WHITE PAPER

*Cover image: False color representation for angles of polarized light from transparent objects (plastics and cell phone cover).*

# GOING POLARIZED

## POLARIZATION ADDS A NEW PERSPECTIVE TO THE IMAGING INDUSTRY

**WHAT'S INSIDE:**

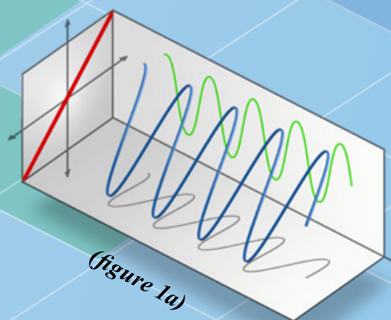


In many machine vision applications the use of polarization cameras can provide information that cannot be obtained with standard monochrome, color, multi-spectral or hyperspectral cameras. Applications that benefit from the use of polarization cameras are those in which reflected and transmitted scenes must be separated, the shape of transparent objects must be analyzed, and where removing specularities and haze is important.

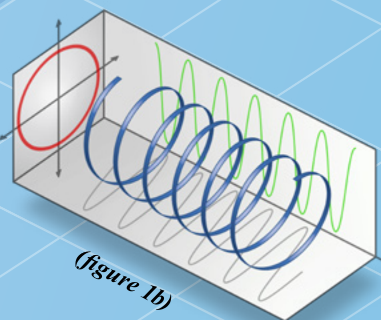
To appreciate how such applications can benefit from the use of polarization, the nature of light and how it interacts with such materials must be understood. Light is an electromagnetic wave that is composed of an electric field and a perpendicular magnetic field. The direction of the electric field is used to define the polarization direction of the light**. It is the interaction of light's electric field with materials that can be leveraged in vision applications with polarization.**

Most light sources encountered every day are not polarized. Unpolarized light from the sun or from an incandescent light bulb, for example, will have electric fields that are oscillating in random directions. To polarize this light, a polarizer is used to absorb components of the random directions, passing components of the light that are aligned in only one oscillation direction. Such polarization is referred to as linear polarization since the electric field points in a single direction ***(figure 2a).*** If the polarizer is polarized in the vertical direction the polarizer will block the horizontal component of all other polarizations.

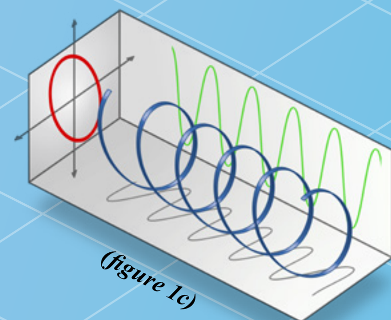
Light reflecting from highly directional sources such as the sun or incandescent lamps can cause glare. Fortunately, this glare can be identified by the polarization signature it carries. When unpolarized light reflects from the surface of an object it becomes partially linear polarized. The amount of polarization is dependent on the angle of reflection and the surface characteristics. Polarizers can then be used to remove the glare.



(figure 1a)



(figure 1b)



(figure 1c)

Polarized light can be represented in a coordinate system by two components. In *figure 1a*, 45° polarized light of some specific wavelength is shown broken down into X and Y components that are smaller in magnitude shown on the wall and floor of the diagram. If the polarized light were vertical, the Y component would be the same magnitude as the original polarized light, and the X component would be zero, having no energy in that component. If we take the two components of the 45° polarized light and phase shift them 90° (such as with a wave plate specifically oriented with axis in X and Y) the sum of those components will be circularly polarized since the electric field vector at any point along the Z direction turns in a circular direction *(figure 1b)*. In general, the two perpendicular light waves can have unequal amplitudes and phases in between 0 and ±90°, resulting in an electric field vector that rotates on an ellipse creating a more generalized case of elliptically polarized light *(figure 1c)*.

