High-Resolution Low-Noise Polarization Imaging Sensor for Astronomical Applications

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High-Resolution Low-Noise Polarization Imaging Sensor for Astronomical Applications

by

Radoslav Marinov

A thesis presented to the Graduate School of Arts and Sciences of Washington University in partial fulfillment of the requirements for the degree of

Master of Science

August 2013
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ABSTRACT OF THE THESIS

High-Resolution Low-Noise Polarization Imaging Sensor for Astronomical Applications

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Washington University in St. Louis, August 2013

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Polarization imaging is useful to the field of astronomy because the polarization state caused by reflections, scattering events, and magnetic fields can be used to infer properties such as shape and index of refraction about celestial bodies. This work presents a low-noise high-resolution polarization imaging sensor consisting of a CCD imager overlaid with a nanowire linear polarizer filter array of four different orientations (0°, 45°, 90°, and 135°) matched to the pixel pitch. Fabrication details and experimental setup for characterization are discussed. The performance of the sensor is assessed over a range of polarization states, light intensities, wavelengths, and incident angles; a model for crosstalk is also presented.
Chapter 1

Introduction

1.1 Motivation

Figure 1.1: Comparison of images showing intensity (a) and degree of linear polarization (b)

The polarization state of light contains information which is generally not utilized by image sensors. Using polarization information, the shape or refractive index of an object can be determined if the other is known. Scattering media and magnetic fields can also affect the polarization state of light. Thus, polarization imaging is particularly relevant to astronomy. For example, the lunar maria appear as darker features in an intensity image; however, the second image shows that the maria have a degree of linear polarization (Figure 1.1). Said
higher degree of linear polarization is due to the higher refractive index, which in turn is due to the material composition.

For the purposes of astronomical imaging, high resolution and low noise are of utmost importance. Higher resolution means an image with more spatial detail. Low noise permits long-exposure image capture, which is critical when imaging dim light from distant objects. A division-of-focal-plane polarimeter based on a CCD imager provides high-resolution low-noise imaging that is well-suited to astronomy. In this thesis, I will describe my approach toward designing such a sensor. The end result is a working prototype of an imaging sensor that can be used by astronomers and astrophysics researchers.

1.2 Visible Light

Visible light represents a small fraction of the spectrum of electromagnetic radiation (Figure 1.2). Electromagnetic radiation is energy propagating through space in a wave-like fashion; it has an electric field component and a magnetic field component, which are orthogonal to each other and perpendicular to the direction of travel (Figure 1.3).

Figure 1.2: The electromagnetic radiation spectrum [9]
As a subset of the electromagnetic spectrum, visible light has three fundamental properties: intensity, color and polarization. Intensity (or irradiance) is the power per unit area. Color corresponds to the wavelength of the light. The polarization state of light is defined by the shape and locus of the tip of the electric field vector as a function of time at a fixed point in space.

1.3 Polarization

There are several possible states of polarization: unpolarized, elliptically polarized, circularly polarized and linearly polarized. The types of polarization are named after the shape traced out by the electric field vector; hence, the electric field vector of elliptically polarized light traces out an ellipse, the electric field vector of circularly polarized light traces out a circle, and the electric field vector of linearly polarized light traces out a line. Linear and circular polarization are actually specific cases of elliptical polarization. In the case of linear
polarization, the minor axis of the ellipse becomes zero; in the case of circular polarization, the major and minor axes of the ellipse are equal.

Polarization can be more easily visualized and understood with the aid of the polarization ellipse. The Stokes parameters (Equation 1.1) are a convenient description of polarization state (Figure 1.4), where I is the total intensity, p is the degree of polarization, ψ is the orientation angle, and χ is the ellipticity angle.

\[
\begin{align*}
S_0 & = I \\
S_1 & = pI \cos 2\psi \cos 2\chi \\
S_2 & = pI \sin 2\psi \cos 2\chi \\
S_3 & = pI \sin 2\chi
\end{align*}
\] (1.1)

Figure 1.4: Polarization ellipse
The Stokes parameters can be used to calculate further parameters of interest such as Degree of Linear Polarization (DoLP, Equation 1.2)) and Angle of Polarization (AoP, Equation 1.3)) as described below:

\[
DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} 
\]

\[
AoP = \frac{1}{2} \arctan \left( \frac{S_2}{S_1} \right) 
\]

1.4 Reflection

Because the human eye cannot perceive polarization, most imaging sensors are not sensitive to it, but only to intensity and color. However, the polarization state of light contains additional information. The polarization state is altered when light is reflected or scattered. Both reflection and scattering are dependent upon the shape of the object and the refractive indices of the media. Thus, if the index of refraction is known, polarization imaging can be used to reconstruct the shape of an object; conversely, if the shape of an object is known, the index of the refraction can be determined.

