The Power and Limitations of Polymers and Liquid Crystals for Polarization Control

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Types of Optics Discussed

- Polarizers
  - Calcite and other crystals
  - Dichroic polymer films
  - Nanoparticles
  - Wire grid
  - Polarizing beamsplitter cubes
  - Polarization gratings
- Waveplates or Retarders
  - Solid crystals
  - Polymers
  - Liquid crystals

This information focuses on polarizers and waveplates, which are the two primary types of components crucial for altering or selecting polarization states. As many are aware, traditionally, high-quality polarizers have been crafted from crystal materials, with calcite being a prominent example.

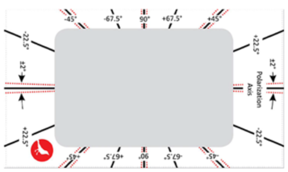
Crystal polarizers

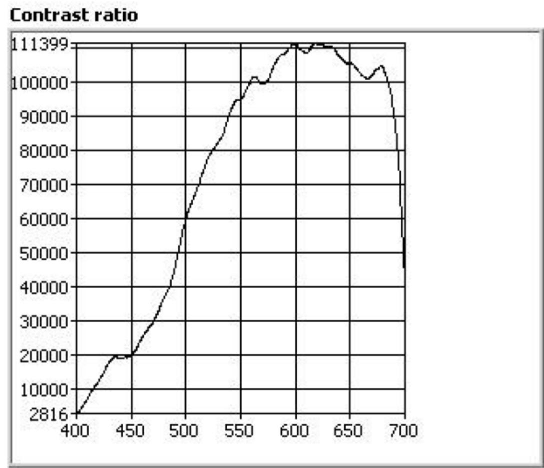
- Usually made using calcite crystal.
- Glan-Thompson is most common.
- Magnesium fluoride used for DUV.
- Gold standard for polarization purity and high transmission over a broad wavelength range (320 nm to 2300 nm).
- Extinction ratios in excess of 10^6
- Clear aperture limited to about 3 cm.
- Limited Angular field of about 5°.

The Glan Thompson polarizer is a common type used. However, when working in the UV spectrum, a different material such as magnesium fluoride is often necessary. These polarizers are known for their very high purity and effectiveness across a wide wavelength range, as listed here. They exhibit extinction ratios exceeding a million to one in some cases. Nevertheless, there are drawbacks. The clear aperture is limited due to calcite not being commonly grown but mined, making obtaining optical-quality material difficult and expensive. Additionally, the angular field of view is small. In the examples of Glan Thompson polarizers shown in the figure, you can observe their less-than-optimal aspect ratio; they are longer than they are wide. This aspect, along with their relatively high cost, poses further disadvantages.

Dichroic sheet polarizers

- Apertures exceeding 1 meter.
- Excellent performance over visible wavelengths.
- Angular field of view< 30°.
- Low flux tolerance of 3W/cm^{2}.
- Limited UV and IR options.





More commonly used today are dichroic sheet polarizers, which you may already be familiar with, especially if you're viewing this webinar on a computer screen. These polarizers have large apertures, essential for display applications, and they exhibit excellent performance across visible wavelengths. They also offer a wide angular field of view. However, their flux tolerance is relatively low, and there are limited options for UV and infrared versions. Meadowlark provides business card-sized polarizer samples upon request, clearly marked with axis direction, as illustrated in the chart on the right side of this slide. These polarizers demonstrate outstanding performance in terms of contrast ratio, exceeding 100,000 to one for certain portions of the visible spectrum. However, like many polarizers, their performance tends to decrease in the blue wavelengths compared to longer wavelengths.

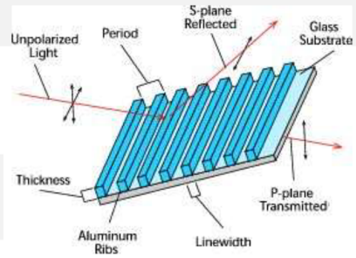
Silver Nanoparticle Polarizers

- Function by "Resonant absorption by elongated silver nanoparticles" imbedded in stretched glass.
- Rejection mostly by absorption.
- Very poor transmitted wavefront quality (Several waves/cm).
- Sold by:
  - Laser Components (Colorpol/ Codixx)
  - Corning (Polarcor)
- Colorpol
  - 350 to 5,000 nm center wavelengths (100 nm to 1000 nm bandpass).
  - Can be patterned to match detector pixels.
  - 100x60 mm max size.
  - Extinction ratio exceeds 100,000:1 (600nm-1200nm)
  - Shortest wavelength is 357 nm.
- Polarcor
  - 600 to 2,300 nm center wavelengths
  - Similar bandpass widths
  - 30 mm max size.

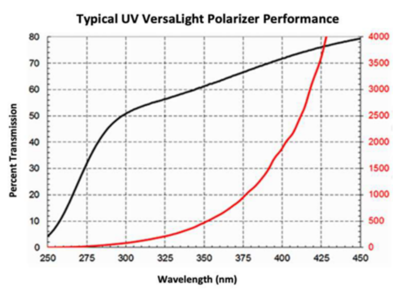
Photo courtesy of Laser Components

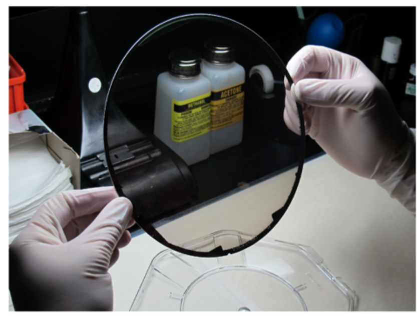
Another type that's quite common these days is known as silver nanoparticle polarizers. They operate through resonant absorption in elongated silver nanoparticles embedded in stretched glass. The glass, which contains silver oxide material, undergoes a heating and stretching process. During this process, the silver oxide particles within the glass are stretched alongside it. Subsequently, while the glass is still hot, it is exposed to a hydrogen atmosphere to reduce the silver oxide to silver, forming the silver nanoparticles. These polarizers are marketed under names such as Colorpol and Codixx, as well as by Corning under the name Polarcor. They cover various wavelength ranges, primarily in the visible and infrared spectra. However, the transmitting wavefront quality is often poor due to the stretched glass, which cannot be polished afterward. This is because the reduction of silver oxide to silver only occurs on the surface. Consequently, attempts to polish the surface for improved wavefront quality risk damaging the polarizer itself. This limitation can be significantly mitigated by laminating the polarizer between optical glass flats.

Wire grid polarizers



- Subwavelength (70nm)"wire" spacing on glass or fused silica substrate.
- IR versions to 15 microns wavelength on silicon or sapphire substrates.
- 18 cm largest size
- Poor flatness but good transmitted wavefront.
- Delicate surface unless AR coated over wires.



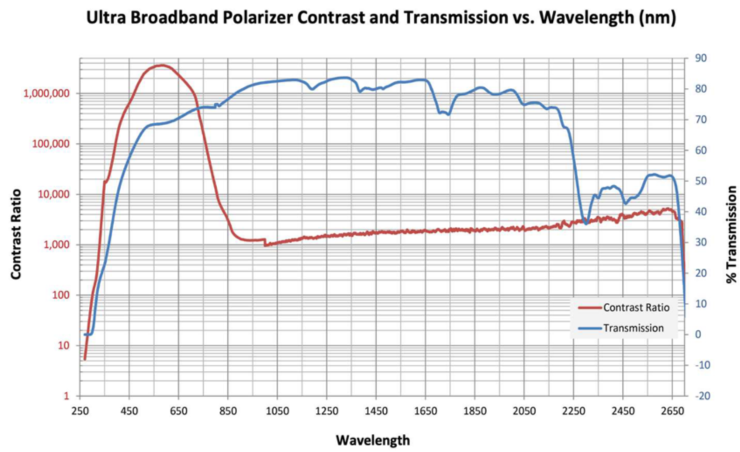


Wiregrid polarizers have seen significant improvement over the past couple of decades, largely driven by demands from the LCD video projector industry, particularly for high-power polarizers usable with visible wavelengths. While infrared versions have been available for some time, achieving optimal performance requires sub-wavelength wire spacing. Currently, the commonly achieved spacing is around 70 nanometers. These wiregrid polarizers are produced by a company called MoxTech based in Utah, using aluminum wires typically deposited on glass or fused silica substrates. However, for infrared applications, silicon or sapphire substrates can be used to enhance transmission in that spectrum.

The largest available size for these polarizers is approximately 18 centimeters in clear aperture, produced on a 20-centimeter wafer. However, the flatness of these wafers is compromised as they need to be thin enough to flex during production, affecting the quality of the reflected wavefront. The graph below illustrates that these polarizers can offer reasonable performance even in the UV range, down to wavelengths around 350 or 325 nanometers.

It's important to note that the surface of wiregrid polarizers is delicate unless it's been coated for protection. Some manufacturers apply an overcoating that also provides anti-reflection properties to safeguard the wire grid surface.

Hybrid Polarizer



- Thickness less than 3 mm.
- Clear apertures to 100 mm.