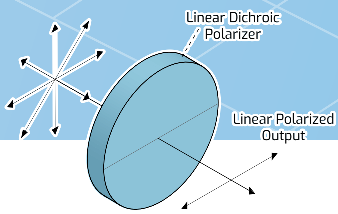



***figure 2a***

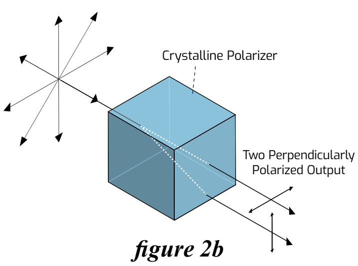



***figure 2b***

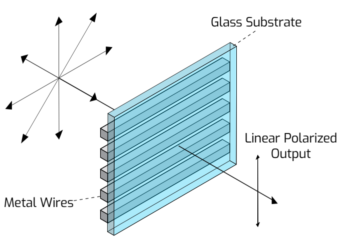



***figure 2c***

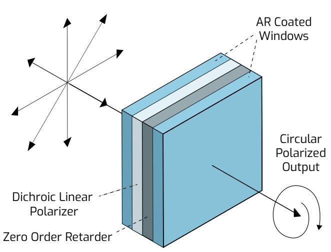



***figure 2d***

## Polarizing Light

**A number of different methods can be used to polarize light. These include the use of dichroic, crystalline, and wire grid polarizers.** Linear dichroic polarizers are constructed by laminating a stretched and dyed polymer film between two coated glass windows ***(figure 2a)***. Passing unpolarized light though such a polarizer will result in linearly polarized light in the orientation of the polarizing axis of the filter.

Crystalline polarizers rely on the effects of birefringence in crystalline materials ***(figure 2b)***. Such polarizers exploit the property of double refraction of certain anisotropic crystals such as calcite. In such crystals, the refractive index differs along more than one of the crystal axes from the asymmetric molecular spacing having different electron fields in the axes interacting with light's electric field. Incident light with components in both crystal axis will split into two beams with perpendicular components moving at different speeds. These two beams that are doubly refracted can be separated resulting in two linearly polarized beams.

Fabricated lithographically, wire grid polarizers feature an array of narrow sub-wavelength parallel metal wires placed on glass or a suitable substrate ***(figure 2c)***. When unpolarized light is incident on these wire grid polarizers, the incoming light with an electric field vector components parallel to the wires is reflected or absorbed, with the remaining electric field vector components perpendicular to the wires is transmitted through. Polarization components can act differently at different wavelengths. Visible light polarizers may not function well at all UV or IR wavelengths while wave plates are usually designed for a specific wavelength.

Circular dichroic polarizers are a combination of both a quarter wave retarder and a linear dichroic polarizer ***(figure 2d)***. This quarter wave retarder (π/2) is used to transform circularly polarized light to linearly polarized light which is then blocked or passed by the linear polarizer. In the reverse direction, unpolarized light is linearly polarized by the dichroic polarizer. This linear polarization is then transformed to circular polarization by the phase shift of the retarder.

**Each polarizer type has different performance characteristics.** By examining these characteristics, the correct polarizer can be chosen *(table 1)*. While all these different types of polarizers can be used in applications from biomedical, machine vision, and microscopy, linear dichroic polarizers are the least expensive and most commonly used. In applications where glare may need to be reduced, the use of dichroic polarizers may be most practical because of their low cost whereas applications that require broad spectrum ultraviolet (UV) to infrared (IR) polarization with high extinction ratios may benefit from crystalline polarizers.

| | CRYSTALLINE | DICHROIC GLASS | DICHROIC POLYMER | DIELECTRIC BEAMSPLITTING | WIRE GRID |
|---|---|---|---|---|---|
| Clear Aperture (mm) | 5 - 10 | 1 - 30.4 | 10 - 50+ | 10 - 20 | 1 - 200 |
| Acceptance Angle | ± 5° | ± 20° | ± 10° | ± 2° | 45° |
| Part Cost | \$500 - \$5000 | \$500 - \$5000 | \$1 - \$1000 | \$100 - \$5000 | \$100 - \$5000 |
| Contrast Ratio | $10^5$ | $10^6$ | $10^4$ | $10^3$ | $10^4$ |
| Damage Resistance (per cm$^2$) | 25 - 30 W | 1 W | 1 W | 500 W | 50 KW |
| Mechanical Thickness (mm) | 22.5 - 38.1 | 0.5 - 6.9 | 3.3 - 12.7 | 12.7 - 25.4 | 0.7 - 1.5 |
| Transmission* | 85 - 95% | 39 - 98% | 45 - 90% | 95% | 70 - 85% |
| Wavelength Range (nm) | 320 - 2300 | 325 - 2000 | 325 - 1800 | 440 - 1600 | 400 - 2000+ |

*Table 1:* Each polarizer type, whether it be linear dichroic, circular dichroic, crystalline or wire grid has different performance characteristics. * This is the transmission for light that is aligned with the polarization axis of the polarizer.