Figure 1.5: Refraction of light at the interface between two media
\[ \theta_1 = \theta_3, \quad n_1 \sin \theta_1 = n_2 \sin \theta_2 \Rightarrow \theta_2 = \arcsin \left( \frac{n_1}{n_2} \sin \theta_2 \right) \quad (1.4) \]

When an electromagnetic wave encounters an interface between two media, a fraction of the photons are reflected (Figure 1.5). The reflection is dependent upon the incident angle and the indices of refraction of the media. Snell’s law (Equation 1.4) describes the reflection, where \( n_1 \) and \( n_2 \) are the indices of refraction, \( \theta_1 \) is the incident angle, \( \theta_2 \) is the transmitted angle, and \( \theta_3 \) is the reflected angle.

However, the reflection is also dependent upon the polarization state of the incident light. When dealing with reflections from an interface, it is convenient to describe the polarization state of the incident light in relation to the plane of incidence. The plane of incidence is the plane containing the vector of the propagation direction and the normal vector of the plane of the reflecting surface. Light which is linearly polarized such that the electric field is parallel to the plane of incidence is said to be P-polarized (P from parallel), and light which is linearly polarized such that the electric field is perpendicular to the plane of incidence is said to be S-polarized (S from senkrecht, German for perpendicular). S- and P-polarized incident light beams have different reflection coefficients, as shown in Equation (1.5) below. \( R_{\perp} \) and \( R_{\parallel} \) are functions of the incident angle \( \theta_1 \) and the indices of refraction \( n_1 \) and \( n_2 \) – that is, the shape and material of the object.

- S-polarized incident light: \( R_{\perp} = \frac{\sin^2(\theta_1 - \theta_2)}{\sin^2(\theta_1 + \theta_2)} \)
- P-polarized incident light: \( R_{\parallel} = \frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)} \) \quad (1.5)

## 1.5 Polarization Imaging

Due to the appeal of the extra information held in polarization, several schemes have been developed to measure it. The most straightforward and readily obvious approach is division-of-time polarimetry (Figure 1.6). A division-of-time polarimeter consists of a sensor and a linear polarizer. Data is captured with the linear polarizer rotated to different angles. The separate measurements are then used to calculate the Stokes vector. While such a device is
relatively simple, its major drawback is the requirement that the objects being imaged be stationary.

Figure 1.6: Division-of-time polarimeter illustration

Another arrangement is the division-of-aperture polarimeter (Figure 1.7). The incident light is split into four parts. Each beam passes through a linear polarized oriented at 0°, 45°, 90°, and 135°, and the beams are then measured individually. The arrangement can be expanded by the addition of more beam splitters and polarizers and also wave plates in order to measure circular polarization. While this allows each of the measurements to be taken simultaneously, the necessary optics are complex and reduce the intensity of the light for each image.
The design utilized for this project is division-of-focal-plane (Figure 1.8). An imaging array is overlaid with a pattern of linear polarizers. The polarizers are matched to the size of the pixels and have four different orientations: $0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$. The differently-oriented filters are arranged in a regular repeating 2x2 pattern. Each 2x2 cluster of pixels makes up a superpixel where the Stokes vector can be calculated [6]. A feature of this design is that it captures the polarization information at once; a division-of-time polarimeter would be unsuitable for astronomical imaging, as the scene would change between the different polarization state measurements.

The advantages of such a scheme include the capability to use commonly available optical elements. However, the scheme described here does not measure circular polarization. There is a reduction in spatial resolution, though that can be mitigated, in part, by interpolation [3]. Equation (1.6) shows the calculation of Stokes parameters from pixel intensities within a superpixel.

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}(I_{0^\circ} + I_{45^\circ} + I_{90^\circ} + I_{135^\circ}) \\ (I_{0^\circ} - I_{90^\circ}) \\ (I_{45^\circ} - I_{135^\circ}) \end{bmatrix} \quad (1.6)$$
A division-of-focal-plane polarimeter based on a commercial CCD camera is well-suited to applications in astronomy. Such an arrangement permits low-noise real-time polarization imaging. Even lower noise is possible if the imager chip, along with the attached nanowire polarizers, is installed in a special housing and cooled to reduce dark currents and thermal noise. Low noise is crucial for astronomy applications, as long integration times may be necessary to image distant objects. While light emitted from stars is unpolarized [4], objects which reflect or scatter light provide useful polarization signatures; thus, this device can be used to collect information about the shape or refractive index (and hence composition) of astronomical objects.
Chapter 2

Design and Fabrication

2.1 Design

The polarization camera described herein is based on a commercially-available CCD (Kodak KAI-04022) (Figure 2.1). This particular sensor was chosen for its characteristics. The sensor has a high resolution of 2056 x 2060 (4.2 megapixels), and large pixel size of 7.4µm x 7.4µm. The imager features a high dynamic range of 72 dB and its readout noise is low at 10 electrons (RMS).

Figure 2.1: Kodak KAI-04022 image sensor [2]
The image sensor is modified by the addition of specially fabricated pixel-patterned polarization filters. The filters are aligned to the pixels of the sensor and are flip-chip bonded (Figure 2.2).

![Diagram of image sensor with attached nanowire polarization filters](image)

Figure 2.2: Diagram of image sensor with attached nanowire polarization filters

The linear nanowire polarizers are a special type of the wire-grid polarizer. A wire-grid polarizer consists of fine parallel metal wires; incident light which has an electric field component along the direction of the wires is reflected back toward the source, while incident light which has an electric field component perpendicular to the wires is transmitted (Figure 2.3).

