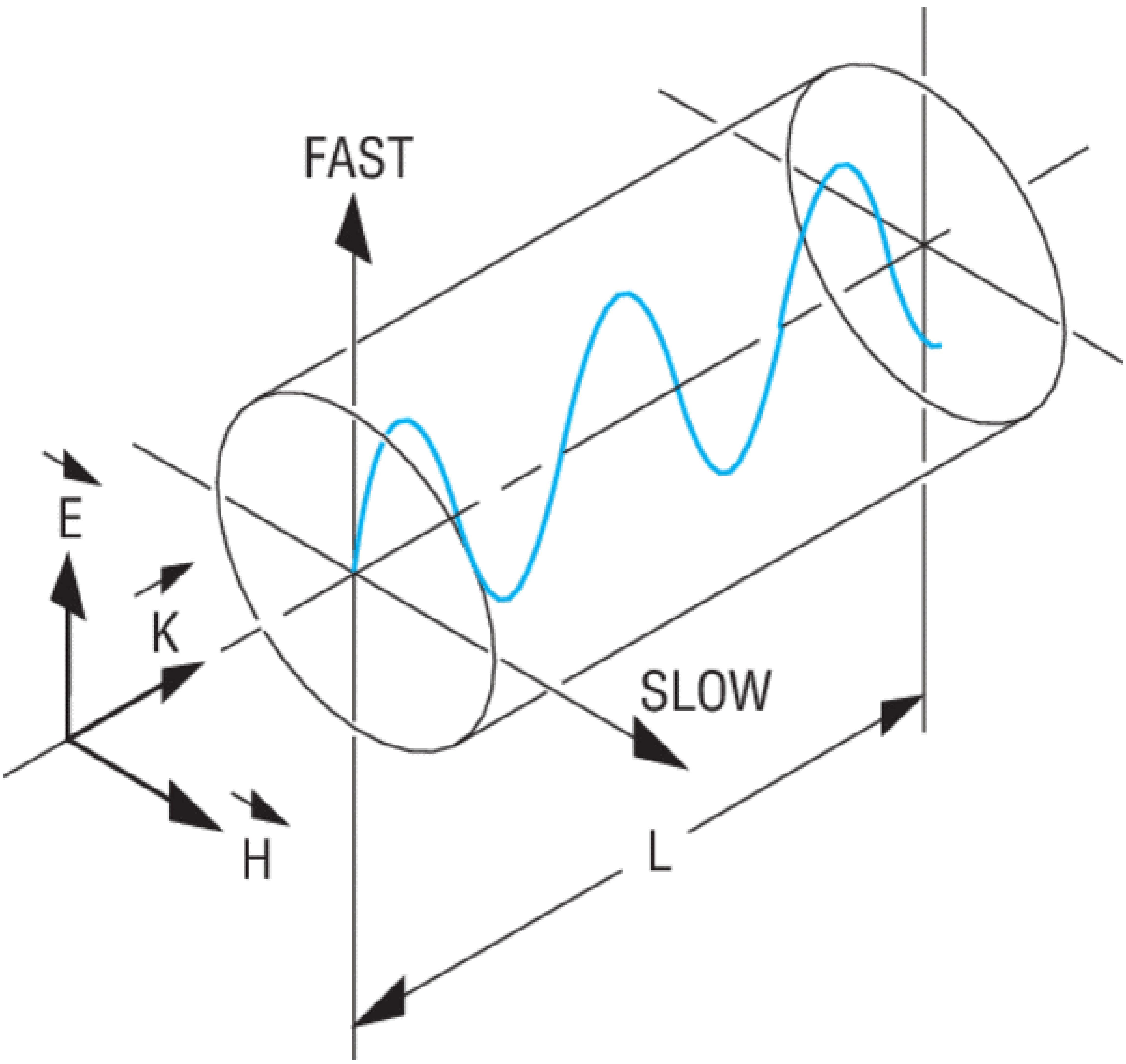


Figure 1. A wave is polarized along the fast axis.

A linearly polarized wave with its plane rotated 90° will propagate with the maximum index of refraction and minimum phase velocity, as shown in Figure 2. This wave is polarized along the slow axis.