## All Aboard a Single-Chip

Wire grid polarization is the principle behind Sony's IMX250MZR and IMX250MYR CMOS sensors, a 2464 x 2056 global shutter imager that uses four directional polarizing filters at 0º, 90º, 45º, and 135º on every four 3.45µm pixels *(figure 3)*. Light passing through these four filters can then be linearly interpolated to provide a single intensity pixel value with its associated angle of linear polarization (AoLP) and degree of linear polarization (DoLP). The resulting image will then be one quarter of the original 2464 x 2056 pixels or 1232 x 1028 pixels, or can be interpolated to provide the full resolution similar to traditional bayer pattern display.

**Fabricated on-chip as opposed to on-glass, the polarizer array is positioned below the micro lens to reduce crosstalk from polarized angles being incorrectly detected by the wrong pixel.** Since the imager employs linear polarizers, it can be used to calculate the DoLP of light. For the sensor to measure circular polarization, it would be necessary to add a quarter-wave (π/2) wave plate to the imaging path. Although at present no commercially available circular micro-polarizers have been fabricated on-chip, researchers have demonstrated how such a concept could be achieved.

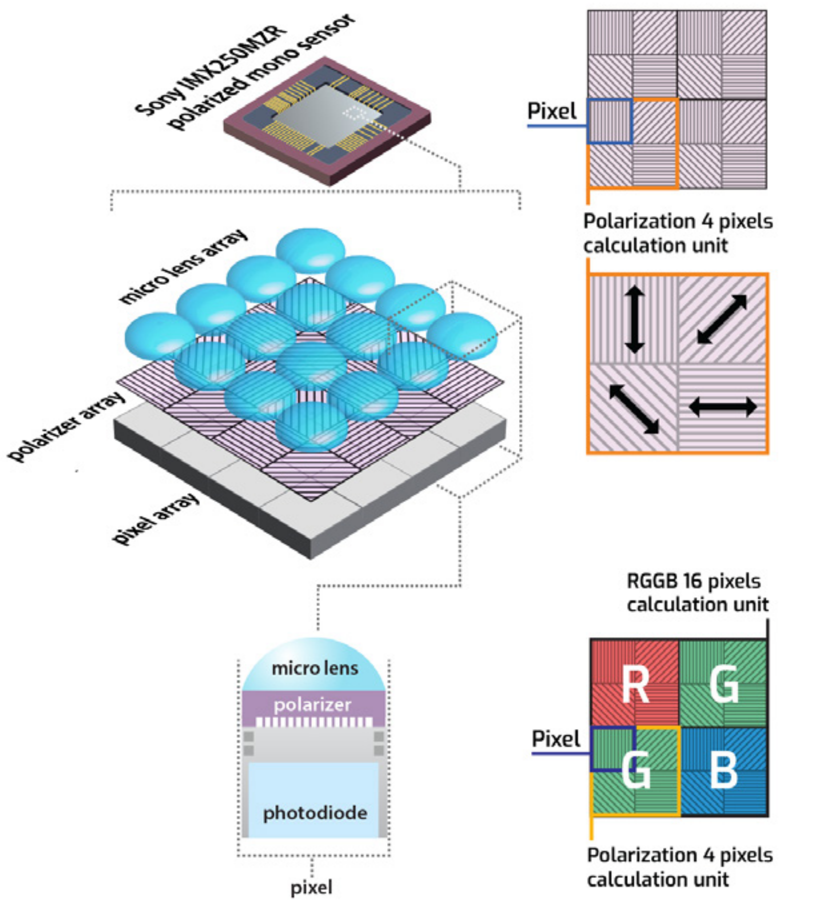
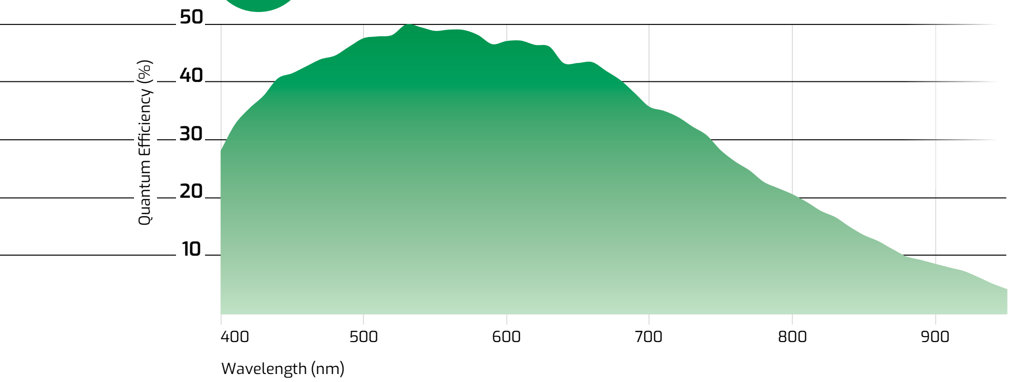