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Nowadays, it's feasible to combine various types of polarizers, such as linear polarizers, to create a highly broadband polarizer. This is a product that Meadowlark offers, and it performs effectively, extending into the infrared up to about 2.7 microns. In the graph provided, the blue curve represents transmission over this wavelength range, while the red curve indicates the contrast ratio, which exceeds 1,000 to one overall, though it's slightly lower at the shortest wavelengths shown.

These broadband polarizers can feature clear apertures larger than those of calcite polarizers and typically have thicknesses of only 2 or 3 millimeters.

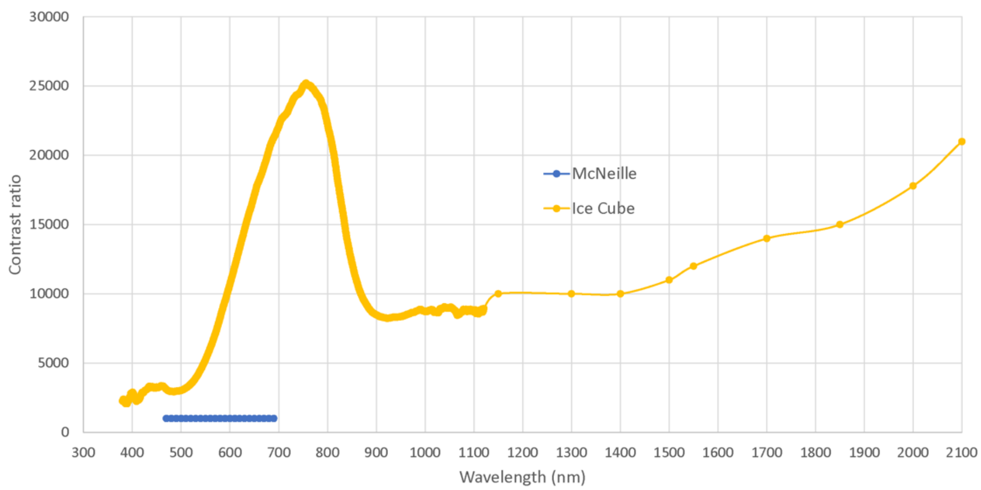
Beamsplitting Polarizers

- Ice cube – wire grid
  - Fixed polarization direction.
  - Wide (±30°)angular acceptance
  - Poor reflected wavefront distortion.
  - About 15- 20% absorption of reflected beam.
- MacNeile – thin film
  - Polarization direction rotates with plane of incidence
  - Narrow angular field

Certainly, beam-splitting polarizers are commonly employed. Historically, the MacNeille Polarizer, consisting of a thin film stack deposited on the hypotenuse of a pair of right-angle prisms and then bonded together, provides linear polarization in two states: one transmitted (the p-state) and one reflected (the s-state). However, these polarizers have limitations. Their wavelength range is quite restricted, and they offer a narrow angular field of view. Additionally, the polarization direction rotates with the plane of incidence, making it inconsistent for non-collimated beams, which can pose challenges.

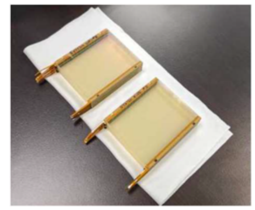
In recent years, variations of these beam-splitting cubes have been developed, including one by MoxTech, where the wire grid is laminated between the right-angle prisms. This design has advantages: the wire grid sets the polarization direction independently of the plane of incidence, and it offers a wide angular acceptance. However, there are drawbacks. The reflected wavefront may exhibit distortion of two or three waves due to the non-flat substrate on which the wires are deposited. There is also some absorption in the reflected beam that needs consideration. Additionally, the wire direction determines the polarization direction for both transmission and reflection. It's even possible to set this direction at 45 degrees to the edges of the cube, if for some reason that is necessary.

Beamsplitter cube comparison

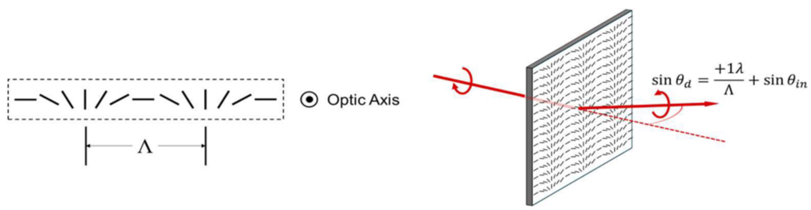


For comparison of performance across wavelengths between the MacNeille cube (shown in the blue line) and the Ice Cube™, you'll notice a significant difference in contrast ratio. The Ice Cube™ exhibits notably higher contrast ratios, extending well into the infrared and maintaining reasonable performance even in the blue spectrum. However, it's worth noting that beyond the range shown here for the MacNeille cube, the polarization or extinction ratio diminishes considerably.

Polarization Gratings as Polarizers



- Act as a beamsplitting polarizer for circularly polarized light.
- Splitting angle increases with decreasing grating pitch, Λ.
- Splitting angles to 37° at least and contrast ratios of a few hundred to one.
- Unpolarized incident light split into left and right hand circularly polarized light at angles of ±θ.
- Also called diffractive waveplates.
- Consists of a spun coat, photoaligned, optical polymer half wave retarder layer with a cycloidal spatial variation in fast axis direction.
- Polymer retarder layer is 2-3 microns thick since birefringence is 0.15 at visible wavelengths.
- Made by BEAM Engineering and Boulder Nonlinear Systems as well as Meta.



(a) (b)

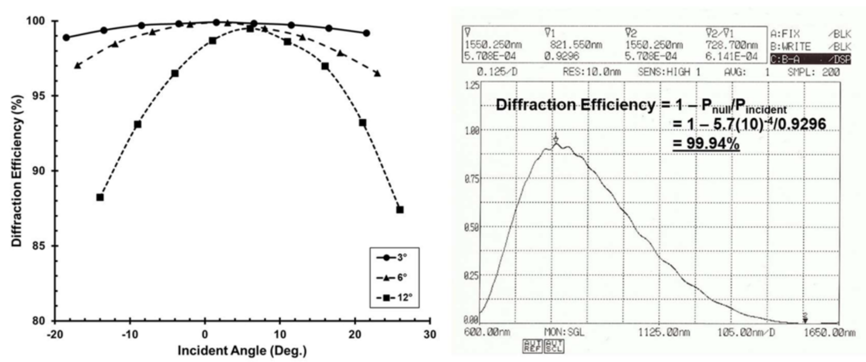
A newer type of beam-splitting polarizer is known as a polarization grating, sometimes referred to as a diffractive waveplate. These polarizers consist of a polymer layer spun-coated over a photo-alignment layer. Functioning as half-wave retarder waveplates, their access direction varies in a cycloidal manner, as depicted in the accompanying diagram. The angle of deflection of the transmitted beam is determined by a specific equation.

For unpolarized incident light, not only is one beam deflected in the positive direction, but there's also an opposite-handedness beam deflected in the negative direction. This characteristic enables them to serve as beam-splitting polarizers. Unlike traditional cubes, the splitting angle between these beams is determined by the period of the grating deposited on it, denoted as gamma.

While this technology is relatively new and not widely available, versions of it are manufactured by companies like BEAM Engineering in Florida, Boulder Nonlinear Systems, and Meta, which has acquired Michael Escuti's company, Imagine Optix Corporation. It's anticipated that this technology will become more prevalent in future products. In full disclosure, it's important to note that Boulder Nonlinear Systems was acquired by Meadowlark Optics in April 2023.

Polarization Gratings-II

- Diffraction efficiency depends on angle of incidence and the steering angle θ.
- Steering angle is switchable by controlling input polarization with a liquid crystal variable retarder.



(a) (b)

Further details about polarization gratings: Their contrast ratios typically range from a few hundred to one, and they function as gratings. The graph illustrates that their diffraction efficiency is generally very high, surpassing what you would typically achieve with a traditional ruled grating. Naturally, there's a wavelength dependency in these gratings, similar to what you'd observe with a ruled grating.

Polarization grating applications

- Lidar for wind sensing for wind turbines
- Lidar for autonomous vehicles
- Free space lasercom
- Microscopy and neurophotonics
- Nonmechanical shutters
- Step variable focal length lenses for microscopy

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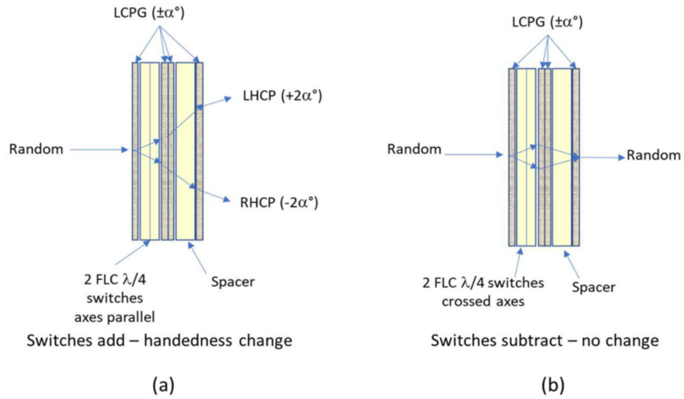
An intriguing application of these gratings has been in Lidar beams. The direction of the beam can be altered by adjusting the polarization direction introduced to the grating using a liquid crystal variable retarder. Lidar technology is crucial for wind sensing in wind turbines, obstacle detection by autonomous vehicles, and steering laser beams in free space laser communications.