![Wire-grid polarizer](image)

Figure 2.3: Wire-grid polarizer [7]
Conventional photolithography is unsuitable for the fabrication of nanowire polarizers in the visible spectrum due to limits imposed by diffraction. In order to create the periodic nanowire pattern, a technique called interference lithography is utilized. The substrate is prepared by the deposition of aluminum, silicon dioxide, and photoresist, in that order. A Nd:YAG (neodymium-doped yttrium aluminum garnet) continuous wave laser is used to frequency doubled twice to produce ultraviolet light with a wavelength of 266 nm. Two 266 nm beams are set up to interfere at an angle of 110°; the resulting interference pattern has a period of 140 nm. Said interference pattern is used to expose the photoresist film. The photoresist is then developed and the silicon dioxide beneath it is etched. The remaining silicon dioxide serves as a mask for etching the aluminum (Figure 2.4).

![Figure 2.4: Nanowire polarizer fabrication process](image)

After the aluminum is etched, the nanowires form a wire-grid polarizer (Figure 2.5). Ultimately, at end of the nanowire polarizer fabrication process, the finished filter consists of a regular repeating pattern of linear polarizers oriented at each of the following angles (relative to the horizontal axis of the image sensor): 0°, 45°, 90°, and 135°. The glass substrate supports the filters, and remains part of the final device. Figure 2.6 shows the nanowire polarizer array pattern.

In Figure 2.7, image (a) shows the 0° filters transmitting 100% intensity, the 90° filters transmitting 0% intensity, and the 45° and 135° filters transmitting 50% intensity; image (b) shows the 45° filters transmitting 100% intensity, the 135° filters transmitting 0% intensity, and the 0° and 90° filters transmitting 50% intensity; image (c) shows the 90° filters transmitting 100% intensity, the 0° filters transmitting 0% intensity, and the 45° and 135° filters
transmitting 50% intensity; image (d) shows the 135° filters transmitting 100% intensity, the 45° filters transmitting 0% intensity, and the 0° and 90° filters transmitting 50% intensity.
Figure 2.6: Diagram of filter, showing orientation and pattern of the different polarizer orientations

The checker pattern is due to Malus’ law (Equation 2.1). The light impinging on the nanowire filters is linearly polarized. Malus’ law explains the transmission of linearly polarized light by a linear polarizer, where $I_t$ is the intensity of the transmitted light, $I_0$ is the intensity of the incident light, and $\theta$ is the angle between the polarization of the light and the axis of the polarizer. In the checker pattern, the bright pixels are those with polarizers parallel to the polarization of the light, the dark pixels are those with polarizers perpendicular to the polarization of the light, and the gray pixels are those with polarizers at $45^\circ$ to the polarization of the light (Equation 2.2).

$$I_t = I_0 \cos^2 \theta$$  \hspace{1cm} (2.1)

$$I_t = I_0 \cos^2 \theta$$

$$\theta = 0^\circ, I_t = I_0 \cos^2 0^\circ \rightarrow I_t = I_0$$

$$\theta = 90^\circ, I_t = I_0 \cos^2 90^\circ \rightarrow I_t = 0$$

$$\theta = 45^\circ, I_t = I_0 \cos^2 45^\circ \rightarrow I_t = \frac{1}{2} I_0$$  \hspace{1cm} (2.2)
In preparation for alignment to the image sensor, the filter is glued to a section of a glass slide with Dymax OP-30 low-stress clear optical adhesive. The refractive index of the OP-30 adhesive is closely matched to the refractive index of glass. Thus, losses due to Fresnel reflection at the glass-adhesive interfaces are minimized. The substrate of the filter is matched closely to the dimensions of the pixel array on the image sensor; the piece of glass slide not only holds the filter in place, but it provides a place where the slide and filter conglomerate can be attached to the package of the sensor. The glass slide segment also covers and protects the bonding wires and the area between the pixel array and the package, preventing accidental bonding wire damage and reducing the possibility of debris contaminating the nanowire filter or the image sensor itself.

In order to facilitate alignment and subsequent easy removal of the temporary parts used solely for the alignment process, the glass slide section is attached to an entire glass slide.
Figure 2.8: Diagram of filter and glass slide segment attached to glass slide with bonding wax by means of bonding wax (Figure 2.8). Bonding wax simultaneously provides a strong hold and also permits easy removal.

