Polarimetry: From the Sun to Stars and Stellar Environments
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New Optics for Astronomical Polarimetry

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Abstract. There is a variety of new polarization optics that can be employed for polarimetry and for polarization control. Many are enabled by new materials including polymers and liquid crystals. We survey here these and other relatively new devices and components available commercially that open new possibilities for astronomers.

Keywords. instrumentation: polarimeters

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1. Introduction

New devices open new possibilities for studying our sun and stars. The CCD detector first introduced now more than fifty years ago is a prime example of this. The primary components for polarimetry are polarizers and retarders or waveplates. Polarizers, until the last thirty years, have been mostly dichroic sheet polarizers such as those made for years by Polaroid Corporation and calcite or quartz polarizers for use at wavelengths outside the visible range. Retarders have been mostly made from quartz, mica and calcite with the latter two limited in size by what mother nature provides since they are only mined and not grown commercially. Quartz can be grown large enough to provide retarders with a clear aperture up to about 15 cm but presently not larger. There is a need for other polarizer and retarder materials that can cover a larger wavelength range and do so with larger clear apertures compatible with todays much larger telescopes. The sheet polarizers are limited to the visible and the near infrared by the available dichroic dyes. The range of size and wavelengths available in polarization components is greatly expanded by employing new materials including liquid crystals and polymers. We also describe here component performance gains made by using modern tools of holography and microlithography to create useful microstructures.

2. Liquid Crystals

Liquid crystals provide electrical control of polarization at low voltages. The most common types are nematic and ferroelectric. For both types the supplied drive voltage must be DC balanced to avoid damage to these materials.

The nematic liquid crystals are usually configured as variable retarders. Their response to a 2.0 kHz square wave drive voltage is nonlinear as shown in Figure 1. The retardation does not track the AC drive voltage but does have a small amount of ripple at 4 kHz. The amplitude of the ripple is a fraction of a percent with appropriate choice of materials. The retardation does not reach zero for voltages below 20 V but a fixed retarder can be subtracted from the variable liquid crystal one to reach zero retardance. Figure 2 shows that the transmission of one standard nematic liquid crystal material is sufficient for good performance in the infrared out to about $5.7\,\mu$m and at some wavelengths out to $11\,\mu$m (Petrak & Baur 2014). These variable retarders can also be optimized for performance at shorter wavelengths down to 300 nm in the UV with some reduction in transmission.