Moreover, these gratings aren't limited to linear configurations; they can also be circular. This enables the creation of lenses with step-variable focal lengths, which can be beneficial in microscopy and neuro-photonics applications.

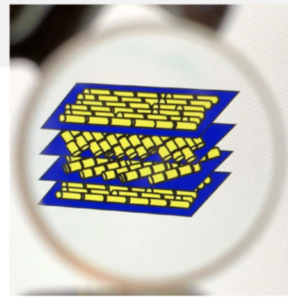
Polarization independent shutter

- Allows for less than 10% transmission loss for unpolarized input light.
- Liquid crystal variable retarders provide nonmechanical switching.
- Shutter open and close times are sub-millisecond.

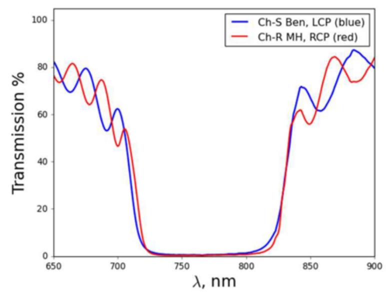


Another potential application involves creating non-mechanical shutters using these components. The graphic illustrates a configuration of liquid crystal electrically adjustable devices combined with polarization gratings. This setup can transmit approximately 90% of unpolarized light and switch it on and off as a shutter, providing a non-mechanical means of opening and closing.

Circular Polarizers



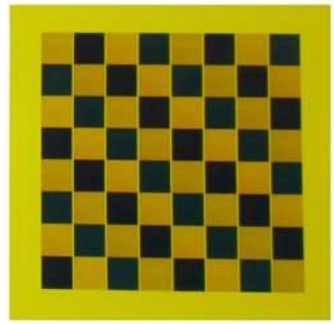
- Traditionally made by following a linear polarizer with a quarter wave retarder.
- Now these can be a single component cholesteric liquid crystal.
  - Higher contrast ratio (1000:1 vs. 100:1).
  - Higher damage threshold since rejection is by reflection.
  - Pitch length determines wavelength.
  - Birefringence determines bandpass width.



In addition to linear polarizers, circular polarizers are also available, although they are less commonly used. These are typically created by combining a linear polarizer with quarter-wave retarders. However, an alternative method involves utilizing cholesteric liquid crystals, where the rod-shaped molecules exhibit a twist throughout the layer. When this twist period is appropriately adjusted, it functions as a Bragg reflector for one-handedness of circular polarization while transmitting the opposite-handedness. The graph on the lower right illustrates the expected performance passband. The rejection of the opposite handedness is typically determined by the pitch length of the twist of the liquid crystals, while the width of the passband is influenced by the refringence of the cholesteric liquid crystal.

Spatially patterned polarizers

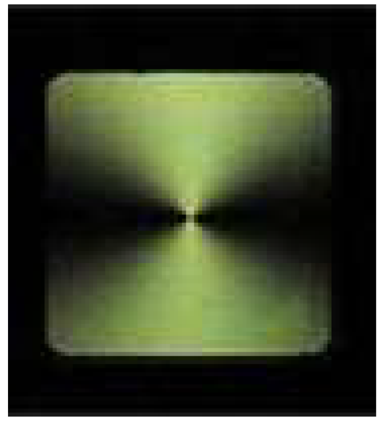
- Designed to match pixel pitch on CMOS cameras
- Superpixels allow direct images in linear polarization.



There are methods available for patterning both silver nanoparticle polarizers and using photoalignment materials. With wire grid polarizers, it's also feasible to create patterns that match the pixel pitch on CMOS and CCD cameras. By grouping individual polarizers in these patterns, it becomes possible to form superpixels, resulting in a camera capable of directly imaging in linear polarization.

Azimuthal and radial polarizers

- Continously variable polarization direction.
- Available from ArcOptix in Switzerland and nanophoton in Japan.
- Custom products from Meadowlark as well.
- Radial sometimes called z polarizers.
- Photo courtesy of ArcOptix.



There's also the option to create continuously variable polarization direction polarizers. These are offered by companies like ArcOptix in Switzerland and Nanophoton in Japan. On the right, you can see an example of such a polarizer when viewed through a linear polarizer. Meadowlark has also conducted some work in this area. These radial polarizers are sometimes referred to as "z polarizers."

Depolarizers

- Spatial scrambling of polarization using patterned photoaligned polymer retarders is new type of “depolarizer”.
- Depolarizers are really polarization scramblers over
  - Wavelength
  - Time
  - Aperture area

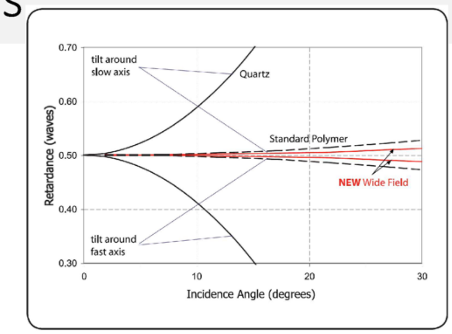
Depolarizers are often used, but they are polarization scramblers. Typically, these devices scramble polarization over a specific wavelength range and can vary in terms of wavelength or time. Additionally, they can exhibit variability across the aperture area, which can be achieved by creating a patterned retarder using techniques similar to those used for making pattern polarizers.

Retarders or waveplates

- True zero order polymer films
- True zero order spun coat films
- Patterned retarder films
- Achromatic and superachromatic
- Wide angular field
- Liquid crystal variable retarders
- LCOS spatial light modulators

Transitioning to the topic of retarders, the discussion will now center on polymer films commonly employed for this purpose. It's important to note that retarders serve as polarization modifiers rather than polarizers, which specifically select polarizations. Discussion will delve into both polymer films and spun-coat films, along with touching on the patterned films mentioned earlier.

True zero order polymer retarders

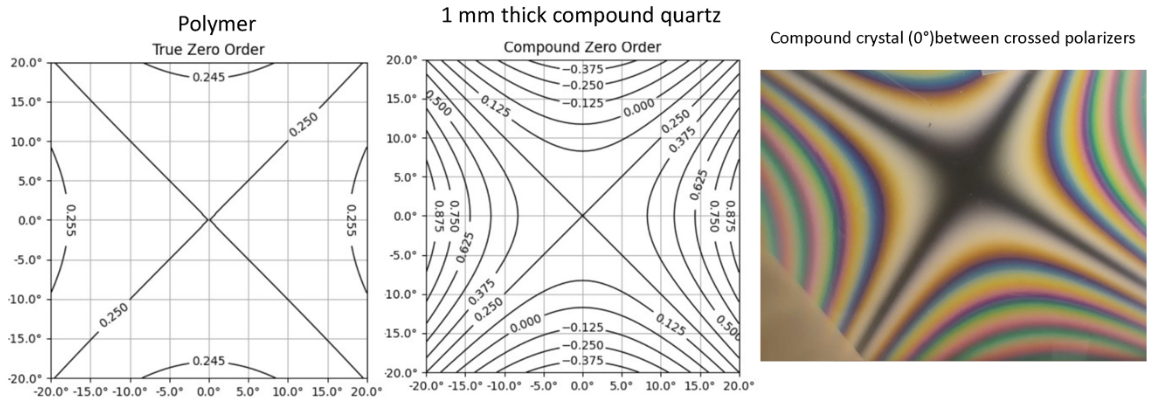


- Huge angular field of view advantage over solid crystals
- Lower cost in small quantities
- Formed by heating polymer film to softening and stretching to orient long chain polymer molecules creating a birefringence amount dependent on process conditions.
- Both positive and negative birefringence polymers are available.
- Retardances of a 125micron film as high as 5000 nm.
- Lamination between optical windows provides low transmitted wavefront distortion.
- Damage threshold above 500W/cm2 at visible wavelengths.
- Polymer films used
  - Polyvinyl alcohol (PVA)
  - Polyimide
  - Cyclic olefin copolymer
  - Polycarbonate
  - Poly(methyl methacrylate) (PMMA)
  - Polystyrene

Why opt for a polymer waveplate? One compelling reason is their cost-effectiveness. Additionally, they offer a much broader angular field of view compared to compound zero-order quartz retarders. In non-collimated beams, standard polymer true zero-order retarders prove superior, as depicted by the dashed lines in the graph to the right. Typically, these polymer films can be cast at thicknesses of 125 microns or even thinner, down to 10 microns. By subjecting them to heating and stretching, the long-chain polymers within the cast films become oriented, resulting in an anisotropy that induces birefringence in the film. The degree of birefringence depends on the process conditions of heat and stretch distance.

