INTEGRATED POLARIZATION-ANALYZING CMOS IMAGE SENSOR FOR DETECTING INCOMING LIGHT RAY DIRECTION

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***Abstract*—A CMOS image sensor with an integrated wire grid polarizer to sense the polarization of light is presented. The chip consists of an array of 128 by 128 pixels, it occupies an area of 5x4 mm^2 and it has been designed and fabricated in a CMOS 180nm process. The integrated grid polarizer is oriented in various directions to compute the Stokes parameters which can be used to determine the degree of polarization of the incoming light ray.**

Keywords: CMOS image sensor, Polarization, Metal grid, Stokes parameters

I. INTRODUCTION

Direct sunlight is always unpolarized. When this unpolarized light enters the earth's atmosphere, it collides with the air molecules or is scattered because of the fluctuations in the air density. This scattering depends on the wavelength of the incoming light, and the intensity of the scattering is inversely proportional to the fourth power of the wavelength.

The light scattered by the air molecules (the perceived skylight) is partially polarized, which means that it is a combination of both the unpolarized natural light and a linearly polarized component [1]. Circular and elliptical polarization do not usually occur in the sky and thus only the linear polarized component is of importance. The skylight polarization depends mainly on the angle between the viewing direction and the sun, and on the clearness of the sky in the viewing direction [2]. When the scattering angle is 0º, the skylight is completely unpolarized. The maximum degree of polarization would occur for a scattering angle of 90º. The degree of linear polarization is not constant over the entire sky but depends on the position of the sun [2]. The strongest linear degree of polarization is observed during the sunset at 90° from the sun position.

A conventional analog sun sensor measures the position of the sun by allowing the light from the sun to pass through a pin hole array and illuminating a certain region of the imaging array [3] as shown in figure 1. The position of the illumination is then used to compute the altitude and direction of the sun with respect to the sensor. State of the art digital sun sensors such as [4] use the centroid method to compute the angular position of the sun. A mask on the image sensor allows only a quadrant of the image sensor to be illuminated and the centroid information computed digitally from the obtained image is then related to the x and y angular positions of the sun.

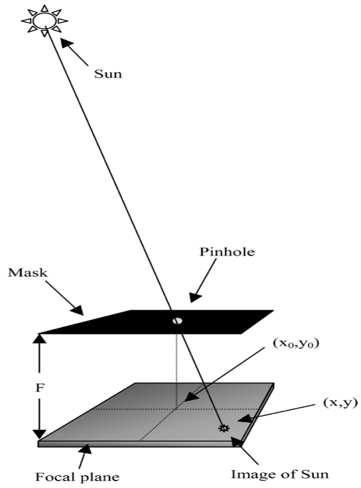


Figure 1: Conventional sun position detection model.

In the model proposed in [5], the winner takes all (WTA) principle is used to determine the region of the illuminated pixel to be tracked for the sun position. In [3] a centroid of each of the quadrant of the imaging array is calculated, the quadrant with maximum centroid value is then used to determine the solar altitude.

The prerequisite of these sun sensors is that they need to see the sun. Even in the absence of the visible sun, the degree of polarization which results from the linear polarization of the skylight is constant for a given angular elevation of the sun and varies with the angular movement of the sun. It has been shown that insects like bees and ants use the natural skylight e-vectors[1] and the degree of polarization to determine the elevation of the sun [6].

A polarization navigation sensor using the Stokes parameters to determine the incoming polarized light ray direction is presented in this paper. The working principle of the sensor is based on egocentric navigation by insects. The image sensor has the capability to sense 0º, 45º and 90º polarized light intensity. These intensities are used to compute the Stokes parameters and hence the azimuth angle of the polarized light ray. The computation of the Stokes parameters is simplified to be able to integrate the computational algorithm on-chip which would result in miniaturized navigational sensors in future. The principle of variation in the degree of polarization of the skylight with the changes in the elevation of the sun [2], [7], is used in our sensor to calculate the elevation of the sun. Though this

[1] The e-vector is the electric field vector of the polarized light.

principle is very common in insects, it has not yet been explored in sensors to our knowledge.