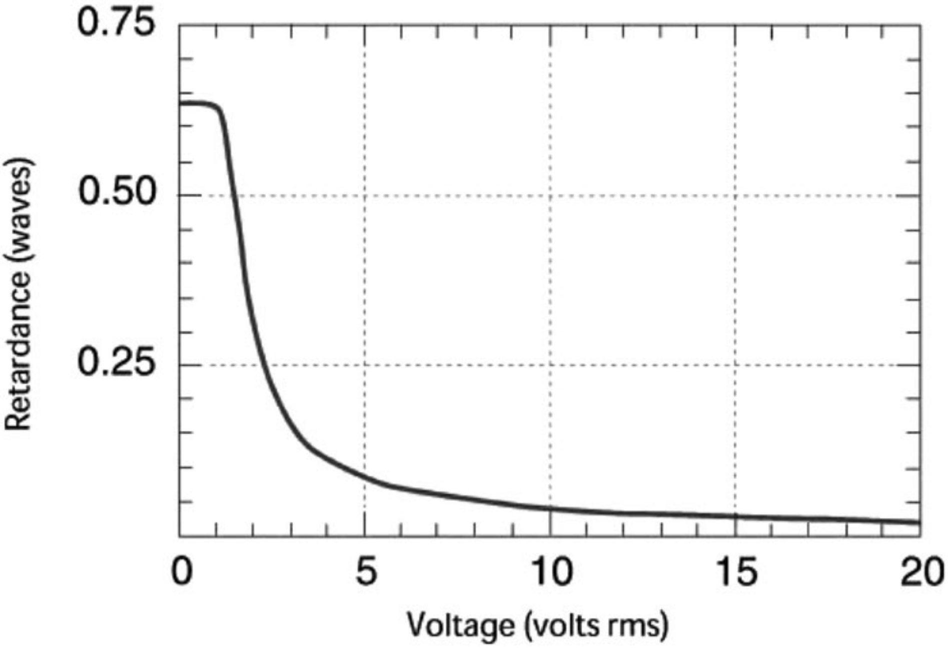

Figure 1. Voltage response function for a liquid crystal variable retarder. Retardance can be forced to reach zero by subtracting a polymer retarder.

However, strong UV radiation can damage the liquid crystals. There is a small undesirable azimuthal rotation of the slow axis direction as a function of voltage. The amount of this rotation depends on the choice of liquid crystal and on the thickness of the liquid crystal layer. Typical birefringences for nematic liquid crystals are in the range of 0.05 to 0.25. Typical zero voltage retardances are above half wave at visible wavelengths for liquid crystal layers that are less than 5 μm thick. Figure 3 shows a typical nematic liquid crystal variable retarder response time of about 5 ms when voltage is applied and about 30 ms when voltage is removed. In some cases this speed can be increased five to ten times with special drive schemes and with heating to reduce viscosity. The maximum practical nematic liquid crystal thickness is about 15 μm, which provides a maximum retardance of about six or seven waves at visible wavelengths. Nematic liquid crystals can also be configured to be achromatic polarization rotators for 90° rotation using a twisted nematic configuration (Schadt & Helfrich 1971).

Ferroelectric liquid crystals have faster response times, on the order of 100 μs. They have a fixed retardance but the optic axis direction is electrically switched, usually by 45°. They are usually configured to be half wave at some wavelength by setting an appropriate thickness of the liquid crystal layer for that wavelength. The optic axis rotates through 45° when the liquid crystal cell is driven electrically. This produces a rotation of input linear polarization by 90° if that input polarization direction is at 45° to the optic axis.

There is no fundamental limit to the size of the clear aperture of liquid crystal devices although the processing equipment at our company has a maximum size capacity of 20 cm diameter. Both nematic and ferroelectric liquid crystals can also be used as static retarders with good uniformity of retardance and with low transmitted wavefront distortion.

Longitudinal Pockels cells are an alternative to liquid crystals when even faster response time is required. These devices are electrically variable retarders that switch in less than

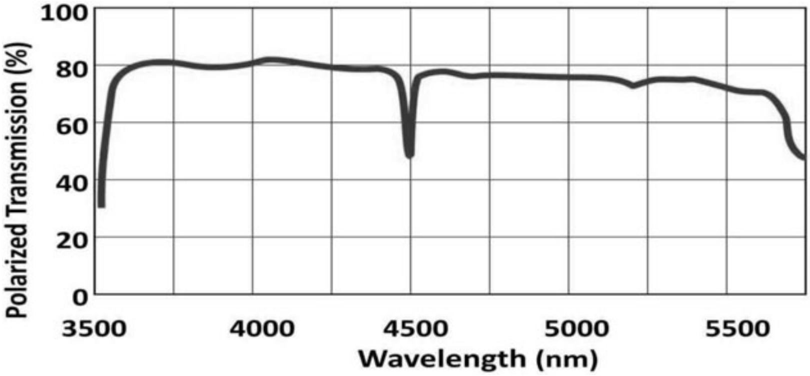

Figure 2. Infrared transmission of a liquid crystal variable retarder built using germanium windows. Transmission remains high for most wavelengths out to 11 μm.