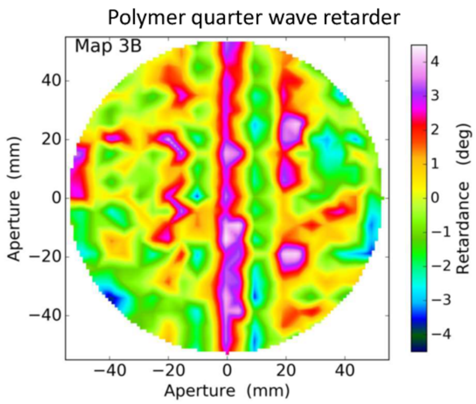
Both positive and negative birefringent polymers are available, offering good transmitted wavefront distribution, typically surpassing quarter-wave peak-to-valley at 633 nanometers when laminated between optically flat windows using a high-quality index-matching adhesive. Damage thresholds are reasonable, with a capability of withstanding up to 500 watts per square centimeter in the visible spectrum. Above is a list of some of the polymers commonly used for manufacturing such waveplates or retarders.

Angular Effects Details

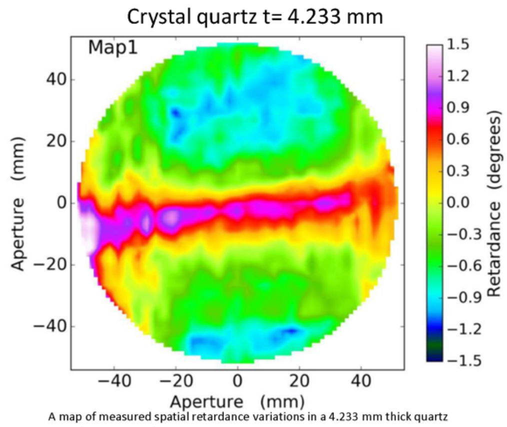


To delve further into the angular effects of a polymer retarder compared to a quartz retarder, consider the two graphs displayed in the middle and left. They illustrate how the retardance of a quarter waveplate varies with angle, noting that it's influenced by azimuth and distance from the normal beam. The compound quartz exhibits more rapid changes, with its behavior also being azimuthally dependent and dependent on the angle of incidence itself. This is visually demonstrated in the photograph on the right, showing a zero-wave magnesium fluoride waveplate sandwiched between cross polarizers and backlit. Here, you can observe that the retardance is indeed zero between cross-polarizers at the center and remains relatively consistent along the axis directions. However, it diminishes significantly orthogonal to those directions, or at 45 degrees to them. Therefore, spatial uniformity can be a crucial factor to consider.

Spatial Uniformity



Measured retardance uniformity of an 11 cm diameter polymer retarder with an average retardance of 157.7at 633 nm wavelength. Attribution: The complete rectangular map, measured by MLO, is represented in Figure 32(a) from SPIE JATIS, 6(3), 038001 (2020). https://doi.org/10.1117/1.JATIS.6.3.038001. Notice: Re-printed under Creative Commons License CC BY 4.0, see https://creativecommons.org/licenses/by/4.0/ .



A map of measured spatial retardance variations in a 4.233 mm thick quartz waveplate measured at a wavelength of 631 nm. Map of Meadowlark Optics measured data. Attribution: Figure 37(a) from SPIE JATIS, 6(3), 038001 (2020). https://doi.org/10.1117/1.JATIS.6.3.038001. Notice: Re-printed under Creative Commons License CC BY 4.0, see https://creativecommons.org/licenses/by/4.0/ .

Meadowlark frequently collaborate with astronomers, particularly with the Daniel K. Inouye Solar Telescope in Hawaii. This telescope, with its 4-meter primary, requires large optics near the focus, typically around a 12 cm clear aperture. A comparison between polymer and crystal quartz quarter-wave retarders, conducted by David Harrington at the telescope, reveals that crystal quartz offers significantly better uniformity, potentially by a factor of three or more.

Achieving uniformity with crystal quartz requires precise polishing to within a fraction of a micron spatially, corresponding to a wedge in the quartz of less than a second of arc across the aperture. Despite meticulous polishing, as demonstrated by a sample polished deterministically using the fluid jet polishing technique, there is still variation in retardance across the piece. This variability in retardance explains why birefringence values can vary, even within a single crystal of quartz.

Thermal dependence of retardance at 517 nm wavelength

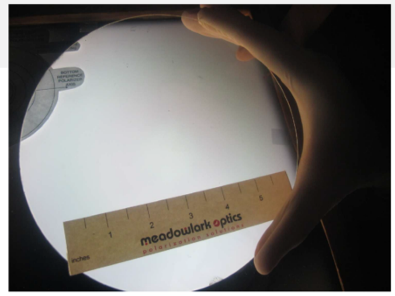
- Quartz = -0.013%/°C
- MgF2=-0.0048%/°C
- Sapphire= -0.0135%/°C
- Polycarbonate = 0.043%/°C
- Nematic liquid crystal (MLC6080: 20°C to 50°C)=-0.2%/°C

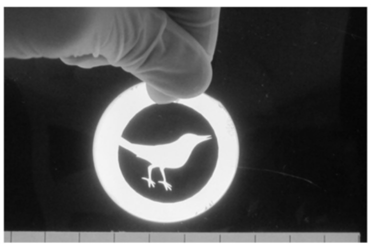
These materials also exhibit a dependence on temperature concerning retardation, as illustrated for some common crystal materials in the list above. Generally, the variations are relatively small. They are approximately a factor of 10 larger for most polymers, including polycarbonate, as measured here by Michael Kraemer. Liquid crystals, on the other hand, display even higher sensitivity to temperature. While the example provided is just one of many liquid crystals, variations between different types typically don't exceed a factor of two.

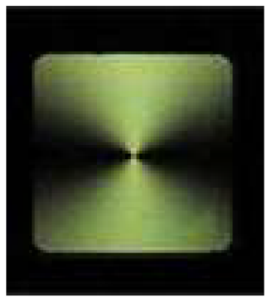
It's crucial to note that the sign of the variation of retardance with temperature differs for different materials, as depicted here.

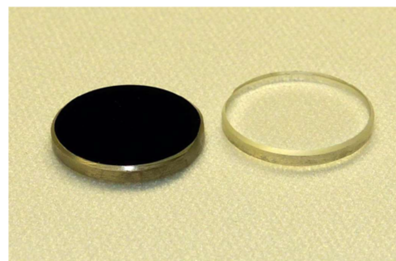
Spun coat retarders

- Crosslinked polymer layer coated over buffed or photo-aligned layer on glass substrate.
- Fast axis direction can be variable if photo-aligned.
- Large sizes available (20 cm).
- Can be applied as a layer on a mirror or lens.
- Thickness less than 10 microns
- Transmission from 400 nm to 3.4 microns.
- UV exposure can reduce retardance if not laminated
- Heating reduces retardance.









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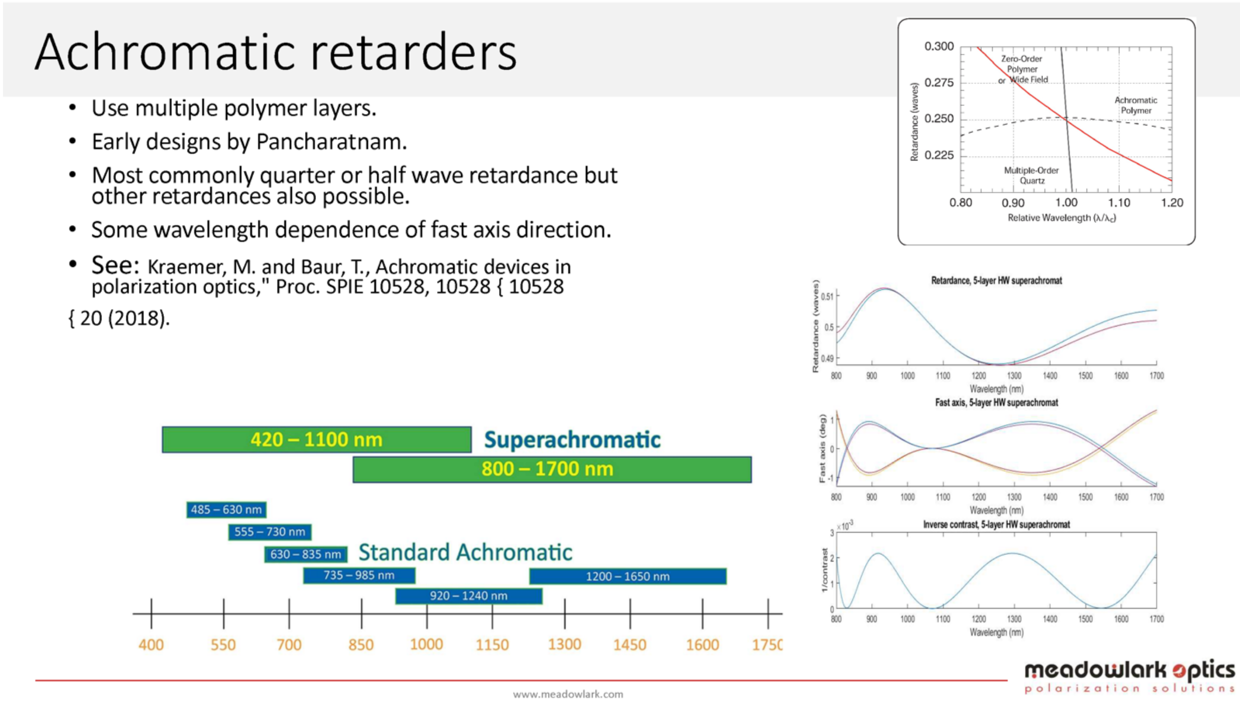
Another type of retarder involves placing a spun coat polymer layer on top of a glass substrate. The glass substrate must have a polymer direction defined by either a buffed polymer layer, which is spun-coated on first, or by a photo-aligned layer. In the case of a photo-aligned layer, a polymer layer is spun-coated and then aligned by exposure to UV linearly polarized light. The direction of polarization determines the alignment direction of the overlying polymer layer, which acts as a retarder. If recalled correctly, the alignment direction is perpendicular to the linear polarization direction used to set it.