In this paper, section I and II covers the introduction and theory behind polarization of light and celestial compass. Section III describes the designed image sensor with polarization sense regions formed with metal wire grid. Finally Section IV presents the experimental results where the incoming light ray direction is measured when the angular position of the light source is changed. The measurement results conclude that it is indeed possible to compute on-chip the position of the light source based on the light ray direction with little complexity.

II. THEORY

A. Stokes parameters and degree of polarization

Electromagnetic radiation travels as transverse waves, i.e., waves that vibrate in a direction perpendicular to their direction of propagation. Polarization is a phenomenon peculiar to transverse waves. Polarization is the distribution of the electric field in the plane normal to the propagation direction. In an unpolarized or randomly polarized electromagnetic wave the orientation of the electric field vector changes randomly.

The mathematical representation of a plane wave propagating in the z direction is given by equation [1.0]

$$E = E_0 \cos(kz - \omega t + \varphi_0)\ . \qquad [1.0]$$

Where E_0 is the amplitude, k is the propagation (or wave) constant($k=2\pi/\lambda$), ω is the circular frequency ($\omega= kc = 2\pi c/\lambda$), φ_0 is the initial phase and $\varphi =(kz- \omega t+ \varphi_0)$ is the phase of the wave.

Three states of polarization of a light wave are possible: completely unpolarized, completely polarized or partially polarized. An unpolarized electromagnetic wave can be polarized through absorption, reflection, refraction and scattering. In this work we will limit our discussion to polarization of electromagnetic waves caused due to scattering. The scattering of light by air molecules produces linearly polarized light in the plane perpendicular to the incident light. Linear polarization is of two types, vertically or s-polarized and horizontally or p-polarized. A vertically polarized wave is one for which the electric field lies only in the x-z plane and a horizontally polarized wave is one for which the electric field lies only in the y-z plane.

The electric field of an electromagnetic wave polarized by scattering consists of a polarized and an unpolarized component. The polarization state of an electromagnetic wave can be conveniently described by a set of parameters called Stokes parameters which were developed by G.G. Stokes in 1852. The four Stokes parameters are grouped into a column vector, known as Stokes vector as shown in equation [1.1]

$$\vec{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \qquad [1.1]$$

The Stokes parameters represented in equation [1.1] are Intensity (I), degree of polarization (Q), plane of polarization (U) and ellipticity (V).The first Stokes parameter describes the total intensity of light, while the other parameters describe the polarization state of the light. The Stokes vector helps in the measurement of

i. the intensity of light
ii. the degree of linear polarization with respect to vertical and horizontal axes
iii. the degree of linear polarization with respect to the axes oriented at +45º and -45º
iv. the degree of left and right circular polarizations

The vector components [8] are given by equation [1.2]:

$$\begin{aligned} S_0 &= E_{x0}{}^2 + E_{y0}{}^2 \\ S_1 &= E_{x0}{}^2 - E_{y0}{}^2 \\ S_2 &= 2E_{x0}E_{y0}\cos(\nabla\varphi) \\ S_3 &= 2E_xE_y\sin(\nabla\varphi) \end{aligned} \qquad [1.2]$$

Where E_{x0} is the field strength of the parallel polarized light, E_{y0} is the field strength of the perpendicular polarized light and $\nabla\varphi$ is the phase difference between the parallel and perpendicular polarized light.

There are various ways of measuring the Stokes parameters, each corresponding to the measurement of intensity of the beam after it passes through different filter system arrangements, to selectively linearly polarize the incident light. The four Stokes parameters, S_0, S_1, S_2 and S_3 are obtained from the measured intensities and form a column vector of four elements in a four directional space. The Stokes parameters used for this paper are modified [9] as shown in equation [1.3]

$$\begin{aligned} S_0 &= I_{90^\circ} + I_{0^\circ} \\ S_1 &= I_{90^\circ} - I_{0^\circ} \\ S_2 &= I_{45^\circ} - I_{0^\circ} \\ S_3 &= I_{90^\circ} - I_{45^\circ} \end{aligned} \qquad [1.3]$$

Where I_{0° is the intensity of the light after passing through a horizontal linear polarizer, I_{90° is the intensity after a vertical linear polarizer, and I_{45° is the intensity after a linear polarizer placed at 45º.