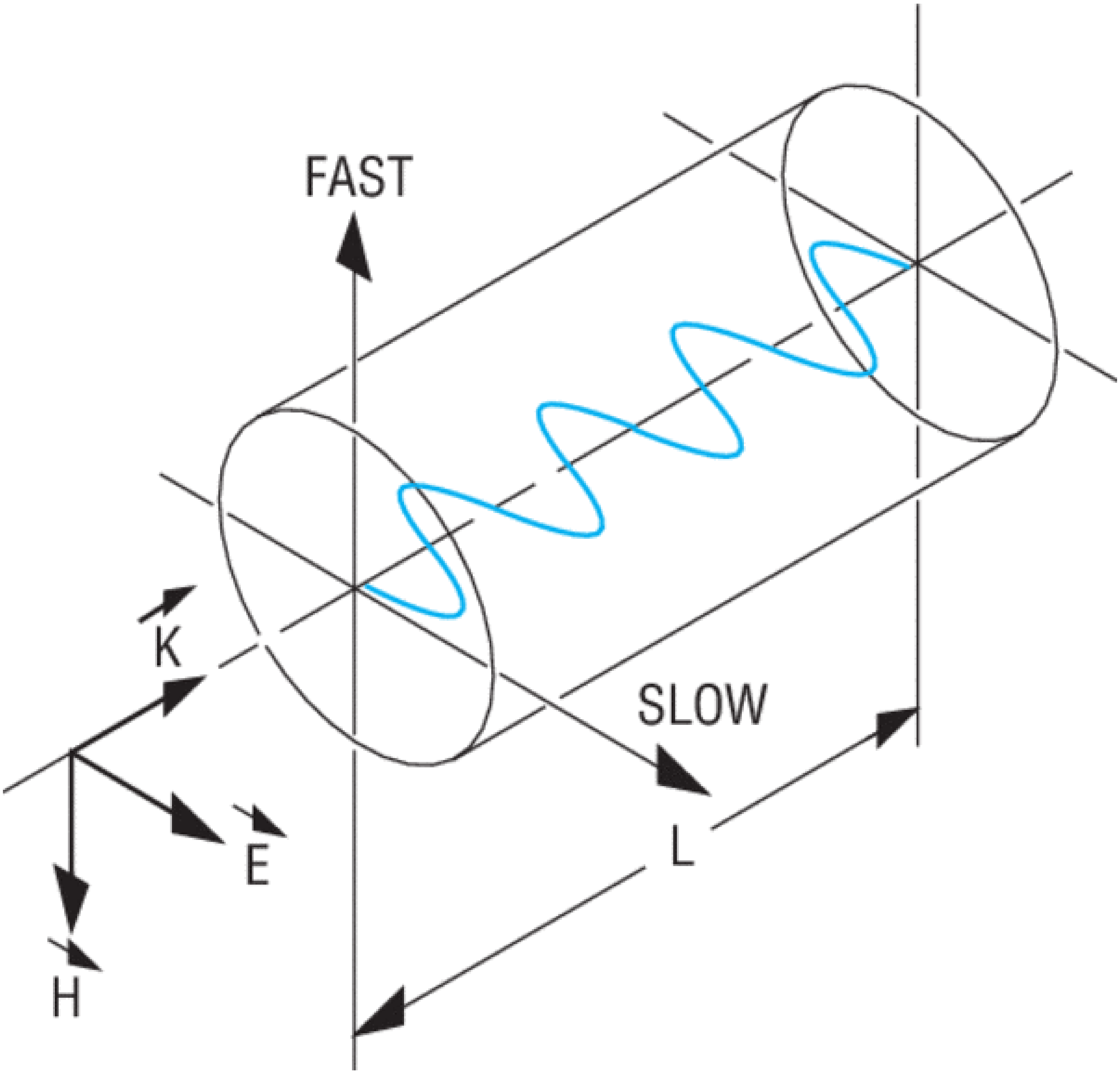


Figure 2. A wave is polarized along the slow axis.

The difference in the number of wavelengths shown in Figures 1 and 2 (2 2/3 and 4, respectively) would imply a ratio of the two indices of refraction $n_{fast} : n_{slow} = 2 : 3$, a much larger difference than in typical natural crystals; the ratio has been exaggerated for clarity.

The propagation phase constant k can be written as $2\pi fn/c$ radians per meter, so that a wave of frequency f will experience a phase shift of $\varphi = 2\pi fnL/c$ radians in traveling a distance L through the crystal. Thus, the phase shift for the wave in Figure 1 will be $\varphi_{fast} = 2\pi fn_{fast}L/c$, and for the wave in Figure 2, $\varphi_{slow} = 2\pi fn_{slow}L/c$. The difference between these two-phase shifts is termed the **retardation**, $\Gamma = 2\pi f(n_{slow} - n_{fast})L/c$. The value of Γ in this formula is in radians, but is more common to express in "wavelengths" or "waves", with a "full-wave" meaning $\Gamma = 2\pi$, a "half-wave" meaning $\Gamma = \pi$, a "quarter-wave" meaning $\Gamma = \pi/2$, and so forth.

Since waves repeat themselves every 2π radians, we could subtract an integral number of 2π's or waves, and for example, call the crystal showing $2\pi(m+1/4)$ radian a quarter waveplate. It would not matter, provided it was only used at exactly the optical frequency designed for the waveplate. However, if the frequency was changed, the retardation would change at a rate faster than it would for a plate that had only 1/4 wave retardation. This difference can be noted by calling it a "multiple order quarter waveplate".

Half-Waveplates

The most commonly used waveplates are the half-waveplate ($\Gamma = \pi$) and the quarter-waveplate ($\Gamma = \pi/2$). Half-waveplates can be used to rotate the plane of linearly polarized light as shown in Figure 3.