These retarders are typically less than 10 microns in thickness and offer good transmission over a wide wavelength range. They can be delicate to handle, so it's advisable to laminate them in glass. Heating before lamination can also alter the retardance. Furthermore, they can be patterned to remove retardance in specific areas.

Additionally, these retarder layers can be spun-coated onto a lens or mirror surface, serving as another optical element in your system. While not a common practice for us, the size limitation is quite reasonable, with pieces up to 20 cm in diameter achievable. This is illustrated in the picture in the upper right, where the retardance appears uniform over the area when viewed between crossed linear polarizers.

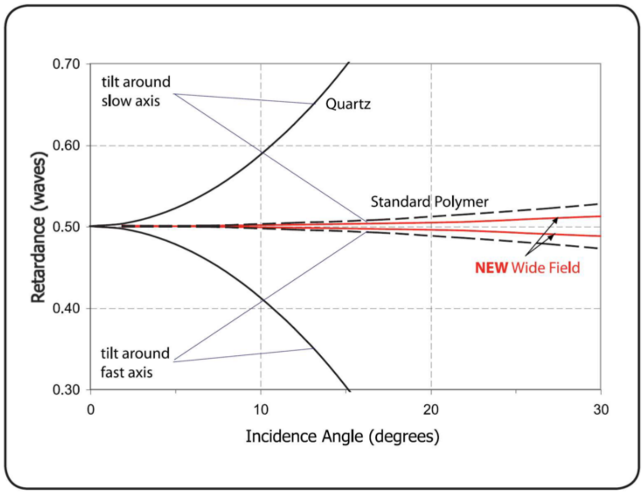


Achromatic retarders are a significant product at Meadowlark and are widely popular. These retarders utilize multiple polymer layers, as they would be prohibitively expensive to make out of crystals. Early designs were pioneered by a gentleman named Pancharatnam. Pancharatnam designs typically consist of three layers of polymers, each with different retardance, and clocked at different fast axis directions. These designs have been further developed by Alan Title, with detailed information available in a referenced paper.

The wavelength range covered by the three-layer Pancharatnam designs is depicted by the blue bars in the graph. Meadowlark Optics' superachromatic retarders consist of five polymer film layers and cover an even larger range, accommodating quarter-wave, half-wave, or any other desired retardance.

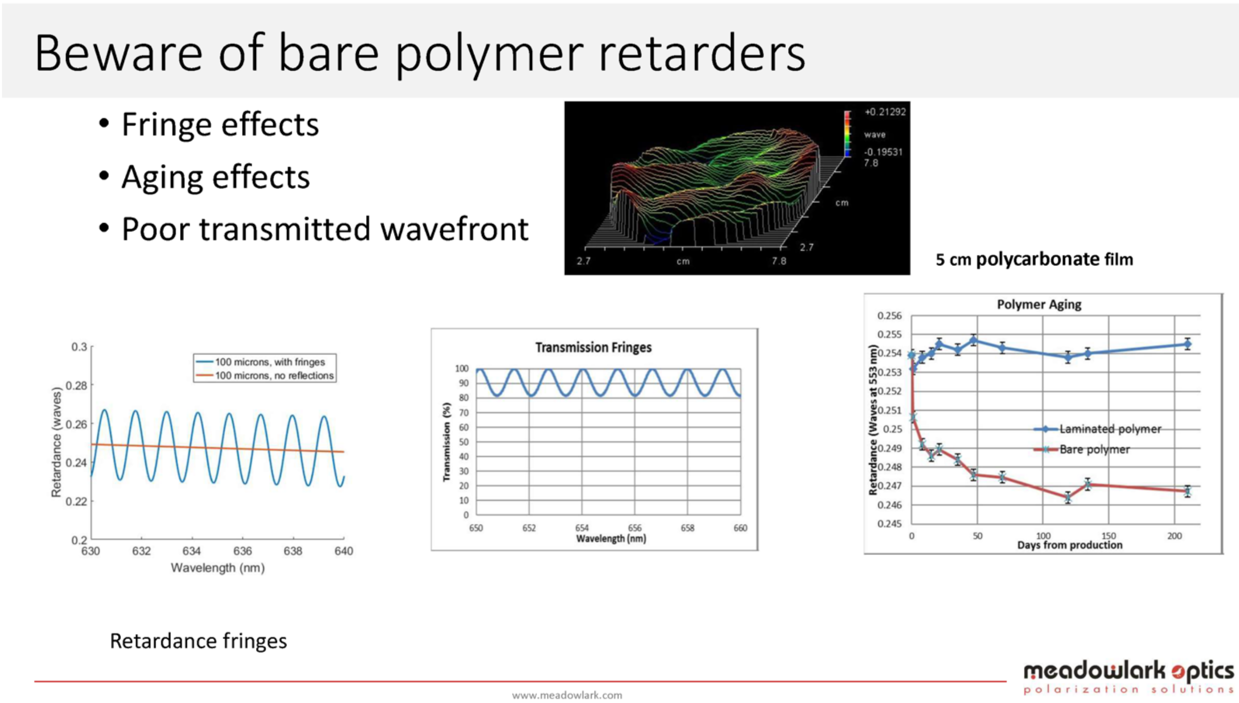
The upper two graphs on the right illustrate that the fast axis direction varies with wavelength, as shown in the middle graph. However, it is possible to reoptimize these designs to reduce the range over which the retardance is uniform in wavelength and to minimize the fast axis wander. Various options are available, and Meadowlark specializes in designing these devices, with Dr. Kraemer having conducted significant work in this area for the company.

Wide field retarders



Combination of a positive and a negative birefringent film.

Meadowlark can also produce retarders with an even wider field of view than our standard polymer true zero-order ones. The variation in the angle of incidence is illustrated by the red lines on this graph. It's worth noting that all the lines on this graph represent the worst-case scenario, occurring when the rays are in the plane of incidence for either the fast or the slow axis of the waveplate. These particularly wide field retarders are a combination of a positive and a negative birefringent film in a specific ratio, resulting in an enhanced angular field.

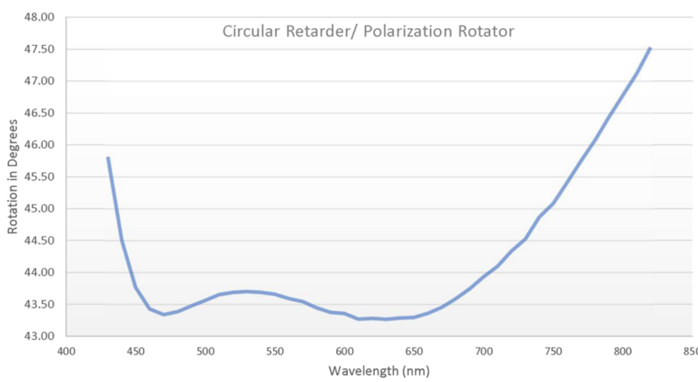


The use of bare polymer retarders is inadvisable due to fringing effects. The free-standing films mentioned earlier exhibit etaloning, affecting both retardance and transmission. These fringes are problematic because they shift rapidly with small changes in wavelength. For instance, in a 100-micron-thick polymer film, the retardance can vary by more than a hundredth of a wave, as demonstrated in this example.

Additionally, unless they are laminated, free-standing polymer films experience aging in terms of retardance over time, as depicted by the graph. The red line represents a bare polymer, while the blue line represents one laminated in glass. The graph shows that laminated ones remain relatively stable over several months, fluctuating by around a thousandth of a wave. Meadowlark's metrology capabilities allow us to measure retardance to a fraction of a thousandth of a wave, enabling precise analysis of these effects.

Furthermore, bare polymers suffer from poor transmitted wavefront distortion, as mentioned earlier. However, this can be improved upon when laminated.