The degree of polarization (DOP) is a measure of the percentage of the electric field of light which is polarized compared to the electric field of total incident light. In terms of the Stokes parameters, the degree of polarization of the light beam is expressed by the equation [1.4].

$$DOP = \delta = \frac{\sqrt{S_1^{\,2} + S_2^{\,2} + S_3^{\,2}}}{S_0} \qquad [1.4]$$

A completely polarized light is represented in terms of the Stokes parameters by $S_0^2 = S_1^2 + S_2^2 + S_3^2$ and has a DOP of 1. For a completely unpolarized light, the Stokes parameters satisfy, $S_1 = S_2 = S_3 = 0$ and the DOP has a value of 0. A partially polarized light satisfies $S_0^2 > S_1^2 + S_2^2 + S_3^2$, where by the DOP varies from 0 to 1.

B. Celestial Compass

The navigational strategies of insects are of great interest to learn how the simple brain architecture of insects is able to process information for navigation. To determine the direction of travel, insects use the celestial compass based on either the pattern of the polarized skylight (polarization compass) or on the direct sunlight (sun compass) [10]. The direct sunlight or solar navigation system uses the sun as a compass. A polarized skylight navigation system uses the extensive pattern of polarized skylight. The scattering of the light ray with the air molecules at the earth hemisphere generates polarized light. In clear sky, the polarization patterns are quite regular and depend very strongly on the position of the sun.

Each partially polarized skylight ray exhibits a predominant vibration direction (e-vector) perpendicular to the plane of the scattering angle. Since the e-vector orientation depends only on the plane of the scattering angle, any scattered radiation possesses an appropriate e-vector orientation nearly independent of the atmospheric disturbance factors. The celestial e-vector pattern is shown in figure 2.

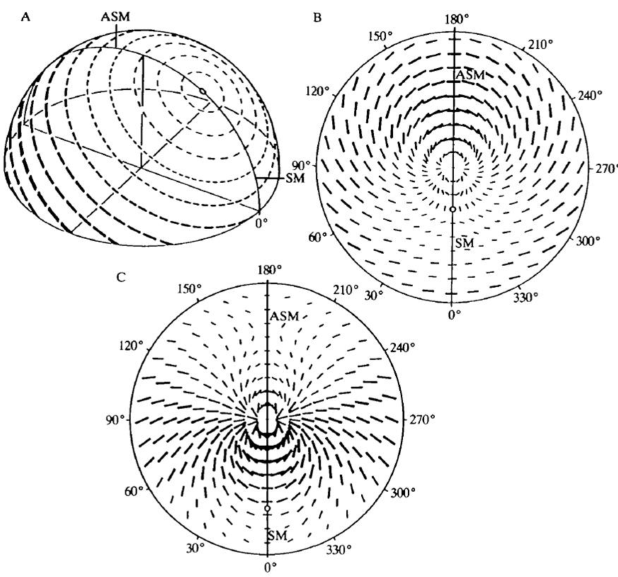


Figure 2: Celestial e-vector pattern. (A) Three-dimensional representation of the e-vector pattern, the orientation and width of each black bar corresponds to e-vector direction and the degree of polarization respectively. (B) Two-dimensional for sun elevation at 60º and (C) Two-dimensional for sun elevation at 24º

The polarization pattern varies in a systematic fashion both in plane (e-vector) and degree of polarization, according to the sun's position. The e-vector patterns in the sky are not visible to humans, but insects use these vector directions as a reference for compass orientation. The degree of polarization depends only on the direction of the observation point relative to the angular position of the sun [11]. The theoretical degree of linear polarization predicted in [11] is plotted in figure 3 along with the measurement results of the experiments found in literature. The dashed line is for results measured on Mauna Lao in Hawaii and the circular dots are for the results measured at Bocaiuva Brazil [12], [13].