Following the attachment of the filter and slide segment to the glass slide, the filter is ready to be aligned and glued to the image sensor of the camera (Figure 2.9). The glass slide is held firmly in place by a vacuum chuck. In order to precisely align the nanowire filter to the image sensor, the camera housing the image sensor is mounted onto a Thorlabs NanoMax six-axis micromanipulator. The stage features manual micrometer drives and piezoelectric actuators with closed-loop control and 10 nm / 0.03 arcsecond precision. The six axes include translation in three axes: X, Y and Z, as well as rotation in three axes: roll, pitch and yaw ($\theta_x$, $\theta_y$, and $\theta_z$, respectively). The fine precision and six degrees of freedom are crucial for achieving sufficiently close alignment of the nanowire filter pattern and the pixels on the image sensor.
Ideally, the filters should be aligned with the pixels of the sensor, flush and level with the surface of the sensor. A live view from the camera is used to align the filters. Successive adjustments to the position of the camera and the orientation of the linear polarizer are made and the image from the camera is appraised to gauge the closeness of the alignment. When alignment has been achieved, the image from the camera exhibits the aforementioned characteristic checker pattern. A crop from an actual checker pattern is shown in Figure 2.10.

Once satisfactory alignment has been achieved, UV-cured epoxy is used to bond the glass slide segment to the sensor package. Subsequently, the vacuum chuck is released, and the
camera is removed from the micromanipulator stage. The glass slide is then removed by heating the bonding wax, which softens and releases. With the large glass removed, the image sensor is only slightly larger than before the augmentation with nanowire polarization filters; thus, the camera enclosure is reassembled and commercially available optical elements can be fitted.
Chapter 3

Electro-optical Evaluation

3.1 Parameters of interest

As previously explained, the DoFP polarimeter combines 2x2 pixels into a superpixel with individual pixels having linear polarizers oriented at 0°, 45°, 90°, and 135°. Thus, the raw outputs are the intensities at each pixel: $I_{0°}$, $I_{45°}$, $I_{90°}$, and $I_{135°}$, respectively. From these, the Stokes vector (except for $S_3$) at a particular superpixel can be calculated, as shown in Equation 1.6.

Using the Stokes vector, the parameters of interest Degree of Linear Polarization (DoLP) and Angle of Polarization (AoP) are computed at each superpixel as described in Equation 1.2 and Equation 1.3, respectively. The DoLP is, essentially, a measure of how linearly polarized the incident light is. The value obtained from the calculation is normalized from 0 to 1. A value of 1 indicates that all of the incident light is linearly polarized; conversely, a value of 0 indicates that none of the light is linearly polarized. The AoP corresponds to the orientation angle of the polarization of the incident light, relative to the horizontal axis of the sensor.

3.2 Experimental Method and Empirical Data

A series of measurements were performed to assess the operation of the polarization image sensor. Each measurement consists of one hundred captured frames, averaged to reduce noise; the noise is reduced by a factor of 10. Four separate experimental setups were used
one each for capturing data with different incident light intensities, different incident light
wavelengths, different incident angles and different incident light degrees of linear polariza-
tion. The data presented is based on a 2000x2000 (4 megapixel) crop of the 2056 x 2060
image. The margins of the image were cropped to exclude pixels with artifacts from the
fabrication process, such as those shown in in false color in Figure 3.1.

Figure 3.1: Example of defects along edge of sensor: mechanical damage of pixels and
adhesive on imager surface

3.2.1 Intensity Measurements

The experimental setup for capturing images under controlled intensity conditions is shown
in Figure 3.2. The light sources comprised LEDs soldered onto custom printed circuit boards.
The LED circuit boards were mounted at the input port of an integrating sphere in order to
eliminate any possible polarization from the LEDs. The LEDs were powered by a DC power
supply operating in constant-current mode. An adjustable iris is mounted at the output port
of the integrating sphere. Light passing through the iris then passes through an aspheric
condensing lens, which produces a tightly collimated beam, approximately 4 cm in diameter. Collimation is important, as divergent light exacerbates optical crosstalk. The collimated light beam passes through a linear polarizer mounted on a computer-controlled rotational stage. Finally, the light is incident upon the pixels of the image sensor.

Circuit boards with LEDs of the following wavelengths were used: 460nm (blue), 515nm (green), 595nm (amber), and 625 nm (red). Measurements were taken with the linear polarizer at angles from 0° to 170° in 10° steps. Cosine regression was used to fit the data to Malus’ law. As shown in Figure 3.3, 10° steps afforded significantly faster data collection over 1° steps without negatively affecting the data fit. The power of the LEDs was varied over approximately 2.5 orders of magnitude. The digital response of the sensor to light of varying intensity from blue, green, amber and red LEDs is shown in Figure 3.4, Figure 3.5, Figure 3.6, and Figure 3.7, respectively.

Figure 3.3: Fit comparison between 1° steps and 10° steps
Figure 3.4: Digital response to 460 nm light as a function of incident light intensity

Figure 3.5: Digital response to 515 nm light as a function of incident light intensity
Figure 3.6: Digital response to 595 nm light as a function of incident light intensity

Figure 3.7: Digital response to 625 nm light as a function of incident light intensity
The sensor exhibits a very linear response as a function of intensity for all the light sources, as shown in Figures 3.8, 3.9, 3.10, and 3.11. Correlation coefficients are shown in the legend. The residuals of the linear fit for each pixel orientation, along with root-mean-square error (RMSE) are shown in Figures 3.12, 3.13, 3.14, and 3.15.