Achromatic Circular Retarder

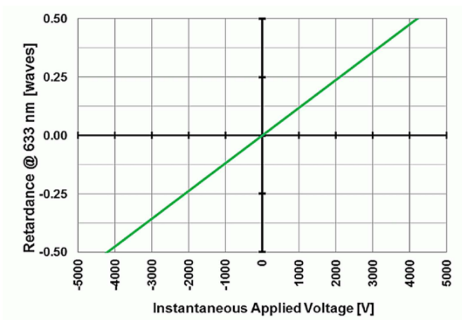


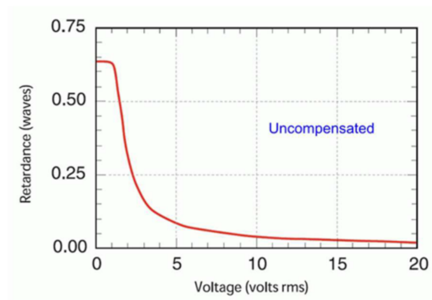
In addition to the linear retarders discussed, it's important to consider other types, such as circular retarders, often referred to as polarization rotators. Traditionally, these have been crafted by cutting quartz, offering monochromatic performance where the degree of rotation strongly depends on wavelength.

However, there are now achromatic alternatives made using polymer films. These devices provide consistent rotation of the plane of linear polarization incident over several hundred nanometers. For example, one such device recently produced at Meadowlark Optics achieves a rotation of approximately 43.5 degrees.

Electrically variable waveplates

- Pockels cells (Kilovolts but nanosecond switching time)
- Liquid crystal variable retarders (10 volts but millisecond switching)



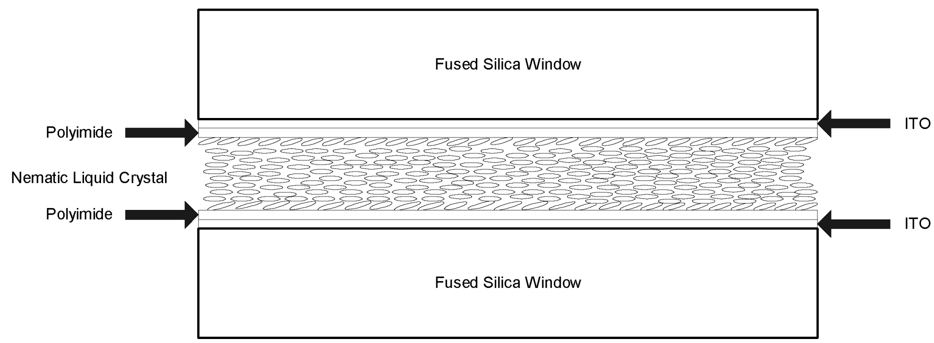


Electrically variable waveplates, essential for precise polarization control without mechanical adjustment, offer versatility in manipulating linear and circular polarization. Meadowlark's pioneering product, Pockels cells, known for rapid switching, require high voltages, around 4 kilovolts for a half-wave switch at visible wavelengths, resulting in significant cost (tens of thousands of dollars) and operational demands.

All electrically variable devices, including Pockels cells, must be DC-balanced to prevent damage. For instance, they cannot operate with square wave signals below approximately 10 hertz.

Liquid crystal retarders, a popular and cost-effective alternative, feature minimal wavefront distortion and sub-millisecond switching. However, their voltage-dependent retardance is nonlinear, primarily between one and four volts. Despite this, they offer aperture sizes up to approximately 1.7 inches (40 millimeters) as standard products.

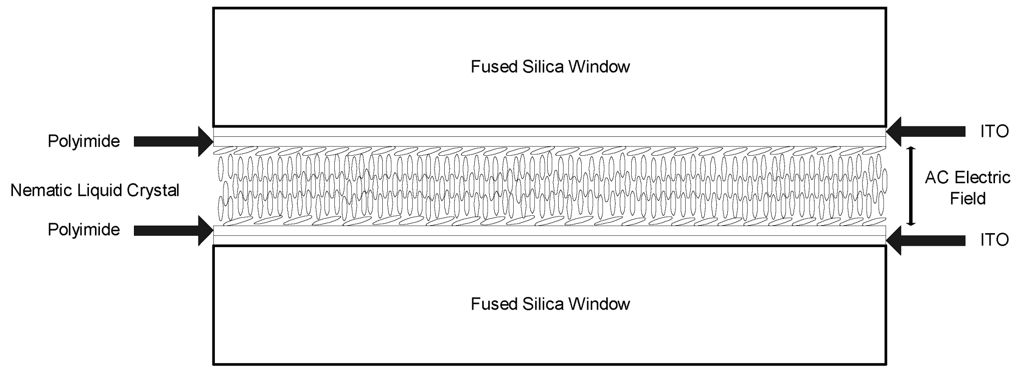
LC Variable Retarder at 0 Volts



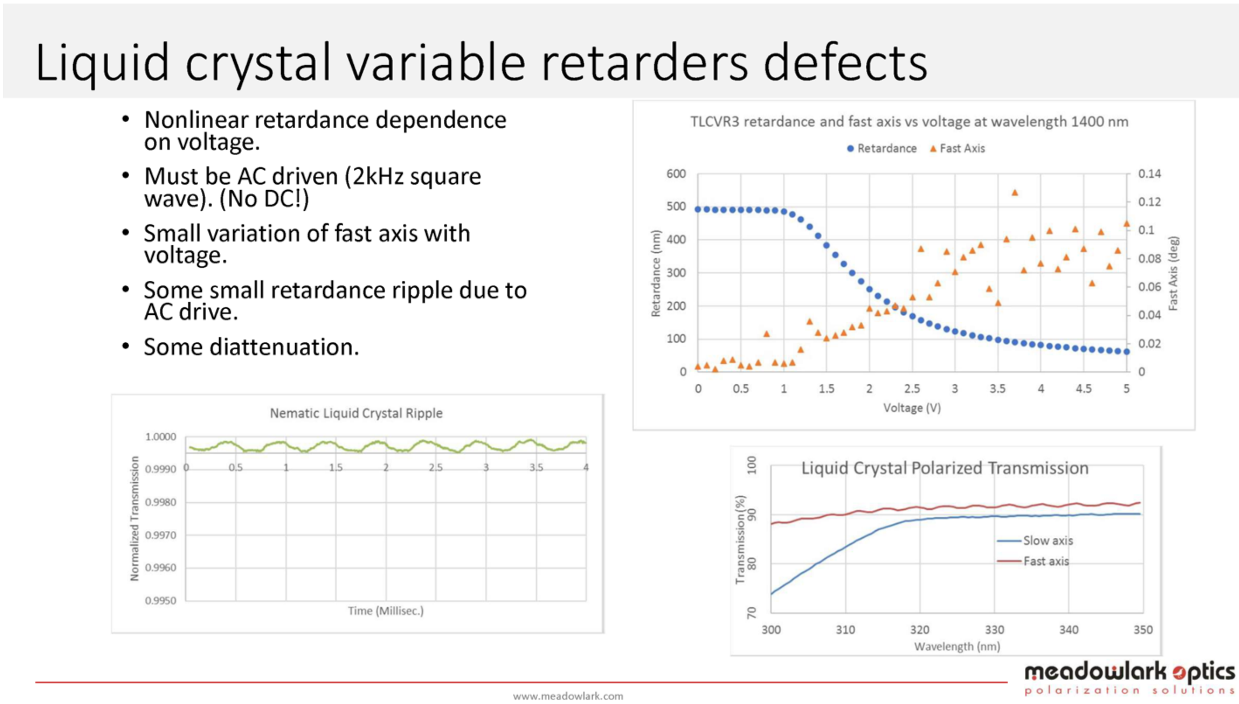
To provide a brief overview, the liquid crystal products depicted here show a cross-sectional view, although the thicknesses are not exactly to scale. They consist of several layers: first, a few silica windows; followed by a thin layer, about 10 nanometers thick, of indium tin oxide, serving as a transparent electrical conductor. Adjacent to this layer is a polyimide layer, buffed with a cloth to align the elongated molecules, as illustrated by the ellipses. The liquid crystal layer, forming the core of the sandwich, is approximately five to 10 microns thick. While the polyimide and indium tin oxide layers are typically 10 nanometers each, the silica windows are several millimeters thick to ensure minimal transmitted wavefront distortion.

Achieving uniformity in the liquid crystal layer's thickness is crucial, requiring precision to within a fraction of a micron across the clear aperture to ensure consistent retardance. In its current state, the retardance is high because the molecules are aligned perpendicular to the light beam's transmission direction.

LC Variable retarder at 5 volts



When a voltage is applied to the indium tin oxide layers, it induces a dipole in the liquid crystal molecules, causing them to stand on end. This reorientation reduces the birefringence for the light passing through because the isotropy is no longer observed. However, some retardance remains due to adjacent molecules being relatively pinned by the alignment layer, which exerts a stronger force than the electrical field torque. As a result, these molecules retain their alignment despite the applied voltage, leading to residual retardance that cannot be eliminated.