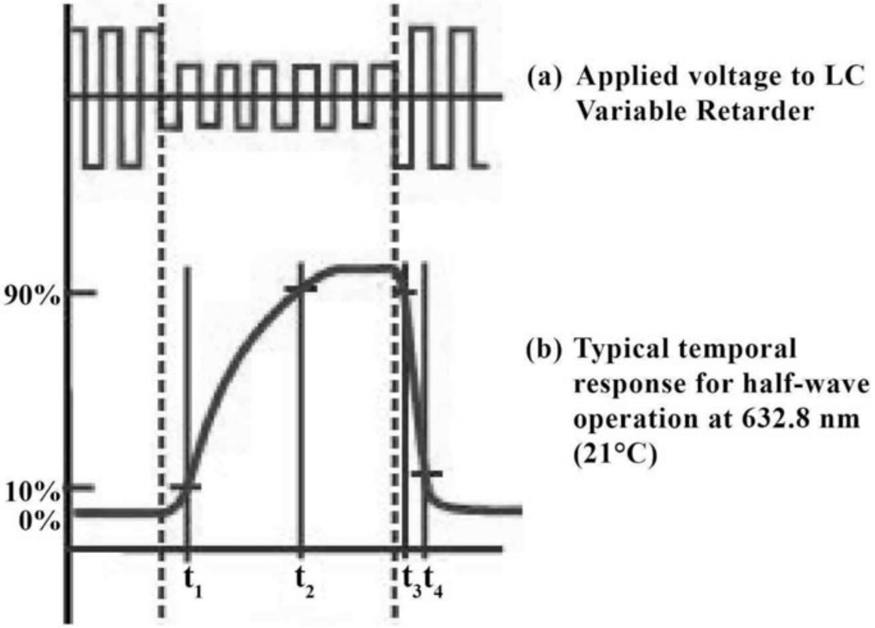

Figure 3. Response time of a liquid crystal retarder is asymmetric. The rise time, $t_2 - t_1$, is typically about 30 ms and the fall time, $t_4 - t_3$, is about 3 to 5 ms. More complex voltage drive schemes can improve on this performance.

10 ns. Their angular field of view is only $1 - 2°$ and half wave switching requires about 4 kV.

3. Polymers

There are several polymer films that are useful as retarders. These include polyvinyl alcohol, polycarbonate, polystyrene and reactive mesogens. The first three on this list are usually cast into films with thicknesses of a few tens of μm. They become birefringent when heated to their glass transition temperature and stretched. Generally birefringences are less than 0.05 for these stretched films, with the birefringence value dependent on stretch distance and process temperature. Transmitted wavefront distortion is one or two

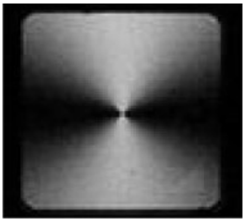

Figure 4. Photograph of an azimuthal polarizer viewed through a linear polarizer. Courtesy of ArcOptix.

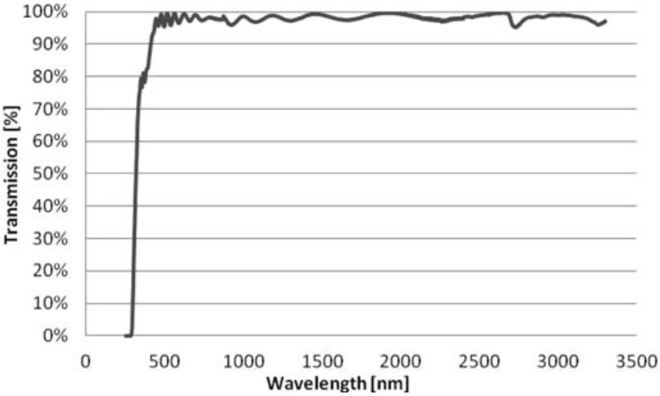

Figure 5. Transmission of a reactive mesogen retarder spun coat onto a fused silica window.

waves but can be reduced to less than 1/8 wave (P-V at 633 nm) when the polymers are laminated between optically flat windows with a good index matching optical adhesive. A single film can be made with retardance as high as 5 μm but good uniformity of retardance is usually restricted to an aperture of 10 cm or less.