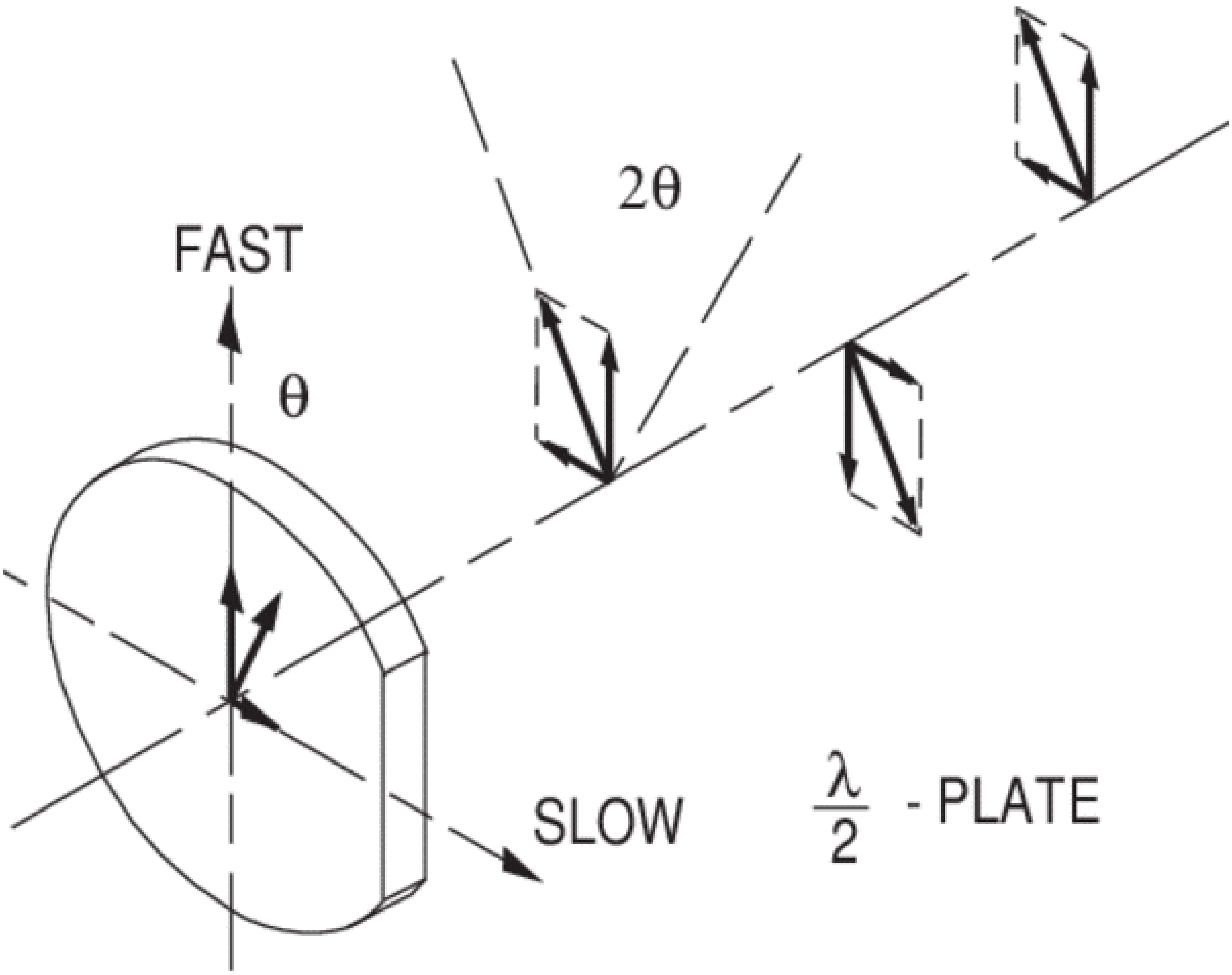


Figure 3. A half-waveplates rotating the plane of linearly polarized light.

Suppose a linearly polarized wave is normally incident on a waveplate, and its plane of polarization is at an angle θ with respect to the fast axis. To see what happens, resolve the incident field into components polarized along the fast and slow axes, as shown. After passing through the plate, pick a point in the wave where the fast component passes through a maximum. Since the slow component is retarded by one half-wave, it will also be a maximum, but 180° out of phase, or pointing along the negative slow axis. If we follow the wave further, we see that the slow component remains exactly 180° out of phase with the original slow component, relative to the fast component. This describes a linearly polarized wave, but making an angle θ on the opposite side of the fast axis. The original polarization axis has been rotated through an angle 2θ. The same result will be found if the incident wave makes an angle θ with respect to the slow axis.

A half-waveplate is very helpful in rotating the plane of polarization from a polarized laser to any other desired plane (especially if the laser is too large to rotate). Most large ion lasers are vertically polarized, for example, so to obtain horizontal polarization, simply place a half-waveplate in the beam with its fast (or slow) axis 45° to the vertical. If it happens that the half-waveplate being used does not have marked axes (or if the markings are obscured by the mount), place a linear polarizer in the beam first and orient it for extinction (horizontally polarized), then interpose the half-waveplate normal to the beam and rotate it around the beam axis, so that the beam remains extinct - one of the axes has now been found. Then, rotate the half-waveplate exactly 45° around the beam axis (in either direction) from this position, and the polarization of the beam will have been rotated by 90°. Check this by rotating the polarizer 90° to see that extinction occurs again. If you need some other angle, instead of 90° polarization rotation, simply rotate the waveplate by half the angle you desire. A convenient waveplate mount calibrated in angle is the RSP-1T or GM-1RA.

Incidentally, if a new polarizer doesn't provide as good an extinction as the ones you used before, it likely means this waveplate isn't exactly a half-waveplate at the operating wavelength of your interest. Small errors in retardation can be corrected by rotating the waveplate a small amount to move the incident beam's plane of polarization towards the fast or slow axes. Moving towards the fast axis decreases the retardation while moving towards the slow axis increases the retardation. Try both ways and use a linear polarizer to check for improvement in the extinction ratio.

Quarter-Waveplates

Quarter-waveplates are used to turn linearly polarized light into circularly polarized light and vice versa. To do this, the waveplate must be oriented so that equal amounts of fast and slow waves are excited. This is achieved by orienting an incident linearly polarized wave at 45° to the fast (or slow) axis, as shown in Figure 4.