![Figure 3.8: Linear fit of digital response to 460 nm light as a function of incident light intensity](image)

Figure 3.8: Linear fit of digital response to 460 nm light as a function of incident light intensity
Figure 3.9: Linear fit of digital response to 515 nm light as a function of incident light intensity

Figure 3.10: Linear fit of digital response to 595 nm light as a function of incident light intensity
Figure 3.11: Linear fit of digital response to 625 nm light as a function of incident light intensity

Figure 3.12: Residuals of linear fit of digital response to 460 nm light as a function of incident light intensity
Figure 3.13: Residuals of linear fit of digital response to 515 nm light as a function of incident light intensity

Figure 3.14: Residuals of linear fit of digital response to 595 nm light as a function of incident light intensity
Figure 3.15: Residuals of linear fit of digital response to 625 nm light as a function of incident light intensity
As previously mentioned, Malus’ law explains the transmission of linearly polarized light by a linear polarizer. Figure 3.16 shows the ideal theoretical response of the sensor to linearly polarized incident light.

![Figure 3.16: Theoretical ideal response of sensor to linearly polarized light](image)

The empirical data differed somewhat from the theoretical model. The digital response of the sensor as a function of angle of polarization to light of varying angle of polarization from blue, green, amber and red LEDs is shown in Figure 3.17, Figure 3.18, Figure 3.19, and Figure 3.20, respectively. The differences from the anticipated and observed behavior of the sensor were modeled and attributed to crosstalk. Said crosstalk also caused disparities between expected and observed performance of the sensor in regards to extinction ratios, angle of polarization, and degree of linear polarization. The crosstalk model is discussed in detail in the following chapter.
Figure 3.17: Digital response to 460 nm light as a function of angle of polarization

Figure 3.18: Digital response to 515 nm light as a function of angle of polarization
Figure 3.19: Digital response to 595 nm light as a function of angle of polarization

Figure 3.20: Digital response to 625 nm light as a function of angle of polarization
As can be seen from the figures showing digital response as a function of incident light intensity and digital response as a function of incident angle of polarization, the response of the sensor to light from blue, green, amber, and red LEDs is similar. Hence, for conciseness, future discussion will focus on measurements performed using green LEDs as the light source.

\[ ER = \frac{I_{\text{max}}}{I_{\text{min}}} \]  

Extinction ratio is a metric commonly used to quantify the performance of polarizers. The extinction ratio is defined as the ratio of the transmission of light of the desired polarization state to the transmission of light of the unwanted polarization state. For example, an ideal linear polarizer oriented so as to transmit vertically polarized light would transmit vertically polarized light without losses and block all horizontally polarized light, as expected from Malus’ Law. Thus, an ideal polarizer would have an extinction ratio of infinity. In practice, however, some of the desired light is not transmitted and some of the unwanted light is not blocked.

![Figure 3.21: Extinction ratio as a function of incident light intensity](image)

Figure 3.21: Extinction ratio as a function of incident light intensity
Extinction ratios were calculated according to Equation 3.1. Since the experimental data was collected in steps of 10°, it is likely that the maximum and minimum values occurred between sampling points. Hence, the maxima and the minima were taken from a cosine fit of the experimental data rather than from the raw data itself.

The observed extinction ratios of the nanowire polarizers are shown in Figure 3.21. The apparent peak at the second-highest intensity is an artifact of the cosine regression; such a peak is not present in extinction ratios calculated using the raw data. Theoretically, the extinction ratio should be constant with intensity; however, the observed ratios of the nanowire polarizers decreased with decreasing intensity, as shown in the figure. This difference was attributed to crosstalk, which is investigated and modeled in the following chapter.

Figure 3.22 shows the angle of incident polarization where maximum intensity was observed, and Figure 3.23 shows the angle of incident polarization where minimum intensity was observed, respectively, as a function of incident light intensity. As the experimental data was collected in steps of 10°, it is probable that the maximum and minimum values occurred at angles which did not coincide with sampling points. Thus, similarly to the calculation of extinction ratios, the locations of the maxima and the minima were based on a cosine fit of the experimental data rather than from the raw data itself.
Figure 3.22: Angle of maximum intensity as a function of incident light intensity

Figure 3.23: Angle of minimum intensity as a function of incident light intensity
Figure 3.24: Average $S_0$ as a function of incident light intensity
As previously discussed, the values of individual pixels are used to calculate the Stokes parameters for a superpixel. $S_0$ represents the total intensity at the superpixel level. As shown in Figure 3.24, $S_0$ varies linearly as a function of intensity.

Figure 3.25: Angle of polarization as a function of incident angle of polarization

Angle of polarization and degree of linear polarization are convenient ways to present polarization information. Figure 3.25 shows angle of polarization as calculated from the Stokes parameters. Figure 3.26 shows the difference between the angle of polarization calculated from the Stokes parameters and the expected values. Figure 3.27 shows degree of linear polarization as a function of incident light intensity. Since the incident light goes through a linear polarizer, the degree of linear polarization should be constant at unity. However, the empirical data shows the degree of linear polarization, as calculated from the Stokes parameters, as decreasing with decreasing intensity to approximately 0.5 at $0.05 \mu w/cm$. This effect is investigated and modeled in the following chapter.
Figure 3.26: Residuals of angle of polarization as a function of incident angle of polarization

Figure 3.27: Degree of linear polarization as a function of incident light intensity
3.2.2 Spectral Measurements

The experimental setup for capturing images with different wavelengths of light is shown in Figure 3.28 below. The light source is a halogen bulb. A computer-controlled monochromator is used to pass a narrow band of the halogen sources spectrum approximately 10 nm Full Width at Half Maximum (FWHM).