*figure 3*
***Sony's IMX250MZR (mono) sensor layout and IMX250MYR (color) RGGB bayer pattern.***

## Polarization Performance

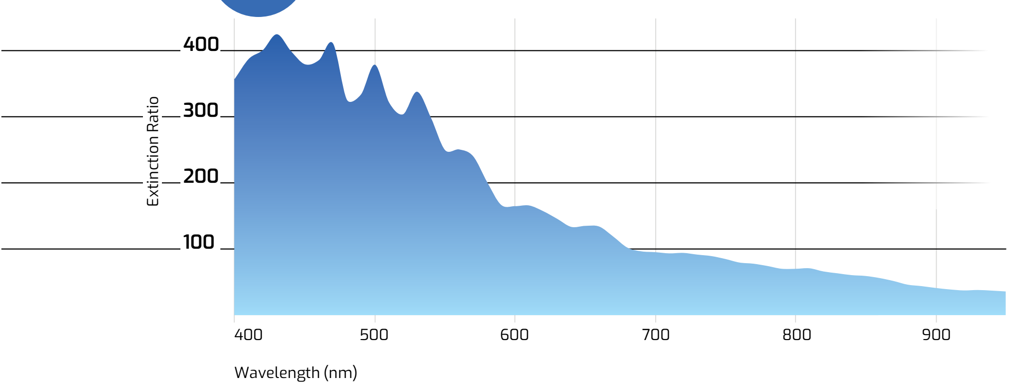
Having polarization filters on the image sensor changes the quantum efficiency (QE) of the sensor. In the case of the Sony IMX250MZR CMOS polarized sensor, measured QE across the 400-950nm spectrum results in a decrease in QE when compared with the Sony IMX250LLR. For example, at 470 nm, 525 nm and 640 nm, the QE of the IMX250 is 53%, 66% and 58% respectively while for the IMX250MZR with polarized light matching the angle of the pixel this is approximately 43%, 48% and 43% respectively ***(figure 4)***.

***figure 4*** Average Quantum Efficiency (QE) Using Polarized Light Matching Angle of Pixel




**A key performance metric of a polarizer or polarization sensor is the ability to block the light polarized perpendicular to the polarizer's transmission axis as much as possible.** The polarization extinction ratio (ER) is the ratio of the maximum signal obtained when a high quality reference polarizer is aligned to a polarization axis of the polarization sensor to the minimum signal when the reference polarizer is "crossed" or rotated by 90°. ERs can vary considerably depending on the polarizer type, quality and wavelength. The Sony IMX250MZR ER has been measured in ***figure 5***.

***figure 5*** Minimum Extinction Ratio (ER) Among 4 Angles at Each Wavelength.




Stokes parameters – a set of values (known as a Stokes vector) describes the polarization state of electromagnetic radiation. These were originally defined by Sir George Stokes in 1852. The four-dimensional Stokes vector is composed of the total intensity of light (I), the intensity difference between polarized components of the electromagnetic wave parallel and perpendicular to the reference plane (Q = p_0 - p_90), the intensity difference between polarized components in planes 45° and 135° to the reference plane (U = p_45 - p_135) and the difference between left and right circularly polarized radiation (V).

Since circular polarization cannot be measured directly using a simple implementation of the Sony IMX250MZR CMOS polarized sensor, only the I, Q and U components are available. From these, we can calculate the degree of linear polarization (DoLP) and the angle of linear polarization (AoLP) using the following equations:

$$\mathrm{DoLP} = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\mathrm{AoLP} = \frac{1}{2}\arctan\frac{U}{Q}$$

Results of the intensity of the 2 x 2 individual directional filters can then be displayed along with the AoLP, DoLP or a combination of both AoLP and DoLP on a graphical user interface.

## Counting the Ways

Many methods of performing polarization analysis exist. One of the simplest of these is to use an inexpensive linear polarizer mounted in front of a standard camera lens. By rotating this polarizer, different images can be captured. This simple method has recently been used by NVIDIA to recover the 3D shape of objects from multiple images at different polarization orientations. Using a Hoya linear polarizer mounted in front of a Canon EOS 7D camera lens, multi-view stereo methods were used to first recover the camera positions and the initial 3D shape of well-textured regions. After the phase angle maps for each view from the corresponding polarized images were then computed, NVIDIA resolved the ambiguities to estimate azimuth angles to recover depth for featureless regions and fused together depth maps to recover the objects 3D shape ***(figure 6)***.