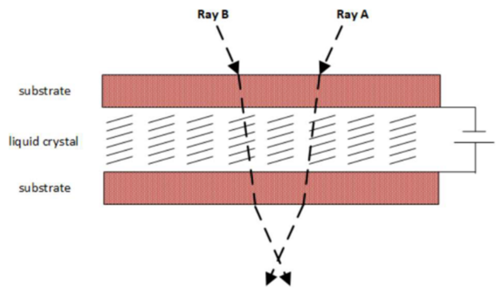


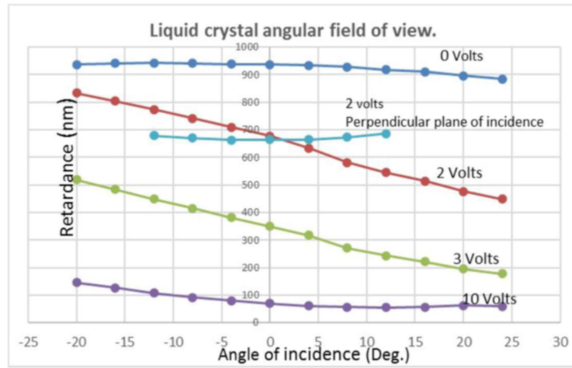
What are some of the other concerns regarding these devices? Firstly, as mentioned earlier, the retardance nonlinearly varies with changes in applied voltage. Additionally, there's a slight variation in the direction of the slow or fast axis of the retarder with voltage, typically around a tenth of a degree when well-aligned. Alignment discrepancies can lead to variations in the access direction of voltage by several degrees, an important consideration when evaluating such products.

Another issue is the non-uniformity of retardance over time, often referred to as a ripple effect. When observed between cross-polarizers, this manifests as an intensity ripple, typically around a hundredth of a percent of the device's transmission.

Finally, there's diattenuation, particularly notable in the UV spectrum, where there's a disparity in transmission for light polarized along the fast or slow axis of the device. While this may not be critical for most applications, it's important to avoid using these devices in the UV unless the intensity is minimal to prevent potential damage to the organic liquid crystal material. The observed ripple effect with wavelength is attributed to Fabry-Perot-type etalon fringes between the interior surfaces of the liquid crystal cell walls, resulting in weak reflections or etalons.

Liquid crystal angular field of view





- Asymmetric field of view along slow axis.
- Worst at intermediate voltages.
- Fixed by using a double cell.

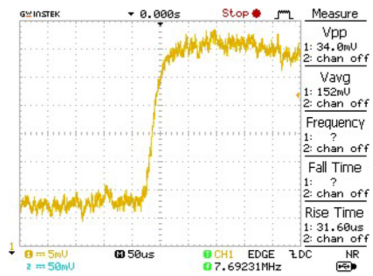
Another important effect to consider is the variation in retardance at intermediate voltages. At these voltages, the elongated molecules are tipped up differently, resulting in varying retardance for light rays traveling through the liquid crystal. This effect is particularly pronounced when the light is polarized along the direction of the buff.

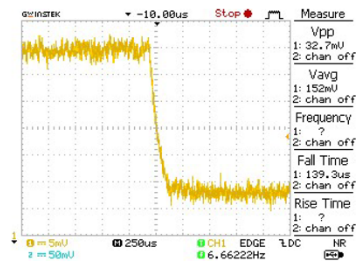
Quantitatively, this variation is illustrated in the graph on the right, which depicts how retardance changes with the angle of incidence in the plane of the buff direction or the slow axis of the variable retarder. This asymmetry is more prominent at intermediate voltages.

To address this issue, employing a second cell with a reversed tip direction, determined by the buff direction (whether buffed from right to left or left to right), can mitigate this asymmetry if both cells have the same thickness.

LC response time optimization

- Use heated high birefringence LC and a voltage overdrive effect called transient nematic effect.
- For half wave stroke at 532 nm the rise time for increased voltage is 32 microseconds and the fall time for reduced voltage is139 microseconds



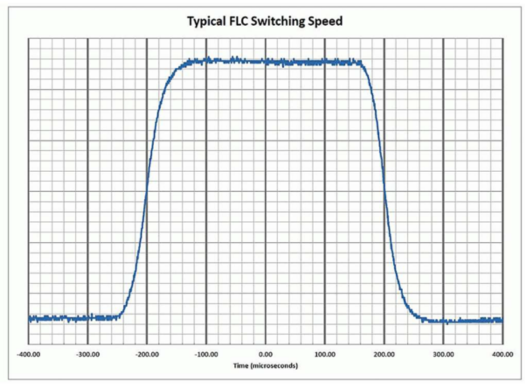


Nematic liquid crystals, commonly used in displays, are generally considered slow. However, with techniques like transient nematic effect and optimized alignment methods, Meadowlark can achieve a response time of 32 microseconds when voltage is applied. When the voltage is removed and the molecules relax, this time increases to about 140 microseconds, as observed at a wavelength of 532 nanometers.

It's important to note that for liquid crystal variable retarders, the response time is proportional to the square of the cell thickness, which also correlates with the retardance. Therefore, as the wavelength increases, requiring a thicker cell for a half-wave stroke, the response times are extended accordingly in a squared manner.

Ferroelectric LC's

- 100 microsecond switching time.
- Constant retardance but binary fast axis direction.
- Axis direction switches 45 deg. with voltage sign change.
- Must be voltage DC balanced.
- Lowest safe switching rate is 1 Hz.
- LC material availability limited.

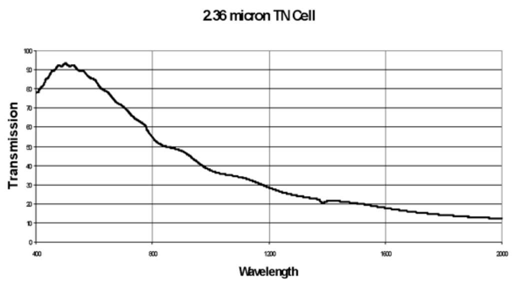


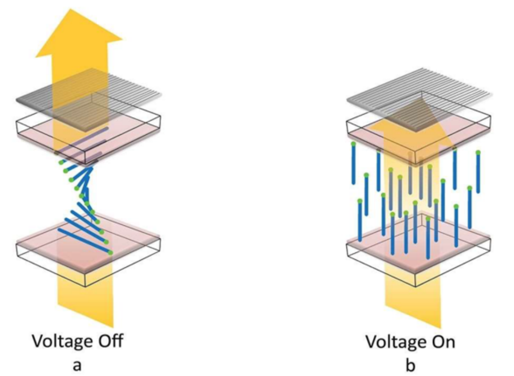
Another type of liquid crystals worth mentioning is ferroelectrics. These exhibit rapid switching capabilities without the need for heating. While their retardance remains fixed, changing the applied voltage's polarity quickly switches the fast axis direction by 45 degrees. By aligning this axis appropriately, such as with a half-wave thickness layer, linear polarization states can be rotated by 90 degrees, making them useful for high-speed shutters, among other applications. However, like with other electrically variable devices, DC-balanced voltage is crucial to prevent damage, limiting the switching rate to around 1 Hertz.

One drawback of using ferroelectric liquid crystals is their limited availability. The supply relied on has become uncertain, posing potential challenges for future availability as a readily purchasable product.

Twisted nematic liquid crystals

- Uses "adiabatic following" effect
- Performs as high contrast shutter (50,000:1)
- Broad wavelength range "open"
- Response times 4.5 and 0.38 millisec. Open and closed respectively at 670 nm.





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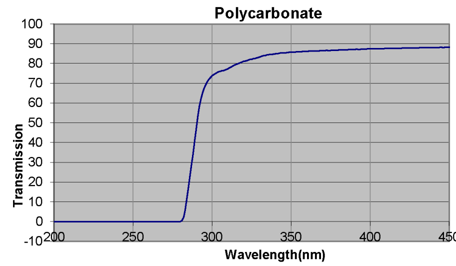
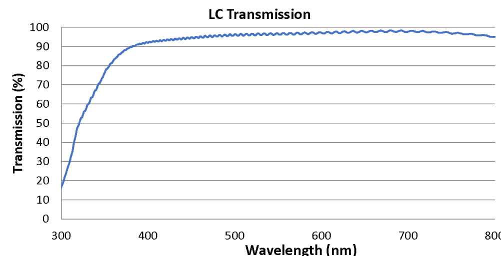
Another type of liquid crystal device utilizes nematic liquid crystals combined with a cholesteric agent. This agent induces a twist in the rod direction between the cell walls, as illustrated in the diagram on the right. When a linearly polarized beam enters, it undergoes adiabatic following, where the polarization direction follows the twist. Initially, when the polarizer directions are crossed in the zero-voltage state, the light is blocked by the exit polarizer. However, when voltage is applied, the molecules stand up, causing no change in the incident polarization, allowing it to pass through the exit polarizer.

These devices exhibit excellent contrast ratios, often reaching several tens of thousands to one. They function effectively as high-contrast shutters, with response times in the open state (voltage off) typically in the range of a few milliseconds. Transmission rates are quite high over a reasonable wavelength range, typically 200 to 300 nanometers. Importantly, the contrast is primarily determined by the quality of the polarizers used on the entrance and exit faces rather than the liquid crystal defect itself.

UV and retarders

- Organic molecules (LC's and polymers) are generally absorptive in UV and can be damaged by it.
- Solid crystals are a better choice with quartz still good at 193 nm and MgF2 even shorter to 110 nm.
- Damage threshold higher for low birefringence LC (1.3 J/cm2 at 351 nm wavelength).