![Diagram of experimental setup](image)

Figure 3.28: Experimental setup for assessing performance over a range of wavelengths

The light from the monochromator is fed into an integrating sphere in order to eliminate any residual polarization. The light then passes through a linear polarizer mounted on a computer-controlled rotational stage. The polarized monochromatic light is then incident upon the pixels of the image sensor. The compactness of the experimental setup was necessitated by the low light power output of the monochromator. Due to said low power output, it was not practical to use the condensing lens to collimate the light. Measurements were taken over the range of 400 nm to 700 nm in 10 nm steps and with the linear polarizer at angles from 0° to 170° in 10° steps.

Figure 3.29 shows the spectral response of the polarization image sensor $S_0$ as a function of incident light wavelength. The overall shape of the graph is similar to the quantum efficiency of the unmodified sensor, as shown in Figure 3.30.
Figure 3.29: $S_0$ as a function of incident light wavelength

Figure 3.30: Kodak KAI-04022 quantum efficiency as a function of wavelength [2]
Figure 3.31 shows $S_0$ as a function of incident angle of polarization. The calculated value of $S_0$ is approximately constant with incident angle of polarization.

![Figure 3.31: $S_0$ as a function of incident angle of polarization](image)

Figure 3.31: $S_0$ as a function of incident angle of polarization
Figure 3.32 shows the calculated angle of polarization as a function of incident angle of polarization. The four waveforms corresponding to 400 nm, 500 nm, 600 nm, and 700 nm are very close to each other, indicating the angle of polarization as calculated from the Stokes parameters is independent of the wavelength of the incident light. The exacerbated difference between incident angle of polarization and calculated angle of polarization is likely due to crosstalk caused by the lack of collimation. Similarly, Figure 3.33 shows the degree of linear polarization, as calculated from the Stokes parameters. The waveforms corresponding to 400 nm, 500 nm, 600 nm, and 700 nm are close to each other, suggesting that degree of linear polarization is independent of the wavelength of the incident light. The variations of the degree of linear polarization with incident angle of polarization are likely due to the uncollimated light and the associated increased crosstalk. The increased crosstalk also caused much lower extinction ratios Figure 3.34.
Figure 3.33: Degree of linear polarization as a function of incident angle of polarization

Figure 3.34: Extinction ratio as a function of wavelength
3.2.3 Angle of Incidence Measurements

The experimental setup for capturing images with light of different horizontal incident angles is shown in Figure 3.35. The setup is very similar to the setup for capturing measurements with different intensities. The light source comprised LEDs of 515 nm wavelength soldered onto custom printed circuit board. The LED circuit boards were mounted at the input port of an integrating sphere in order to eliminate any possible polarization from the LEDs. The LEDs were powered by a DC power supply operating in constant-current mode. An adjustable iris is mounted at the output port of the integrating sphere. Light passing through the iris then passes through an aspheric condensing lens, which produces a tightly collimated beam, approximately 4 cm in diameter. The collimated light beam passes through a linear polarizer mounted on a computer-controlled rotational stage. The light is incident upon the pixels of the image sensor, which is also mounted on a computer-controlled rotational stage. Measurements were taken with the linear polarizer at angles from 0° to 170° in 10° steps. The camera was rotated across a range of 0° to 25° in 5° steps.
Figure 3.36: Average $S_0$ as a function of incident angle

Figure 3.36 shows $S_0$ as a function of incident angle. At incident angles larger than 5°, the calculated value for $S_0$ decreases considerably. Extinction ratios and degree of linear polarization exhibit a similar trend (Figure 3.37 and Figure 3.38, respectively). The calculated value for angle of polarization was also affected by the incident angle. Figure 3.39 shows angle of polarization as a function of incident angle of polarization at 0° angle of incidence. Figure 3.40 shows angle of polarization as a function of incident angle of polarization at 5° angle of incidence, which differs only slightly from that at 0° angle of incidence. However, at 10° and 15° angle of incidence (Figure 3.41 and Figure 3.42, respectively), the angle of polarization measurement becomes very distorted.
Figure 3.37: Extinction ratio as a function of incident angle

Figure 3.38: Degree of linear polarization as a function of incident angle
Figure 3.39: Angle of polarization as a function of incident angle of polarization at 0° angle of incidence

Figure 3.40: Angle of polarization as a function of incident angle of polarization at 5° angle of incidence
Figure 3.41: Angle of polarization as a function of incident angle of polarization at 10° angle of incidence

Figure 3.42: Angle of polarization as a function of incident angle of polarization at 15° angle of incidence
3.2.4 Degree of Linear Polarization Measurements