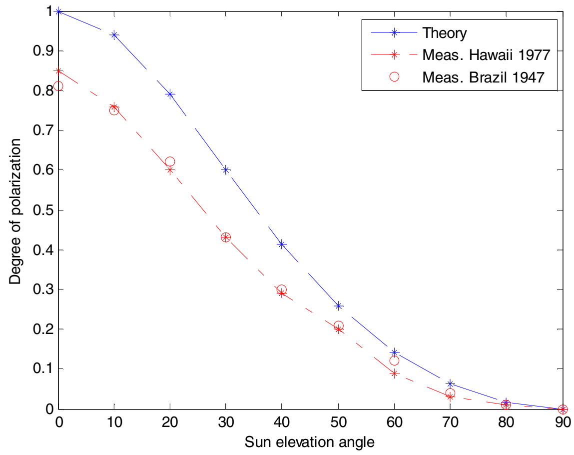


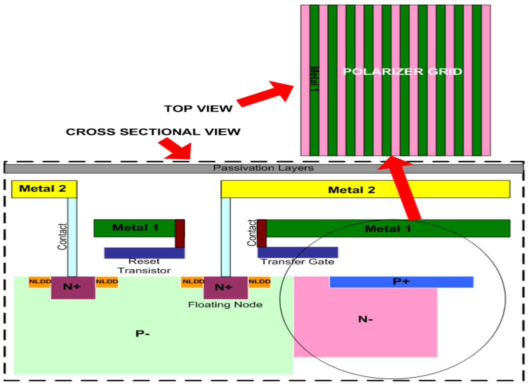
Figure 3: Variation in degree of polarization with changes in the sun elevation angle

III. SENSOR DESCRIPTION

From the aperture theory [14],[15], it is known that for an electromagnetic wave to be absorbed by a wire grid, its wavelength should be larger than the pitch of the wire grid ($\lambda/d>2$; where λ is the wavelength and d is the spacing between the wires in the grid). The visible spectrum wavelengths range from 300 to 720nm and thus a wire grid pitch of less than 300nm is desired. With the scaling of CMOS technologies, the distance between metal layers also decreases, opening up the possibility of using them in a grid structure for the absorption of electromagnetic waves.

State of the art polarization image sensors are based either on a standard CMOS/CCD camera coupled with an external polarization filter controlled externally, or on integrated polarization filters fabricated on top of the pixel array. The later serves to measure polarization information in real time. An embedded wire grid polarizer with an extinction ratio of 2.03 has already been demonstrated [16].

Our polarization sensor has an embedded linear wire grid polarizer in each pixel, realized with the first metal layer of the process on top of a pinned photodiode ($p^+/n^-/p$-sub). The linear wire grid polarizer was implemented using thin metal strips with a line space of 240nm/240nm (pitch of 480nm) as shown in figure 4. Though a pitch of less than 300nm is required to cover the complete visible spectrum wavelength range, the chosen technology allows only for a pitch of 480nm.



`Figure 4: Wire grid Polarizer

The image sensor consists of an array of 128 by 128 pixels, it occupies an area of 5x4mm^2 and it has been designed and fabricated in the 180nm CMOS CIS process from UMC. Table 1 shows the sensor specifications. The sensor architecture is shown in figure 5.

TABLE 1: Sensor specifications

Process	0.18µm 1 poly 3 metals UMC CIS process
On-chip Polarizer	Line/Space = 0.24µm/ 0.24µm (0.48µm pitch)
Active imager size	3.2 mm(H) x 3.2 mm(V)
Chip Size	4 mm(H) x 5 mm(V)
Active pixels	128 x 128
Pixel size	25µm x 25µm
Shutter type	Global shutter
Maximum data rate/master clock	64 MPS / 32 MHz
Supply voltage	1.8V