Reactive mesogen retarding films are produced by spin coating a fluid over a liquid crystal alignment layer on an optically flat window (Tran & Baur 2012). The fluid is cross linked by UV exposure and becomes a solid polymer retarder film with the optic axis aligned parallel to the direction dictated by the alignment layer. The alignment direction is set either by a mechanical buffing process or by exposure to UV polarized light. The UV polarization direction sets the optic axis alignment direction. We can make patterned retarders by patterning the UV exposure to create features as small as a micron. Figure 4 is an example of an azimuthal polarizer made in this way by ArcOptix by combining a patterned retarder with a linear polarizer. Figure 5 shows that the infrared transmission on reactive mesogens is high out to at least 3.3 μm. Reactive mesogen retarding layers can be coated on mirror and lens surfaces as well as on flat windows. Layer thickness for quarter wave retardance at 550 nm is about a micron. We have produced uniform retardance to ±0.01 waves for reactive mesogen layers with a clear aperture up to 20 cm.

Polymer films can be stacked to provide achromatic retarders of any retardance from about 1/8 wave to 1/2 wave using designs similar to those developed by Pancharatnam (1955). Retardance will be within 0.01 wave of the design retardance from 0.85 times the center wavelength to 1.2 times the center wavelength (Fig. 6).

Another type of polymer retarder stack improves the angular field of view over a normal true zero order polymer retarder by about a factor of two. All polymer retarders are a great improvement in angular field of view over compound zero order quartz retarders as shown in Figure 7.

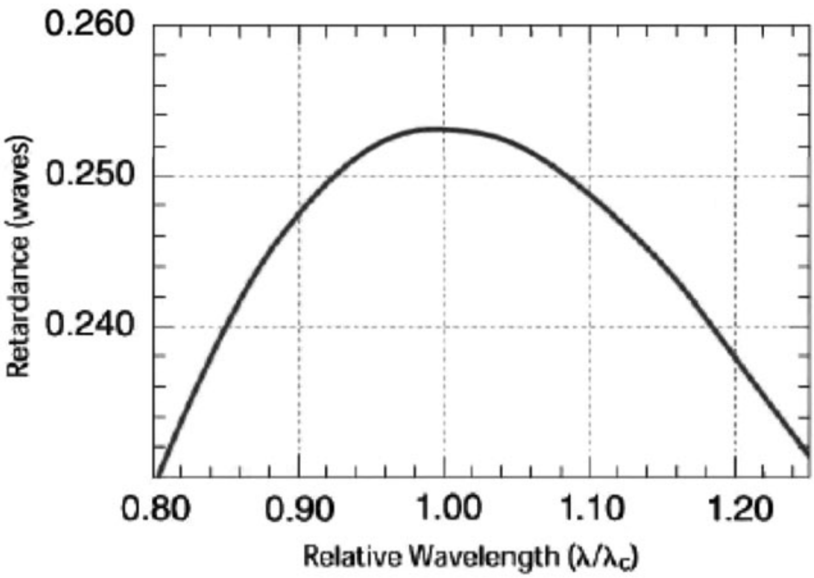

Figure 6. Wavelength dependence of a Pancharatnam quarter wave achromatic retarder made using polymer retarders. Retardance is within 0.01 wave from 0.85 times the center wavelength to 1.2 times the center wavelength for both quarter and half wave retarders.