While polarization cameras can be manufactured by mechanically rotating polarizers and/or waveplates between capturing individual image frames, more sophisticated methods have also been developed. One such method, developed by Bossa Nova Technologies, uses a polarization filter based on ferroelectric liquid crystals (FLC) to acquire the four polarization frames used to calculate the four-dimensional Stokes vector of each pixel of the image ***(figure 7)***. Thus, the camera can determine the degree of linear polarization, the degree of circular polarization, the angle of polarization and the ellipticity angle.

In other implementations, multiple imagers and prisms are used to accomplish the same task. Since at least three exposures with different analyzer or half-wave plate positions are required to estimate the degree and orientation of polarization of the image, Fluxdata uses a 3-way prism beam splitter coupled to three polarizers, each at a different orientation in the design of its FD-1665P camera ***(figure 8)***. Oriented at 0, 45, and 90°, polarized images are then captured by three independent CCD sensors and processed to yield polarization information.

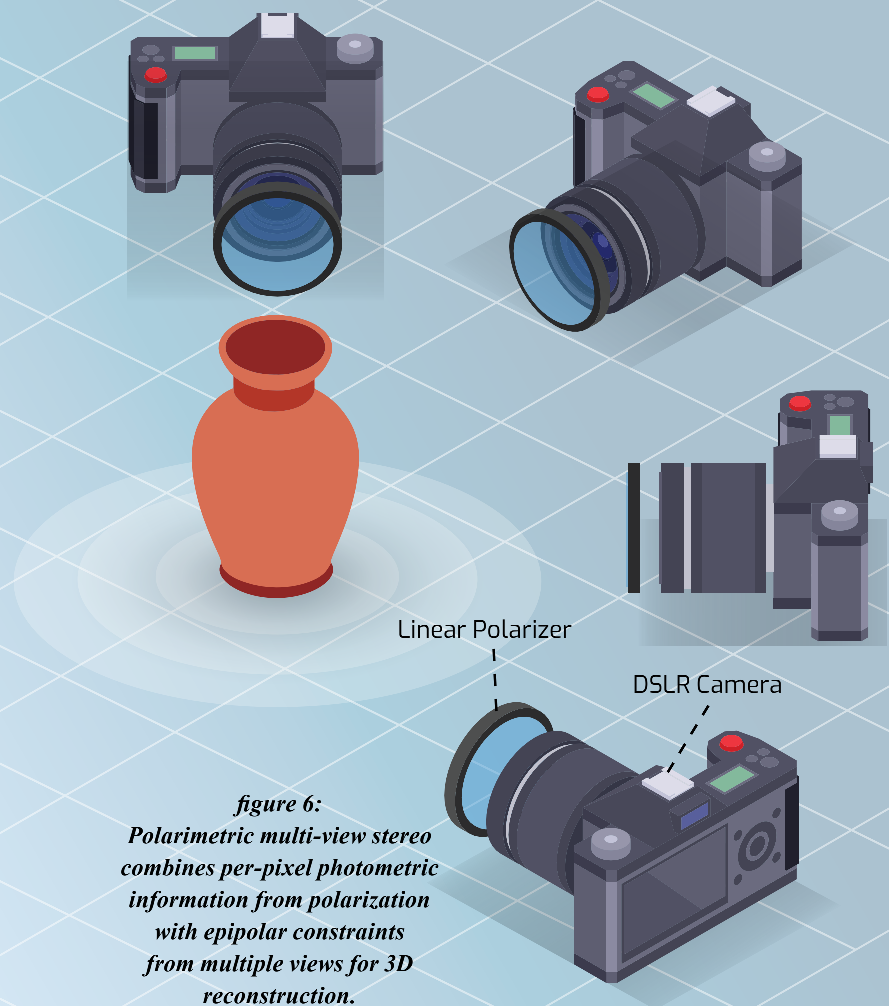



***figure 6:***
***Polarimetric multi-view stereo combines per-pixel photometric information from polarization with epipolar constraints from multiple views for 3D reconstruction.***