![Experimental setup for assessing performance over a range of incident degrees of linear polarization](image)

The experimental setup for capturing images with light of degrees of linear polarization is shown in (Figure 3.43. The setup is similar to the setup for capturing measurements with different intensities. The light source comprised LEDs of 515 nm wavelength soldered onto custom printed circuit board. The LED circuit boards were mounted at the input port of an integrating sphere in order to eliminate any possible polarization from the LEDs. The LEDs were powered by a DC power supply operating in constant-current mode. An adjustable iris is mounted at the output port of the integrating sphere. Light passing through the iris then passes through an aspheric condensing lens, which produces a tightly collimated beam, approximately 5 cm in diameter. The collimated light beam passes through a linear polarizer mounted on a computer-controlled rotational stage. Following the polarizer, the light passes through a quarter-wave plate set at 45° to horizontal. The wave plate has the effect of altering the linearly polarized light into circularly polarized light when the relative angle between the polarization of the incident light and the plate is 45°; when the relative angle between the polarization of the incident light and the plate is 0°, the polarization state of the incident light remains unaffected. The light is incident upon the pixels of the image sensor. Measurements were taken with the linear polarizer at angles from 0° to 85° in 5° steps. Light polarized at 0° and 90° is at 45° to the quarter-wave plate. Hence, when the linear polarizer in the stage is rotated to 0° or 90°, the light incident upon the sensor is circularly polarized. (Figure 3.44 shows the digital responses of the individual pixels as a function of incident
Figure 3.44: Average digital value as a function of incident angle of polarization with a quarter-wave plate at 45°

angle of polarization. The 45° and 135° pixels are aligned with the quarter-wave plate, so their responses are similar to the responses without a wave plate. However, the 0° and 90° are at approximately 50% transmission throughout the sweep across angles of polarization. This is consistent with what is expected, since linear polarizers transmit circularly polarized light the same as unpolarized light. (Figure 3.45 shows average degree of linear polarization as a function of incident angle of polarization. The degree of linear polarization graph follows the expected trend, with a high degree of linear polarization at 45° and low degree of linear polarization at 0°. The maximum is not 1, and the minimum is not 0 due to crosstalk.)
Figure 3.45: Average degree of linear polarization as a function of incident angle of polarization with a quarter-wave plate at 45°
Chapter 4

Model of Observed Performance

As mentioned in the previous chapter, the empirical data from the polarization image sensor differed from expected values. Measurements taken as a function of intensity exhibited a degraded performance in cases where the data should not have varied with intensity. The variations are discussed and modeled below.

4.1 Ideal Pixel Response

The ideal theoretical pixel response follows Malus’ law (Equation 2.1). When Malus’ law is applied, the expected response of each pixel orientation is that described in Equation 4.1 and shown in Figure 4.1

\[
\begin{align*}
I_{0^\circ \text{theoretical}} &= I_0 \cos^2 \theta \\
I_{45^\circ \text{theoretical}} &= I_0 \cos^2 (\theta - 45^\circ) \\
I_{90^\circ \text{theoretical}} &= I_0 \cos^2 (\theta - 90^\circ) \\
I_{135^\circ \text{theoretical}} &= I_0 \cos^2 (\theta - 135^\circ)
\end{align*}
\] (4.1)
4.2 Crosstalk

The real-world performance of the image sensor differs from the theoretical expectation due to factors such as noise, crosstalk and fabrication defects. Crosstalk can be either optical or electrical. Optical crosstalk occurs when light directed at a pixel falls instead on an adjacent or nearby pixel due to an optical phenomenon such as reflection (Figure 4.2). Reflections are possible from the nanowires on the filter and to a lesser extent the filter substrate and glass slide. Electrical crosstalk occurs when photons incident upon a pixel affect other pixels (Figure 4.4).
4.3 Crosstalk Model

The combined effects of possible optical and electrical crosstalk were modeled as described in Equation 4.2, where $I_{0^\circ}$, $I_{45^\circ}$, $I_{90^\circ}$, and $I_{135^\circ}$ are the theoretical intensities of the $0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$ pixels, respectively (as described in Equation 4.1), $c_{th}$ is crosstalk between horizontally-adjacent pixels, $c_{tv}$ is crosstalk between vertically-adjacent pixels, $k$ is a constant coefficient, $I_0$ is the intensity of the incident light, and $c_{ti}$ is an exponential crosstalk component.

\[
\begin{align*}
I_{0^\circ \text{crosstalk}} &= I_{0^\circ} + c_{th} I_{45^\circ} + c_{tv} k I_0^{c_{ti}} I_{135^\circ} \\
I_{45^\circ \text{crosstalk}} &= I_{45^\circ} + c_{th} I_{0^\circ} + c_{tv} k I_0^{c_{ti}} I_{135^\circ} \\
I_{90^\circ \text{crosstalk}} &= I_{90^\circ} + c_{th} I_{135^\circ} + c_{tv} k I_0^{c_{ti}} I_{135^\circ} \\
I_{135^\circ \text{crosstalk}} &= I_{135^\circ} + c_{th} I_{90^\circ} + c_{tv} k I_0^{c_{ti}} I_{135^\circ}
\end{align*}
\] (4.2)