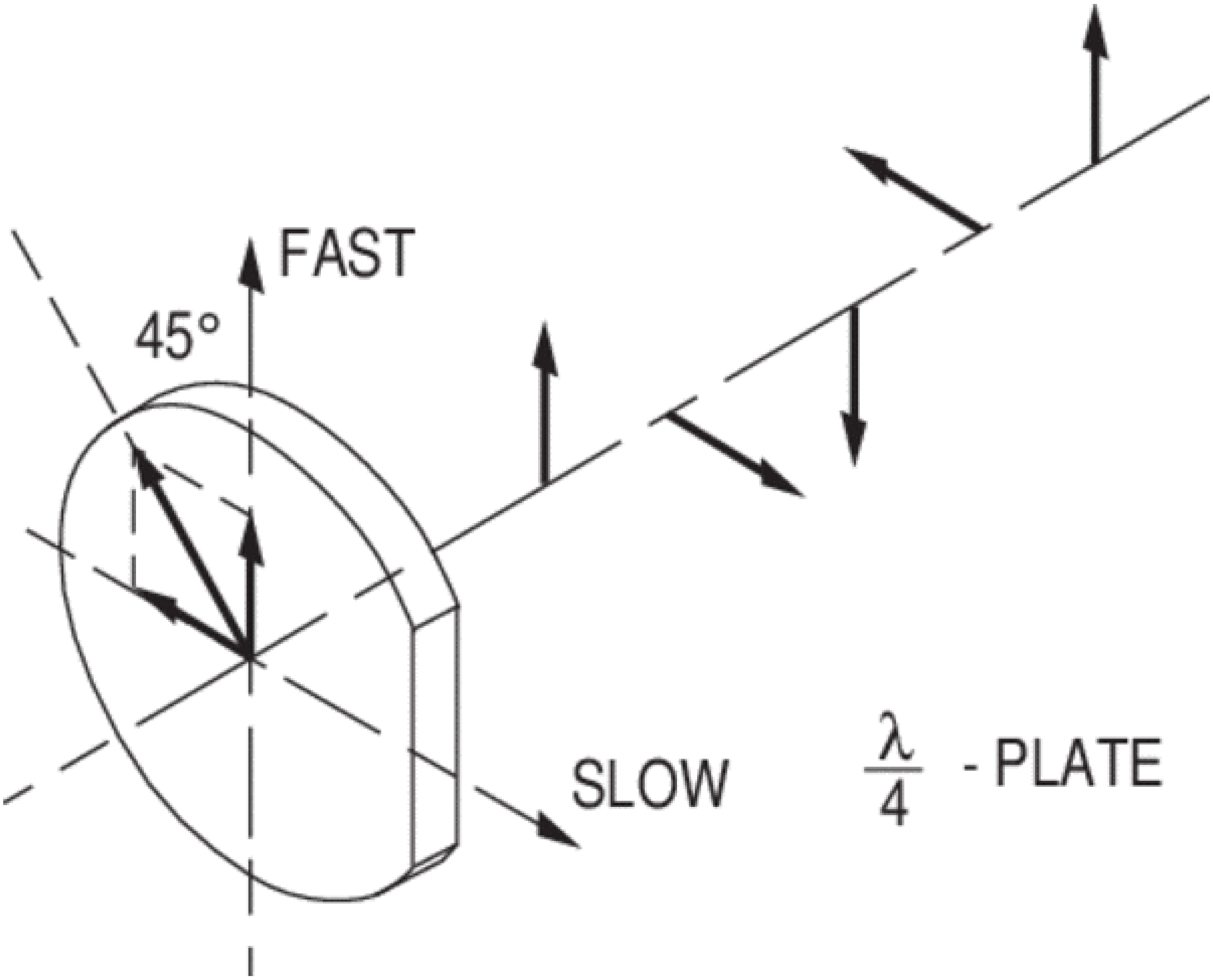


Figure 4. Turning linearly polarized light into circularly polarized light.

On the other side of the plate, examine the wave at a point where the fast-polarized component is at maximum. At this point, the slow-polarized component will be passing through zero, since it has been retarded by a quarter-wave or 90° in phase. Moving an eighth wavelength farther, we will note that the two are the same magnitude, but the fast component is decreasing and the slow component is increasing. Moving another eighth wave, we find the slow component is at maximum and the fast component is zero. If the tip of the total electric vector is traced, we find it traces out a helix, with a period of just one wavelength. This describes **circularly polarized light**. Right-hand circularly polarized light is shown in the Figure; the helix wraps in the opposite sense for left-hand. Left-hand polarized light is produced by rotating either the waveplate or the plane of polarization of the incident light 90° in Figure 4.

Setting up a waveplate to produce circularly polarized light proceeds exactly the same as described for rotating 90° with a half-waveplate: first, cross a polarizer in the beam to find the plane of polarization. Next, insert the quarter-waveplate between the source and the polarizer and rotate the waveplate around the beam axis to find the orientation that retains the extinction. Then rotate the waveplate 45° from this position. Half of the incident light should now be passing through the polarizer (the other half being absorbed or deflected, depending on which kind of polarizer being used). The quality of the circularly polarized light can be checked by rotating the polarizer - the intensity of light passing through the polarizer should remain unchanged. If it varies somewhat, it means that the light is actually **elliptically polarized**, and the waveplate isn't exactly a quarter-waveplate at operating wavelength of your interest. This may be corrected (as with the half-waveplate) by tilting the waveplate about its fast or slow axes slightly, while rotating the polarizer to check for constancy.