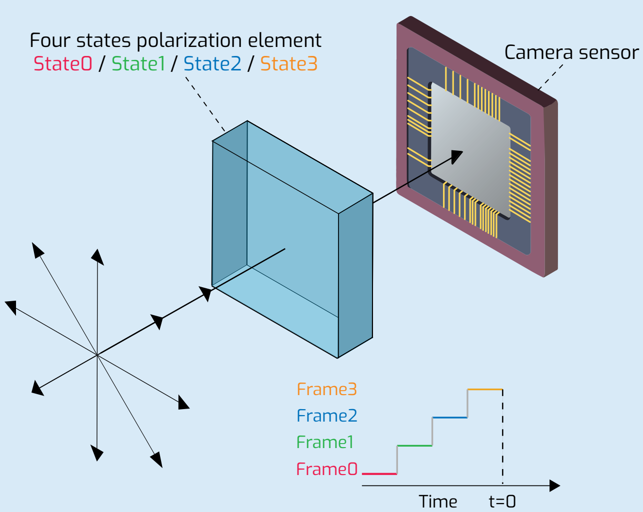



***figure 7***
***Ferroelectric liquid crystal based polarization filter***

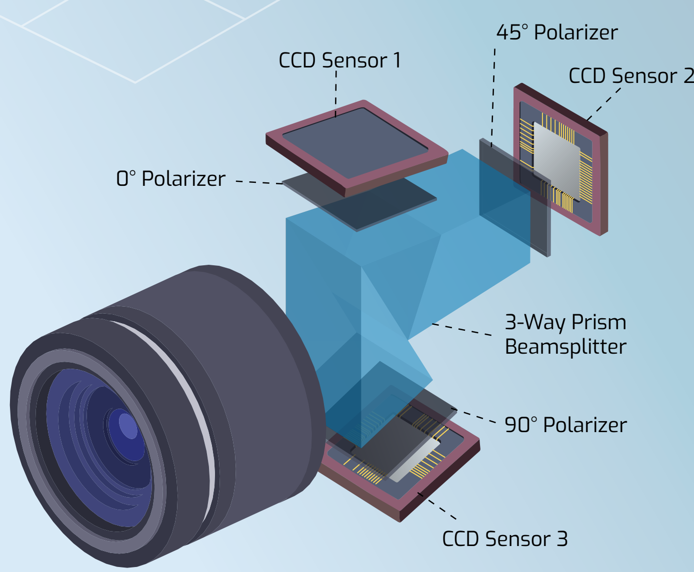



***figure 8***
***3-Way prism beamsplitter with 3 polarizers and 3 sensors***

## Reducing Stress

In many cases it is not necessary to compute the circular polarization of the image or the ellipticity angle. In industrial and machine vision applications, such as measuring stress-induced birefringence in glass, for example, computing the AoLP and DoLP is sufficient. In such applications, **using a solid state micropolarizer camera based on the Sony IMX250MZR polarization sensor, permits single shot data acquisition at frame rates while being extremely compact compared with rotating polarizer-based or prism-based implementations.** Because of this, the new Sony sensors are an ideal fit for LUCID's micro-compact Phoenix camera.

Many applications for such cameras exist including product analysis, defect detection, 3D shape reconstruction and haze removal. One of the unique properties of carbon fibers, for example, is that they polarize incident unpolarized light parallel to the direction of the fiber. To capture the orientation and the position of the carbon fiber bundle to determine which way the fiber is oriented, an unpolarized red light from a commercial ring light illuminating the surface is reflected as polarized light ***figure 9***,. Using a Phoenix polarization camera from LUCID, the camera can then be used to capture image data at 0°, 90°, 45°, and 135° angles. Polka Imaging software from Fraunhofer IIS is then used to perform the required computation for calculating the angle of linear polarization, which directly indicates the direction of the fibers for each pixel. In ***figure 10***, the bottom image shows the measured intensity while the top image shows the false color polarization information, with color depicting the measured angles of the fibers.

Such cameras can also be used for analyzing internal stress of plastics and glass that are not visible with conventional imaging techniques. Furthermore, using polarization can also highlight any scratches or other surface defects. Transparent objects, especially those fabricated from plastic, for example, alter the characteristics of light such that when placed in a beam of polarized light and imaged using a polarizing camera, internal non-uniformities turn the plane of polarization depending on the stress or surface characteristics of the material. While the monochrome image of the cellphone case in ***figure 11*** shows no such surface defects or internal stress characteristics, these are easily visualized using a polarization camera.