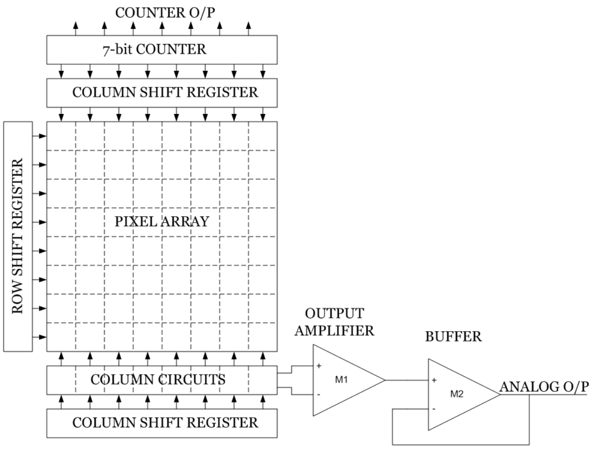


Figure 5: Sensor architecture

The chip is divided into four main blocks. First, the pixel array with the photodiodes and the associated circuitry for analog computations, which occupies most of the chip area. Each pixel contains a pinned photodiode and 32 transistors to perform low level image processing. The size of the photodiode is 10µm x 10µm which corresponds to a 16% pixel fill factor. In this paper we focus on the polarization sensing ability of the sensor thus the low level image processing will not be discussed. Second, placed below the pixel array is the analog readout circuit. The analog readout circuit consists of column level circuits (double differential sampling circuit), an output amplifier, a buffer and the column shift register. The analog output provides the analog voltage at each pixel. Third, placed at the top is the digital readout circuit. The digital readout circuit consists of a 7-bit counter and a column shift register. The 7-bit counter is used to count the number of active high pixels in each row. Finally, the left side is dedicated to a row select logic and timing control blocks to address each row of pixels sequentially.

The array of 128 by 128 pixels was split into three regions as shown in figure 6:

1. A 64x128 array without a metal grid used for normal imaging applications
2. A 64x64 array (sense region 1) consisting of 2 by 2 pixel arrays where two pixels (A and B) measure the intensity while the other two measure the 0º (D), and 90º (C) degree polarized intensity respectively
3. A 64x64 array (sense region 2) consisting of 2 by 2 pixel arrays where one pixel records the intensity of the light (A) while the other 3 record the 0º (B), 45º (C) and 90º (D) polarized intensity.

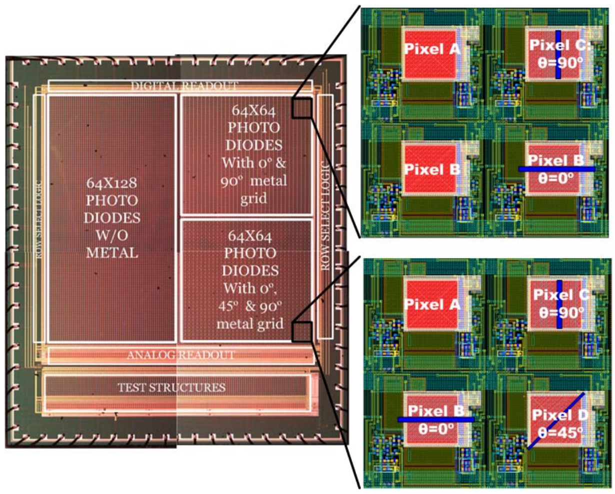


Figure 6: Sensor Regions with different Polarizing angles.

The additional pixel sensitivity to 45º polarized light in sense region 2 is used to compute the Stokes parameters. The pixels dedicated to sense the intensity in regions 1 and 2 are used to normalize the data obtained from the pixels sensitive to the polarization directions.

IV. Performance Analysis

A. Performance of the wire grid polarizer

The measurement setup is shown in figure 7. The sensor was illuminated with a polarized light obtained by passing the light from a DC light source through a linear polarizer.

For the measurement of the wire grid transmittance and the extinction ratio, the transmission axis of the linear polarizer was varied from 0º to 180º in steps of 15º to vary the polarization angle of the light reaching the image sensor.