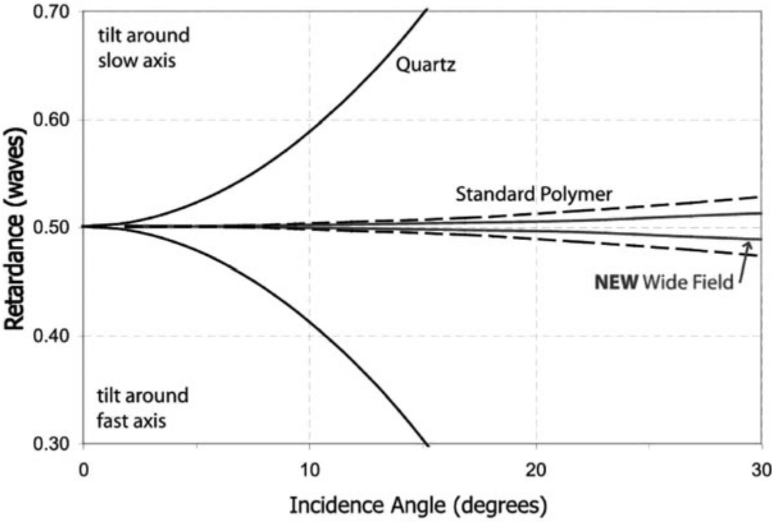

Figure 7. Improvement in angular field of view for true zero order polymer retarders over compound zero order quartz retarders. Also shown is the improvement of performance with a special wide field combination of polymers.

Dual wavelength retarders using combinations of polymers can generally be made to provide arbitrary specified retardances at any two chosen wavelengths. Arbitrary shaped variations of retardance with wavelength can be built using generalization of Solc filter designs (Solc 1965).

Polymer films can be made with a twist in the optic axis direction by adding a chiral dopant to the reactive mesogen layer before it crosslinked (Komanduri *et al.* 2013). These twisted layers can be stacked in interesting ways to provide some of the same functions

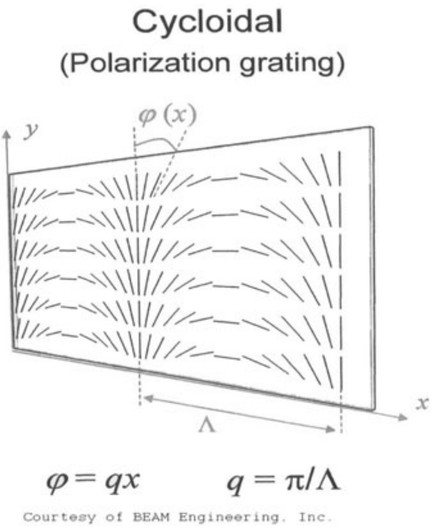

Figure 8. Spatial variation in optic axis direction in a polarization grating. Figure courtesy of Beam Engineering.

normally performed by retarders. These functions include conversion between linear and circular polarization and rotation of linear polarization through an arbitrary angle. A circular polarizer can be made in either a reactive mesogen polymer layer or a nematic liquid crystal layer by matching the product of the pitch length of the twist and the material index of refraction to the wavelength of the light to be polarized. The twisted structure acts as a Bragg reflector for the selected wavelength and rejects light of the unwanted polarization by reflection (Jacobs *et al.* 1988).

4. Microstructures

ImaginOptix, Boulder Nonlinear Systems and Beam Engineering are three companies that make diffractive waveplates using patterned reactive mesogen layers. These are sometimes also called polarization gratings (Figure 8). They can function as polarization beamsplitters and can be combined in interesting ways with a liquid crystal variable retarder to, for example (Tabirian *et al.* 2010), act as a shutter that avoids the normal penalty of throwing away half the light at the entrance polarizer (Oh *et al.* 2008).

The liquid crystal variable retarders already discussed can be patterned into spatially variable retarders, called spatial light modulators (SLMs). Transmissive SLMs are limited typically to less than a thousand individual retarder elements, called pixels, because there must be a “wire” to each pixel. These pixels can be configured to be either phase or amplitude modulators of an incident beam by appropriate choice of the linear polarization direction of that beam. Liquid crystal SLMs can also be reflective devices built on integrated circuits in silicon. Pixel counts in this case can exceed a million since the pixel addressing circuitry is buried in the silicon chip behind the reflective mirrors of the pixels. Pixel sizes on reflective SLMs are typically ten to twenty μm but can be of the order of a millimeter on transmissive SLMs. SLMs have been used in astronomy for adaptive optical elements and for beam steering but are more often used as time variable holographic elements in microscopy applications including optical tweezers.