What effect do retardations other than a half-wave or a quarter-wave have on linearly polarized light? Figure 5 shows the effect of λ/4 retardation on linearly polarized light with the plane of polarization making an arbitrary angle with respect to the fast axis.

The result is elliptically polarized light - where the amount of ellipticity is a function of the retardation of the incident plane wave; and the tilt of the axis is a function of the tilt of the incident plane wave. The exception is a half-wave retardation, in which case the ellipse degenerates into a plane wave making an angle of 2θ with the fast axis. Note that the quarter-waveplate does not produce circularly polarized light here, because equal amounts of fast and slow wave components were not used; the incident tilt angle must be exactly 45° with respect to the fast (or slow) axis to make these components equal.

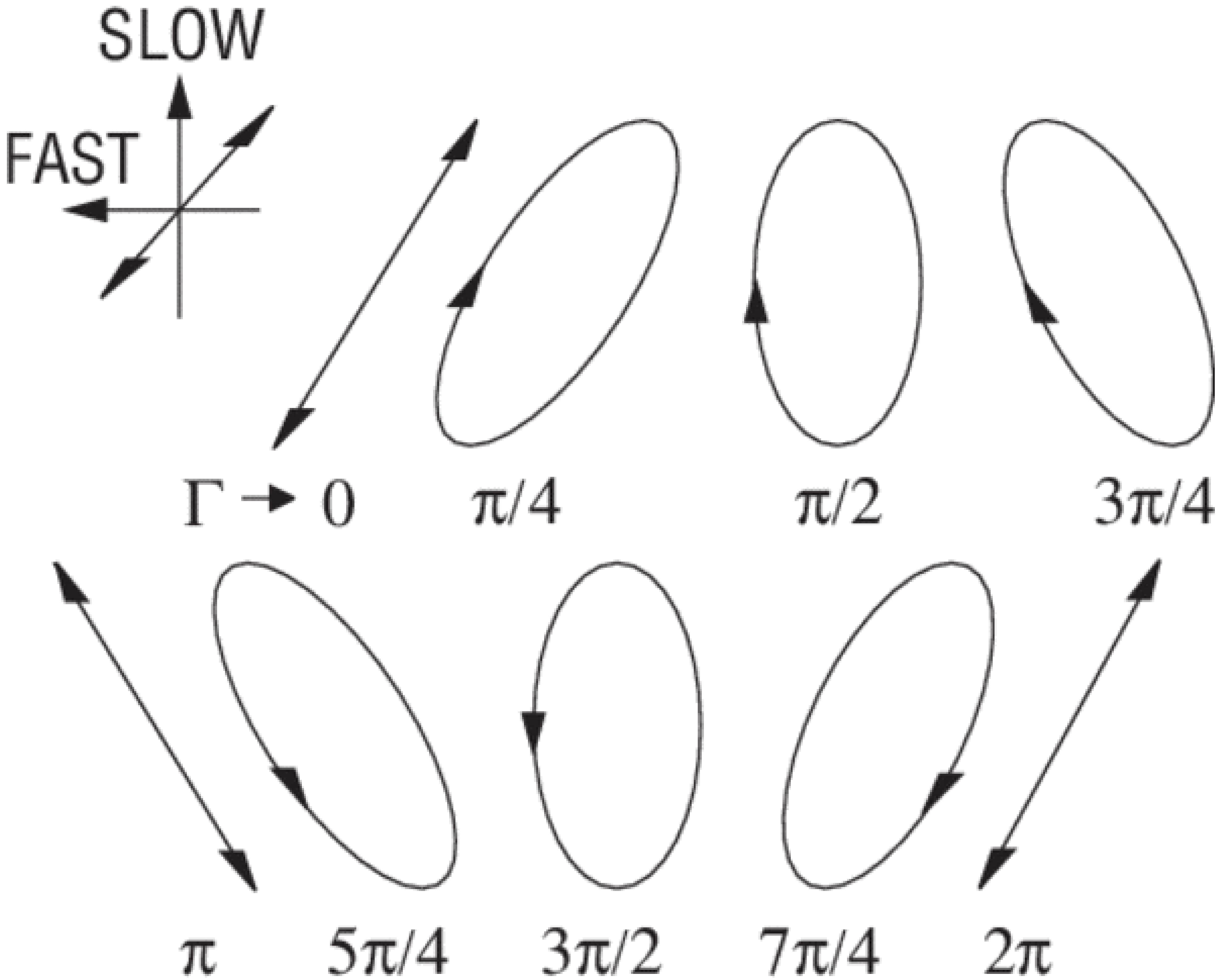
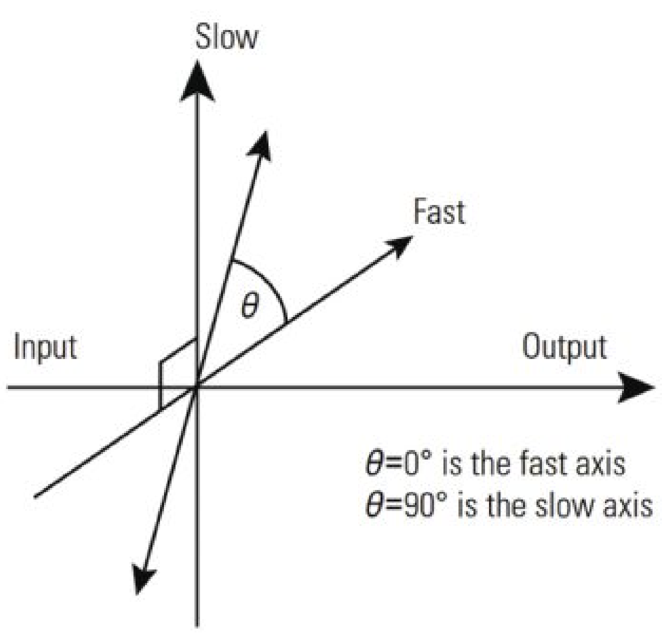