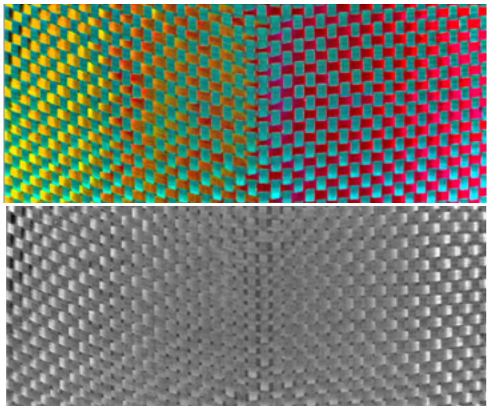


*figure 10*
***Top: False color representing polarized angles. Bottom: Polarization intensity.***



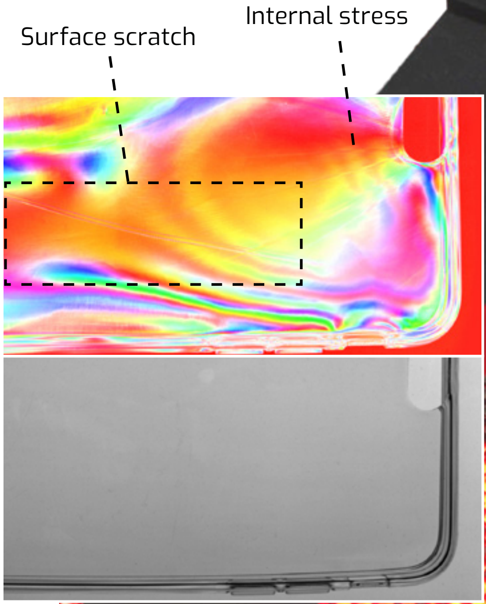



***figure 11***
***Top: Polarization image showing hidden scratch and stress. Bottom: Mono image.***

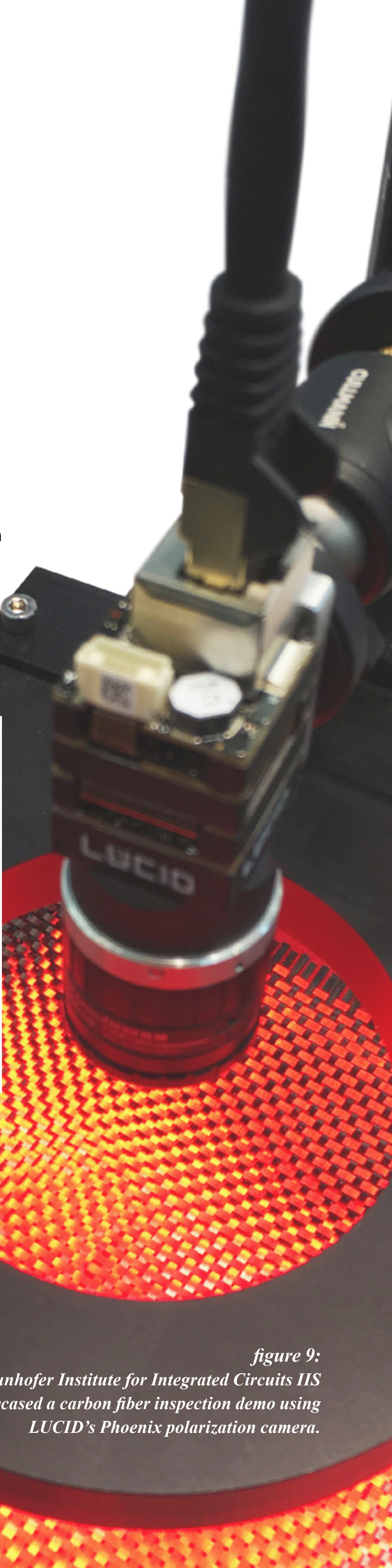



***figure 9:***
***Fraunhofer Institute for Integrated Circuits IIS showcased a carbon fiber inspection demo using LUCID's Phoenix polarization camera.***

While processing polarized images from camera with on-chip polarizers is useful in machine vision applications, it can also be used in other applications such as aiding in de-hazing images. Based on the fact that usually natural illuminating light scattered by the atmosphere is partially polarized, polarizing techniques can be used in conjunction with optical methods to enhance hazy images as Yoav Schechner points out in his paper "Polarization-based vision through haze". Such de-hazing can be accomplished with as few as two images taken through a polarizer at different orientations *(figure 12)*.

*figure 12*
*Left: Hazy image. Right: Enhanced image using polarizing and optical techniques.*


## Future Perspectives

Many applications of polarization imagery exist ranging from remote sensing, microscopy to 3D image reconstruction. Specialized laser-based applications may still demand the use of relatively costly crystalline polarizers while low-cost photography will still employ low-cost linear and circularly polarized filters.