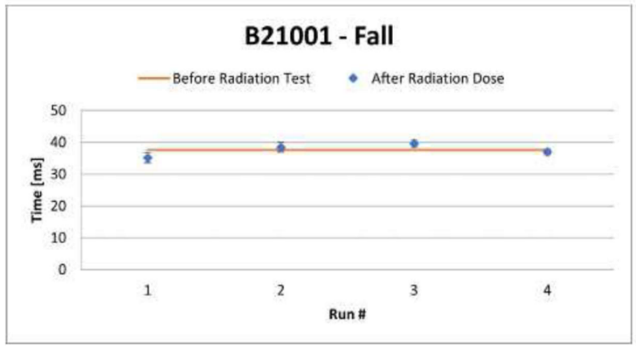


Organic materials, including liquid crystals and polarizers, typically exhibit absorbance in the ultraviolet (UV) range and can be susceptible to damage from UV radiation. UV crosslinking is a common issue with organic materials, posing a potential concern. In such cases, it's advisable to opt for more traditional materials like quartz, magnesium fluoride, sapphire, or even mica, which are commonly used and less susceptible to UV damage.

However, there are possibilities for working in the UV range, down to approximately 320 or 350 nanometers, using low birefringence liquid crystals. In these instances, the damage threshold is around 1.3 joules per square centimeter, as shown above.

Nemactic LC's in Space

- Frequent use in manned space flight environment.
- Must be protected from UV.
- Testing for Solaris mission with a Jupiter flyby indicates no degradation at 100 kRads of Gamma radiation when mission expects 40 kRads total dose.



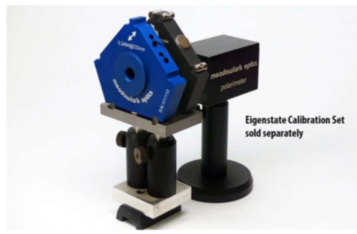
In manned space flight applications, the consensus is that implementing mechanical motion in space can cost up to a million dollars. However, by employing non-mechanical polarization changes using liquid crystals, tasks in space can be performed more efficiently. Nematic liquid crystal devices have been utilized for over three decades in manned space flights, such as the space shuttle, without issue as long as they are shielded from UV radiation.

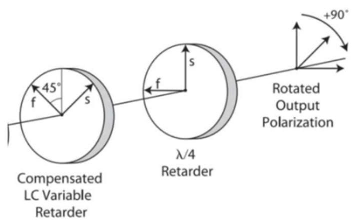
Extensive testing, conducted by Meadowlark, Goddard Space Flight Center, and a Spanish research group, has demonstrated that exposure to gamma radiation does not lead to significant degradation. For instance, in a study for a Solaris mission involving a Jupiter fly-by, where the radiation environment is harsh, no damage was observed even at exposure levels of 100 kilorads of gamma radiation.

The primary failure mechanism in liquid crystals is often the onset of cross-linking, resulting in increased viscosity and longer switching times. However, radiation testing at levels of 100 kilorads has shown no significant change in the response time of the liquid crystals, indicating their suitability for replacing mechanical mechanisms in outer space.

Applications of LC variable retarders

- Glaucoma detection
- Disk drive texturing
- Tattoo removal
- Quantum communication/entanglement
- Wind speed measurement
- ISS docking of Dragon capsule
- Polarimetry
- Tunable passband and notch filters
- Phase shifting for interferometers
- Variable beamsplitters
- Diamond color grading
- Light pollution suppression
- Polarimetry
- Beam steering
- Voltage controlled linear polarization rotation





There are a range of applications for liquid crystal variable retarders. One notable application is in glaucoma detection, where Karl Zeiss utilizes this technique by analyzing the birefringence in the nerve bundle at the back of the eye. This method provides an early diagnosis of glaucoma without the discomfort of traditional air puff tests.

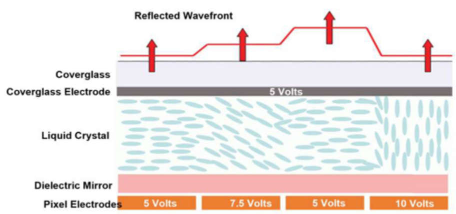
Liquid crystal variable retarders also find utility in laser beam intensity control for tasks like disk drive texturing and tattoo removal. Additionally, they are instrumental in polarimetry, as demonstrated by the compact polarimeter showcased in the provided image.

An intriguing use is in color grading for diamonds, where tunable filters aid in quantitatively determining diamond color. This application is exemplified by the central yellow diamond in the displayed ring, a relatively rare find. The wearer of the ring recently tied the knot, marking a special occasion.

Furthermore, liquid crystals combined with cycloidal polarization gratings enable beam steering, as illustrated by the diagram depicting the rotation of a linearly polarized beam. However, an innovative attempt to synchronize liquid crystal shutters with flickering LED streetlights for light pollution suppression has faced challenges due to changes in LED technology, diminishing the flicker frequency.

LCOS spatial light modulators

- Pixellated LC variable retarders.
- LCOS = liquid crystal on silicon
- Used for either phase or intensity modulation.
- Frame rates up to 1.4 kHz on 1024x1024 pixel array.



Dielectric Mirror Backplane

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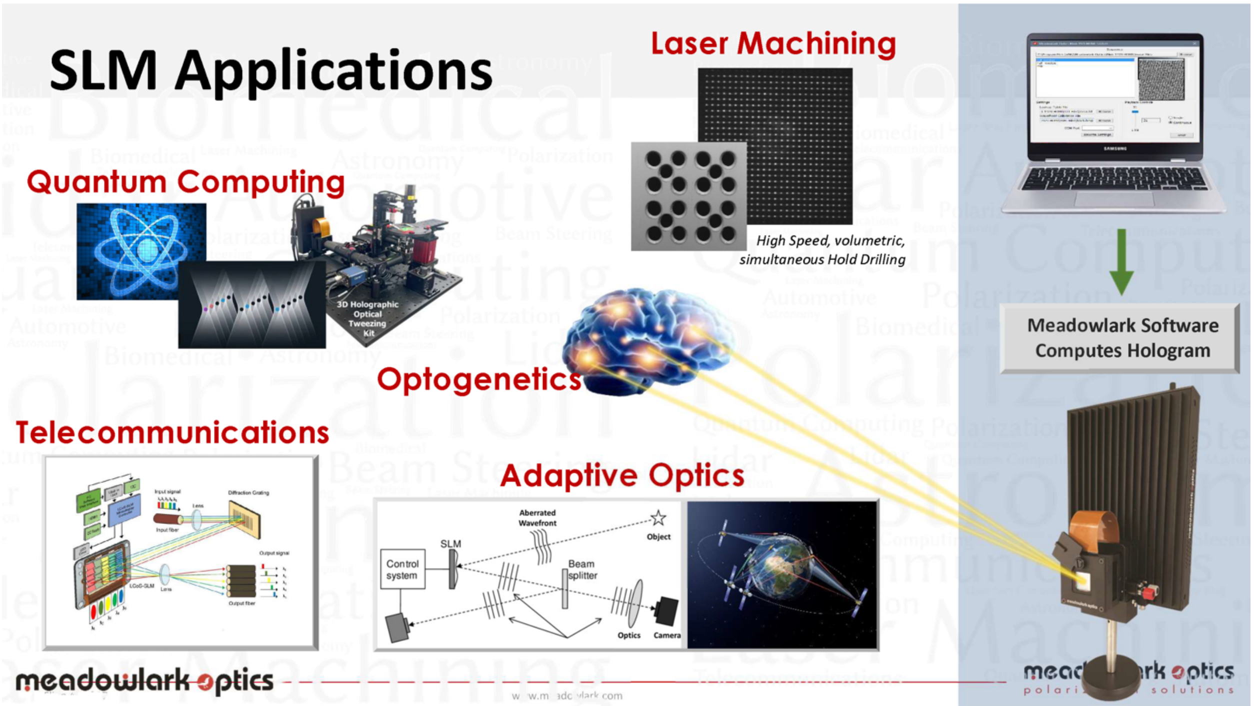
polarization solutions

Liquid crystal variable retarders offer versatility in reflection applications, especially when paired with a silicon backplane coated with a dielectric mirror. By spatially adjusting the refractive index, these devices can manipulate the reflected light's wavefronts or create holograms. This capability enables the generation of arbitrary wavefronts, as demonstrated by the device depicted here, which is a spatial light modulator. With pixel counts exceeding a million and frame rates of up to almost two kilohertz, these devices deliver high-performance reflective capabilities.



Spatial light modulators serve various purposes such as wavefront correction in astronomy and optogenetics, as illustrated here. Additionally, they play crucial roles in quantum computing, wavelength division multiplexing systems, and the creation of multiple beams from a single laser for parallel drilling in metals.

Summary

- New materials and devices provide new polarization control and measurement capabilities.
- Both new and “old” materials have defects and limitations that must be considered when implementing them in devices and systems.

In summary, while there are new materials and devices available, some commercially and some not yet, it's important to acknowledge the defects and limitations inherent in both new and old materials when integrating them into devices and systems.