Modern microlithography has enabled wire grid polarizers to function at wavelengths in the visible as well as the infrared by reducing the aluminum wire spacing to about 70

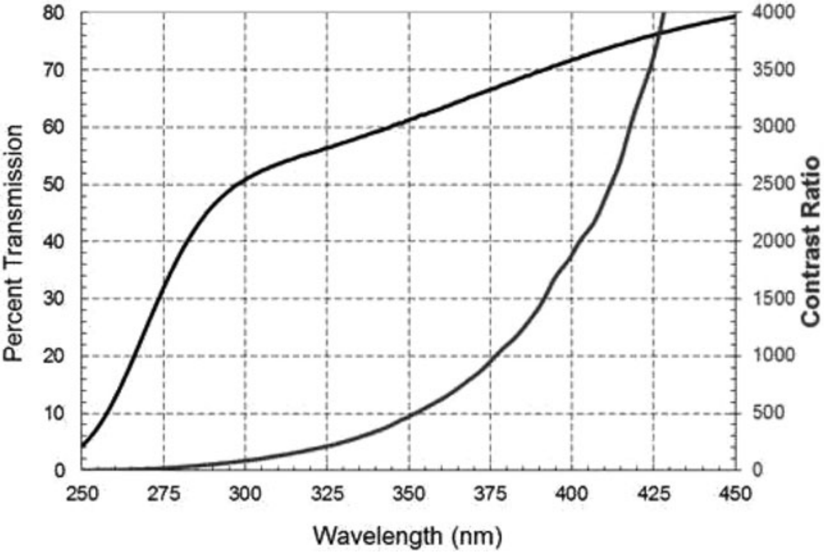

Figure 9. Measured performance over wavelength for a wire grid polarizer made for use at visible wavelengths. The lower curve shows the contrast ratio and the scale for this curve is on the right.

nm (Pentico *et al.* 2001). Figure 9 shows the performance of one type of these polarizers made by Moxtek Corp. Variations on the design provide useful performance from about 350 nm to over 2 μm wavelength when the wires are patterned on glass or fused silica. The market for these is driven by the need in LC video projectors for a polarizer with a high flux tolerance. More recently these wire grid patterns are being deposited on silicon wafers and this extends the useful range of these in the infrared out to 15 μm (George *et al.* 2013). Figure 10 shows the performance of one of these polarizers that has been antireflection coated for use in the midwave IR. Clear apertures of about 18 cm are possible with these wire grid polarizers. These structures can be incorporated into the hypotenuse of a beamsplitting cube to make a beamsplitting polarizer of much wider field of view and much broader wavelength coverage than what is possible with standard thin film MacNielle cubes (Baur 2003).

Three companies, Codixx, Polarcor and Photonic Solutions make polarizers by orienting microscopic metal whiskers in a glass matrix. These can be optimized to perform from wavelengths as short as 190 nm out to the near infrared. The largest apertures are usually less than 10 cm. Both these polarizers and the wire grid type can be patterned to provide a spatially varying polarization direction as shown in Figure 11. The usual application for patterned polarizers is to match the pixel pattern in a CCD detector to build a polarization imaging camera such as those made by 4D Corp.

Our company has combined some polarizer technologies to make a very broadband polarizer sold under the trade name of OWL that performs well from 300 nm to nearly 2.7 μm as shown in Fig. 12. This covers about the same wavelength range as calcite polarizers and is made in apertures as large as 15 cm with a thickness of less than 5 mm.