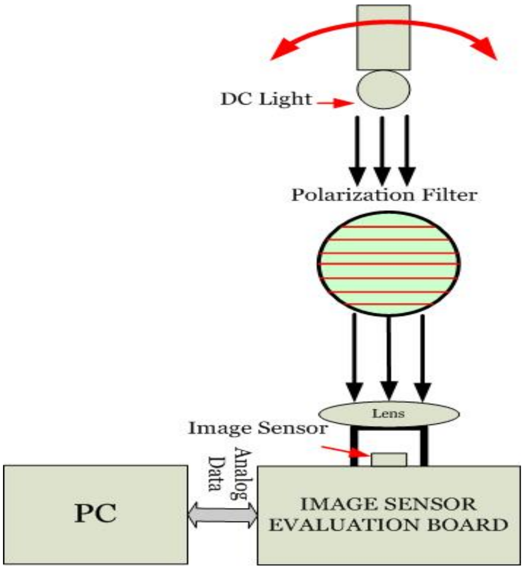


Figure 7: *Measurement setup*.

The corresponding analog outputs of the pixels sensitive to 0º and 90º in the polarization sense region 1 and 0º, 45º and 90º in the polarization sense region 2 are recorded. These obtained signals are then sent to PC for analog and digital computations. For the first version of the sensor the computations were done off-chip to have a proof of concept. Each obtained analog pixel value is normalized with respect to the intensity obtained at the intensity sensitive pixel. The normalized output is the transmittance of the wire grid polarizer. The normalized transmittance as a function of the transmission axis of the linear polarizer (incident polarization angle) for the two polarization sense regions is shown in figure 8 and 9.

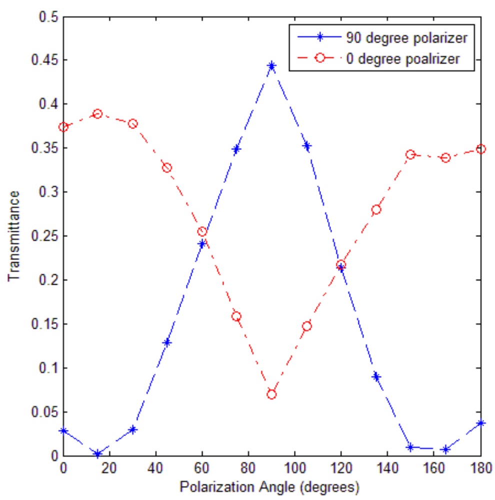


Figure 8: 0º and 90º polarization profile in polarization sense region 1.

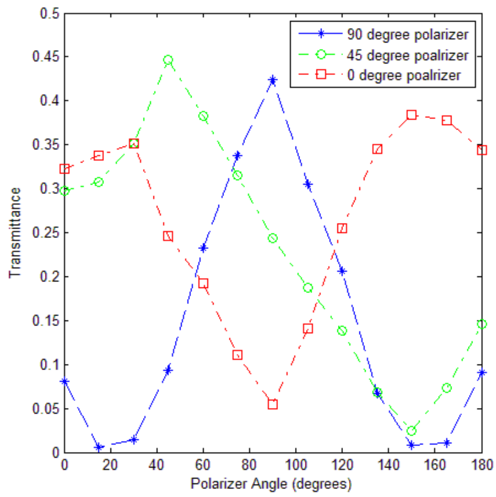


Figure 9: 0º, 90º and 45º polarization profile in polarization sense region 2.

The mean maximum (T_{max}) and minimum (T_{min}) transmittances for the 0º and 90º polarization sensitive pixels in the polarization region 1 and 2 along with the respective extinction ratio (ER) achieved are shown in the Table 2.