Figure 5. The effect of λ/4 retardation on linearly polarized light with the plane of polarization making an arbitrary angle with respect to the fast axis.

Waveplate Applications

The two most common applications of waveplates have been mentioned: rotating the plane of polarization with a half-waveplate and creating circular polarization with a quarter-waveplate. A quarter-waveplate can also be used to create plane-polarization from circular polarization — just reverse the direction of light propagation in Figure 4. The operation of a waveplate and a summary of how quarter and half waveplates convert one polarization state to another are shown in Figure 6.



Input	Output
Quarter-wave	
Linear, θ=45°	Right circular
Linear, θ=-45°	Left circular
Right circular	Linear, θ=-45°
Left circular	Linear, θ=45°
Linear, any $\theta \neq$45°	Elliptical
Half-wave	
Linear, angle θ	Linear, angle -θ
Left circular	Right circular
Right circular	Left circular
Any wave plate	
Linear, θ=0° or 90°	Unchanged

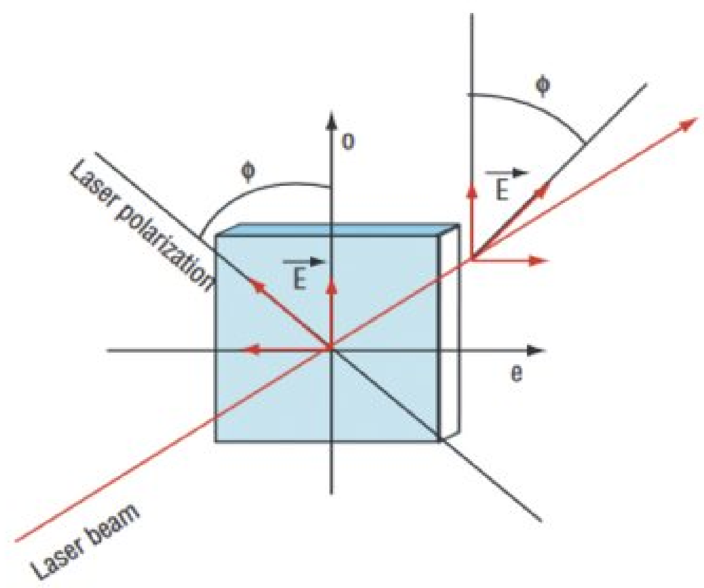


Figure 6. Summary of how quarter and half waveplates convert one polarization state to another.

Optical Isolation - A quarter-waveplate can be used in an optical isolator, that is, a device that eliminates undesired reflections. Such a device uses a quarter-waveplate and a linear polarizer or polarizing beamsplitter cube.

Polarization Cleanup - Often an optical system will require several reflections from metal or dielectric mirrors. There is no change in the polarization state of the reflection if the beam is incident normally on the mirrors, or if the plane of polarization lies in or normal to the plane of incidence. However, if the polarization direction makes some angle with the plane of incidence, then the reflection often makes a small phase shift between the parallel and perpendicular components. This is particularly true for metal mirrors, which always have some loss. The resulting reflected wave is no longer linearly polarized, but will be slightly elliptically polarized. This can easily be determined by its degraded extinction when a polarizer is inserted and rotated. This small ellipticity can often be removed by inserting a full waveplate (which ordinarily does nothing) and tilting it slightly about either fast or slow axes to change the retardation slightly to just cancel the ellipticity.

Waveplate Material and Practice

Materials — Many naturally occurring crystals exhibit birefringence, and could, in principle, be used for waveplates. Calcite and crystalline quartz are typical materials used. While they are durable and of high optical quality, the refractive index difference, n_{slow} - n_{fast} is so large that a true half-waveplate would be too thin to polish, therefore impractical to create.

It is also possible to induce small amounts of birefringence into a normally isotropic material through stress. For example, most polymers exhibit birefringence from stress applied in the manufacture. Polymer waveplate material is available in half or quarter-wave retardation. This material can be sandwiched between two high quality windows to make precision zero-order waveplates.

Multiple-Order Waveplates - One alternative to polishing or cleaving very thin plates is to use a practical thickness of a durable material such as crystalline quartz and obtain a high-order waveplate, for example, a 15.5 waveplate for a 1 mm thickness. Such a plate will behave exactly the same as a half-waveplate at the design wavelength. However, as the optical wavelength is changed, the retardation will change much more rapidly than it would for a true half-waveplate. The formula for this change is easily derived from the definition of Γ:

$$\Gamma = (2m+1)\pi\left(\frac{\delta f}{f_0}\right)$$

$$\approx -(2m+1)\pi\left(\frac{\delta\lambda}{\lambda_0}\right)$$

where f_0 and λ_0 are the design frequency and wavelength, and m is the order of the waveplate. Thus, the rate of change of retardation with frequency σΓ/σf will be 2m + 1 times as large for an mth order plate as a true half-waveplate, (m = 0, or "zero-order" plate). This would be 31 times larger for our 1 mm "15.5-waveplate". Calculate the frequency or wavelength range required by a given system, and see if the error in retardation will be tolerable over that range with a multiple-order waveplate.