5. Summary

Polarization control and astronomical polarimetry can benefit from recent developments in materials and from the application of modern techniques for creating

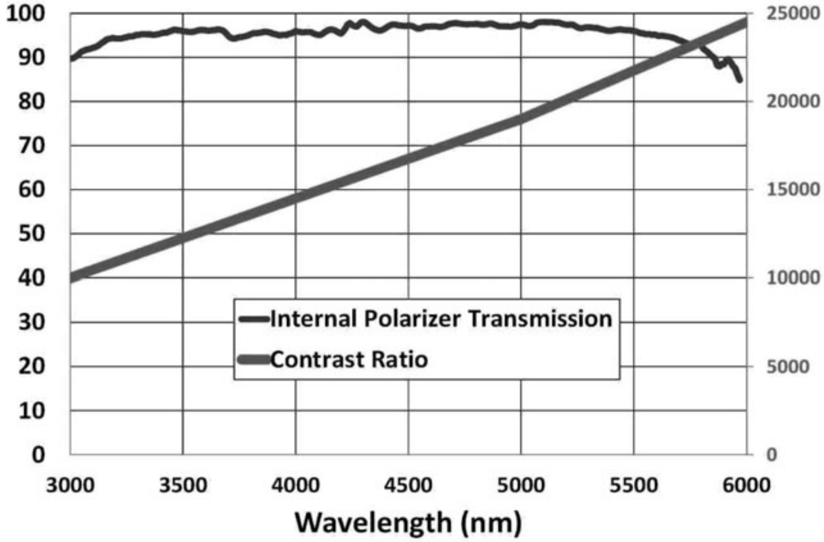

Figure 10. Measured performance in the midwave IR of a wire grid polarizer on a silicon substrate. These show excellent performance out to a 15 μm wavelength with appropriate antireflection coating of the silicon. The lower curve is for the contrast ratio and the scale for this curve is on the right.

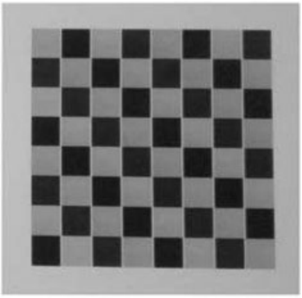

Figure 11. A photograph of a patterned polarizer viewed through a linear polarizer. The polarization transmission axis direction can be varied to arbitrary angles on a spatial scale of a few μm. The scale can be set to match the pixel pitch of a CCD camera to make a polarization imaging camera. Figure courtesy of Codixx.

microstructures sometimes with dimensions less than the wavelength of light. These developments increase the sizes of retarders and expand the wavelength ranges of both high performance polarizers and retarders. Many of these new developments are driven by commercial needs of the display industry, semiconductor industry and by defense and biomedical equipment requirements.

Optical component suppliers can often provide custom solutions not listed in their sales literature so contacting a sales engineer for a discussion is a good idea. This can often lead to a cheaper or better solution than originally envisioned. Share the intended application and function with the supplier to allow the consideration of these possible alternate solutions.

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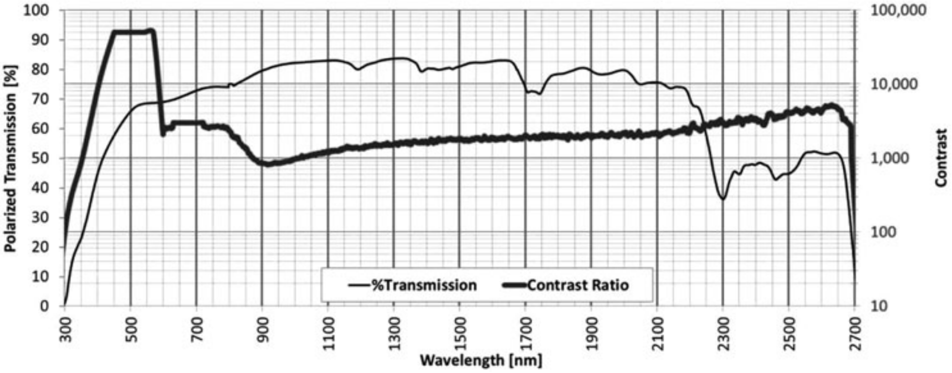

Figure 12. Performance of a very broad band polarizer made using new polarizer materials. The lower curve is for the contrast ratio and the scale for this curve is on the right.

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