**For industrial imaging applications, the expensive mechanical or electro-optical systems required to perform such analysis has been relegated to the past thanks to the introduction of low-cost cameras based on polarizing imagers such as the Sony IMX250MZR.** Not only will this eliminate the need to employ dual polarizers in such systems, it will dramatically reduce the cost of such systems. In the future, the continued trend towards applying different on-chip filters to CMOS imagers will open up new and exciting perspectives to the imaging industry.

***The Phoenix camera with the Sony IMX250MZR polarization sensor.***

**For more information visit our website at thinklucid.com**

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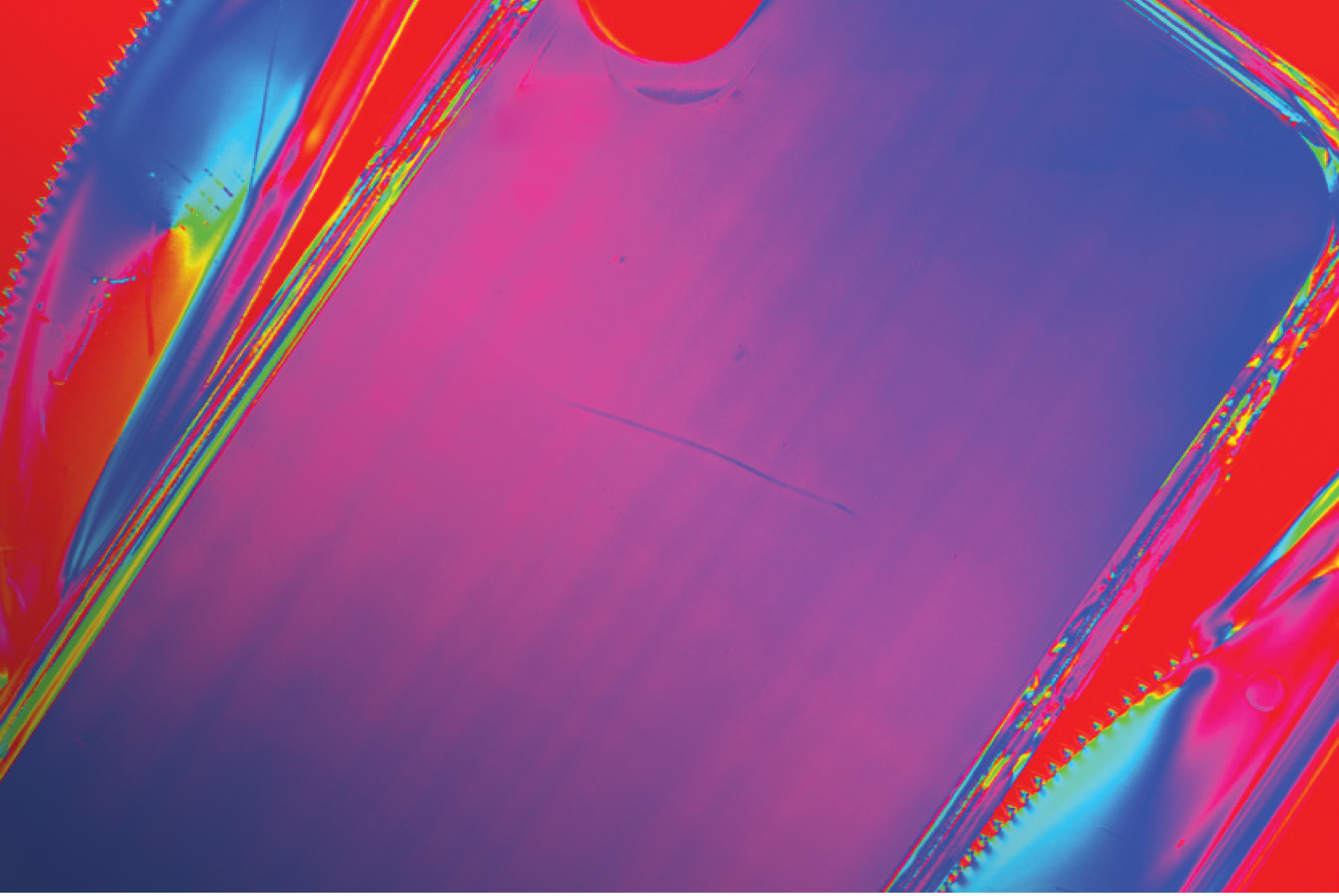


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