Similarly, the sensitivity of the retardation to rotation about the fast and slow axes is found to be about (2m + 1) times larger for a multiple order plate than a true zero-order half-waveplate. This means much smaller rotations are required to correct for retardation errors. But it also means that light rays not parallel to the optical axis will see a (2m + 1) larger change in retardation. Multiple order waveplates are not recommended in strongly converging or diverging beam portions of an optical system. Similarly, the sensitivity of retardation to changes in length caused by changes in temperature is multiplied by (2m + 1), so that tighter temperature control will be required. A typical temperature sensitivity is 0.0015λ per °C for a visible 1 mm thick half-waveplate.

Multiple-order waveplates can be used when a waveplate is required to be used at two discrete wavelengths, for example, the 488 and 514.5 nm wavelengths of an argon-ion laser or the 532 and 1064 nm wavelengths from an Nd:YAG laser. By choosing the thickness to give a $(2m_1 + 1)$ plate at one wavelength and a $(2m_2 + 1)$ plate at the other, both wavelengths will see a "half-waveplate" (but not the wavelengths in between). The integers must be selected by a computer program, since the dispersion in index also has to be accounted for, but it is usually possible to find a plate of reasonable thickness provided the two wavelengths are not too close together.

Zero-Order Waveplates - Fortunately, a technique is available for realizing true half-waveplate performance, while retaining the high optical quality and rugged construction of crystalline quartz waveplates. By combining two waveplates whose retardations differ by exactly half a wave, a true half-waveplate is created. The fast axis of one plate is aligned with the slow axis of the other, so that the net retardation is the difference between the two retardations. The change in retardation with frequency (or wavelength) is minimized as shown in Figure 7. Temperature sensitivity is also reduced to a typical value is 0.0001λ per °C. The change in retardation with rotation is highly dependent on manufacturing conditions and may be equal to or greater than that of a multiple order waveplate.

These waveplates are recommended for use in systems using tunable radiation sources, such as a diode laser or white light sources.