Figure 4.3: Comparison of empirical data and model incorporating crosstalk

The crosstalk was modeled as being constant with intensity for horizontally-adjacent pixels and as increasing with decreasing intensity for vertically-adjacent pixels. Best results were
obtained with the values shown in Equation 4.3. Figure 4.3 shows a comparison of the empirical data and the model incorporating crosstalk.

\[
ct_h = 0.125 \\
ct_h = 0.25 \\
k = 2.8 \\
ct_I = 0.4
\] (4.3)

Increasing crosstalk between vertically-adjacent pixels increases with decreasing intensity can be explained the operation of a photodiode (Equation 4.4), where \( W \) is the width of the depletion region, \( \varepsilon_r \) is the relative permittivity of the material, \( \varepsilon_0 \) is the permittivity of free space, \( q \) the elementary charge, \( N_A \) is the acceptor concentration, \( N_D \) is the donor concentration, \( V_{bi} \) is the built-in voltage, and \( V \) is the applied voltage.

\[
W \approx \left[ \frac{2\varepsilon_r\varepsilon_0}{q} \left( \frac{N_A + N_D}{N_A N_D} \right) (V_{bi} - V) \right]^{\frac{1}{2}}
\] (4.4)

![Image of electrical crosstalk](image.png)

**Figure 4.4: Example of electrical crosstalk**

When the sensor operates over a range of intensities, the only parameter that changes is \( V \), the applied voltage. The applied voltage varies linearly with the photocurrent, which, in turn, varies linearly with incident light intensity. Thus, lower incident light intensities result in a narrower depletion region. When \( e^- - h^+ \) pairs are generated in the depletion region or within one diffusion length, the electrons drift to the cathode, and holes – to the anode.
However, if e\textsuperscript{−}-h\textsuperscript{+} pairs are generated farther than one diffusion length from the depletion region, the charge carriers diffuse to the electrodes. When charge carriers diffuse, there is a greater probability that the photocurrent will manifest in an adjacent pixel instead of the pixel where the photon was incident.

\[ ct \propto I_0^{0.4} \rightarrow ct \propto W \propto I_0^{0.5} \]  \hspace{1cm} (4.5)

The intensity-dependent crosstalk model has approximately the same dependence on incident light intensity as the depletion region width (Equation 4.5, where \( ct \) is the overall crosstalk, \( I_0 \) is the incident light intensity, and \( W \) is the depletion region width).
Chapter 5

Conclusion

5.1 Applications

As previously mentioned, the polarization state of light contains additional information independent of wavelength or intensity. Reflections, magnetic fields and scattering can affect the polarization of light. For example, when the shape of an object is known, the degree of linear polarization can be used to calculate the index of refraction of the material. Conversely, if the index of refraction of an object is known, the shape can be reconstructed from the degree of linear polarization measurement. Other applications are also possible, such as measuring the effect of Faraday rotation or scattering.

5.1.1 Sample Images

The following images of the Moon were taken on 5/20/2013 in St. Louis, MO using a Meade LX 200 10” telescope (Figure 5.1). Figure 5.2, 5.3, and 5.4 are show values calculated from the same raw image. Each pixel of those images corresponds to a superpixel in the raw image. Figure 5.2 shows intensity in conventional grayscale; the vertical line in the center of the image is an artifact of the dual-tap readout circuit of the CCD imager. Figure 5.3 shows degree of linear polarization with a jet color mapping, where red corresponds to 1 (fully linearly polarized light) and blue corresponds to 0 (no linear polarization). The color map has been scaled 15% of the default (red corresponds to a DoLP value of 0.15), since the light reflected from the moon exhibited a degree of linear polarization not greater than 0.15.
Figure 5.4 shows angle of polarization with a hue, saturation, and value (HSV) color map. HSV is convenient, as it readily facilitates displaying both $0^\circ$ and $180^\circ$ as red. Yellow, green, cyan, blue and violet correspond to $30^\circ$, $60^\circ$, $90^\circ$, $120^\circ$, and $150^\circ$, respectively.

Figure 5.1: Meade LX 200 10" telescope with polarization camera attached.
Figure 5.2: Intensity
Figure 5.3: Degree of Linear Polarization
Figure 5.4: Angle of Polarization
5.2 Future Work

In order to reduce noise due to dark currents even further and allow for very long exposure times, it is possible to mount the CCD with the attached nanowire polarizer array to a purpose-built enclosure, such as the one shown in Figure 5.5. This particular enclosure utilizes a Peltier cooling module and can lower the temperature of the imager to $-40^\circ$C.

![Enclosure with Peltier cooling module](image)

Figure 5.5: Enclosure with Peltier cooling module
5.3 Summary

A high-resolution low-noise division-of-focal-plane polarimeter has been demonstrated. The performance of the imager has been thoroughly evaluated. This sensor is especially well-suited to applications in astronomy.
References


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