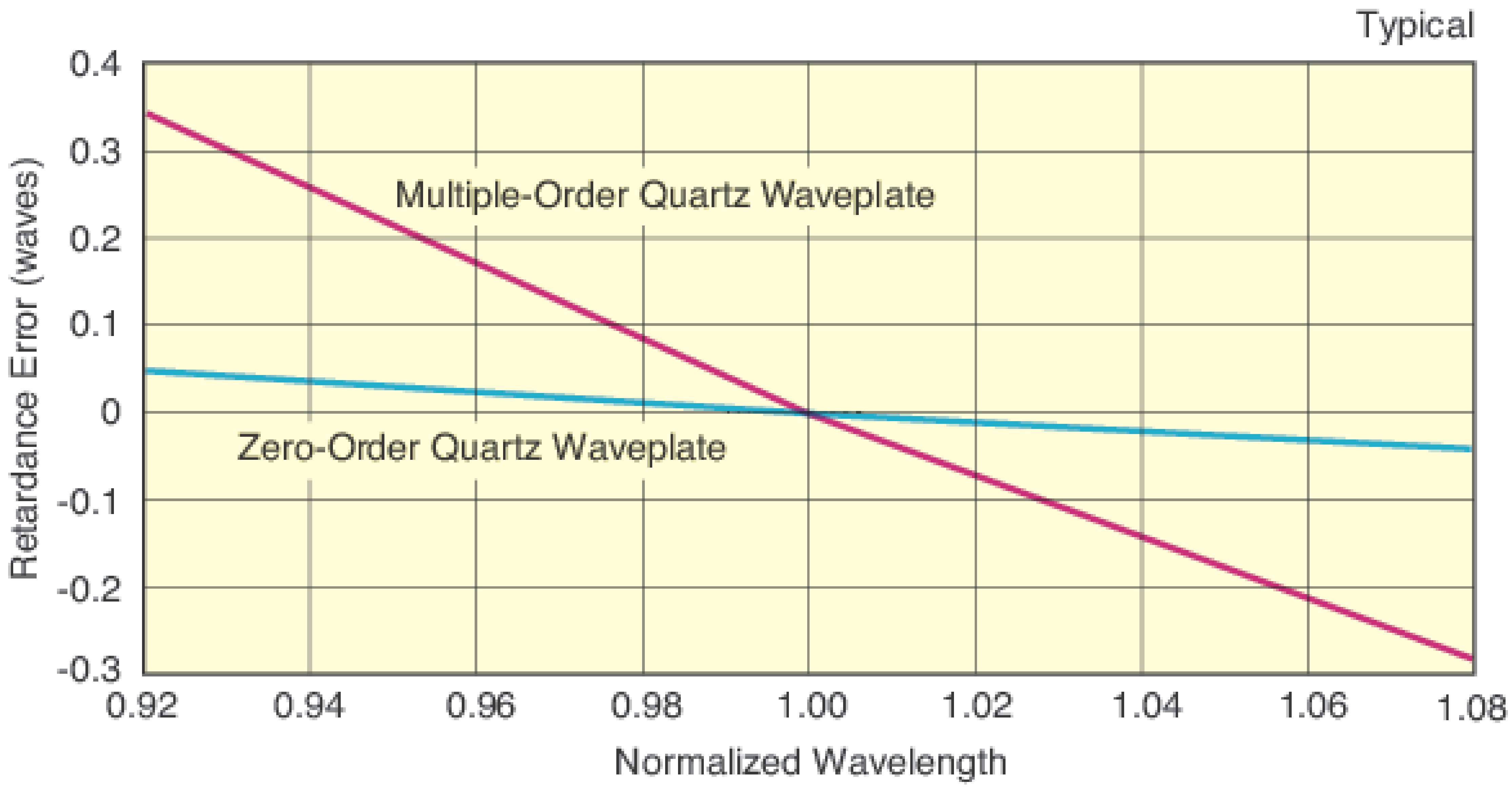


Figure 7. Change in retardation with wavelength.

Achromatic Waveplates - Achromatic waveplates consist of two different materials that are carefully choosen to eliminate chromatic dispersion. The most common type is crystalline quartz and magnesium fluoride birefringent crystals in an air-spaced design. Achromatic polymer waveplates are also avaiable which consitint of film stack laminated between two high-precision AR coated N-BK7 windows. Compared to zero-order waveplates, achromatic waveplates offer better retardation accuracy over broadband wavelength ranges, as example of achromatic quartz-MgF_2 1/2 waveplate shown in Figure 8.

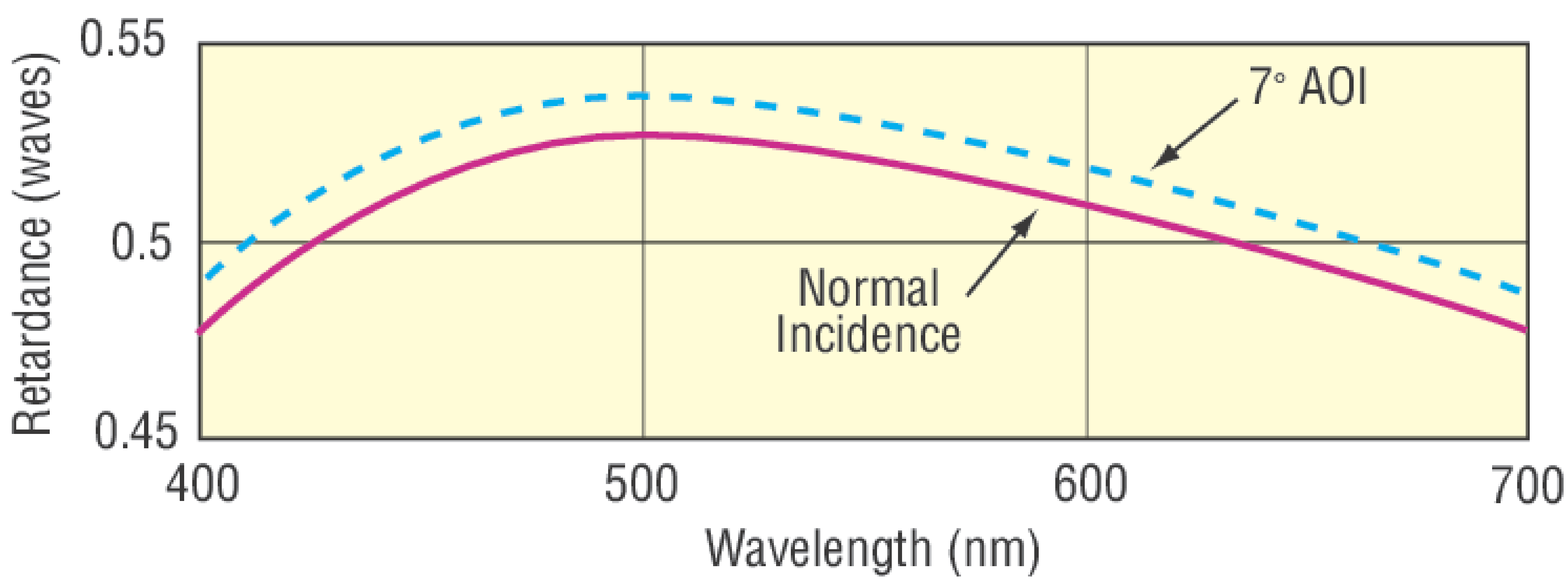


Figure 8. Achromatic waveplates have better retardation accuracy over a broad wavelength range.

Berek's Variable Waveplates - A Berek compensator quantitatively determines the wavelength retardation of a crystal, fiber, mineral, plastic film or any other birefringent material. Berek tunable or variable waveplates have a variable birefringence or thickness that can be tuned to a certain wavelength or shift the retardation value for a single wavelength. If the material's thickness can be measured, this optical device can be used to learn its birefringence value. The Berek compensator works by measuring the rotation angle of a calcite or magnesium fluoride optical plate that is cut perpendicular to the optical microscope's axis.

In 1913, Max Berek developed this style of polarization compensator, as a variable waveplate that imposes a quarter- or half-wave retardation at wavelengths between 200 and 2800 nm. This greatly reduced the number of compensation plates needed to conduct quantitative polarized light microscopy.

MKS Newport offers an outstanding variety of Waveplates, Half-Waveplates and Quarter-Waveplates to provide a wide range of solutions to customer needs. Please contact us if you have any questions or special requests.