TABLE 2: Transmittance (%) and extinction ratio

Region	$T_{MAX}(0^{\circ})$	$T_{MIN}(0^{\circ})$	$T_{MAX}(90^{\circ})$	$T_{MIN}(90^{\circ})$	ER
1	0.389	0.07	0..444	0.01	6.3
2	0.384	0.0545	0.424	0.06	7.7

B. Incoming light ray direction determination

Due to the measurement setup constraints, it was not possible to measure the variations of the degree of polarization with respect to the angular position of the sun under open sky. An indoor experiment was conducted to evaluate the Stokes parameters from the information obtained with pixels sensitive to 0º, 45º and 90º in order to determine the direction of the incoming light rays. The DC light source in figure 7 was made to move in different angles with respect to the image sensor. The unpolarized light from the DC light source passes through the linear polarizer. The transmitted intensity is then measured by the image sensor and sent to the PC for computations of the Stokes parameters.

In this experiment, the polarization sense region 2 is used to exploit the 45º polarized information. The modified Stokes parameters as shown in equation [1.3] are relatively easy for on-chip computations. A differential circuit within the 2 x 2 pixel array can be implemented to calculate the various Stokes parameters. For the current version, the values for $I_{90^{\circ}}$, $I_{0^{\circ}}$ and $I_{45^{\circ}}$ are obtained by averaging the pixel output over 30 frames off chip in the polarization sense region 2 with the linear polarizer filter transmission axis set to 90º, 0º and 45º respectively. The degree of polarization is computed using equation [1.4].

Here we have assumed that the circular and elliptical components of the polarized light coexist with the linear component and thus the ellipticity angle of the ellipse of the

Poincare sphere is to be determined as [8]. Poincare sphere allows convenient description of polarized signal (Stokes parameters).

$$\chi = \frac{1}{2}\sin^{-1}\left(\frac{S_3}{\delta * S_0}\right) \qquad [1.5]$$

The measured ellipticity angle for 10º, 15º and 30º incidence is shown as "Result 2" in the figure 10. A correlation coefficient of 0.98 is obtained which implies a very strong correlation between the theoretical and the measured results.

The computation of the degree of polarization in equation [1.4] that needs to be used in equation [1.5] is relatively difficult to compute on chip as it needs squaring and square-root arithmetic operations. In [17] the degree of polarization was related to the maximum and minimum transmitted intensity as shown in equation [1.6]

$$DOP = \delta(x,y) = \frac{I_{\max}(x,y) - I_{\min}(x,y)}{I_{\max}(x,y) + I_{\min}(x,y)} \qquad [1.6]$$

Where I_{max} and I_{min} are the maximum and minimum transmitted intensity for the pixel at coordinated x and y. This degree of computation is relatively easy to implement on chip as it needs simple arithmetic which are easier to be implement in analog domain.

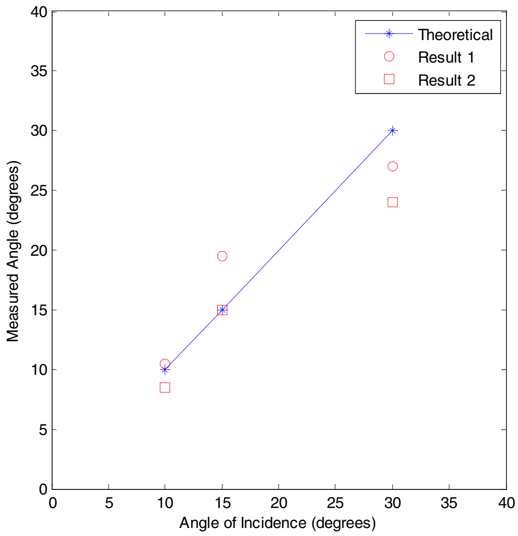


Figure 10: Measurement of incident light ray angle

Using equation [1.3] in equation [1.2] the ellipticity angle is computed and plotted as "Result 1" in figure 10. A correlation coefficient of 0.94 is obtained for the theoretical and measured values.

IV. Conclusion

A CMOS image sensor using a wire grid to measure polarization information has been designed. The sensor working principle is based on the insect's principle form of egocentric navigation in which the skylight polarization is used as a compass. The degree of polarization of the skylight for a given elevation of the sun is a constant, and this principle can be used as a compass clue. Though this principle is very common in insects, it has not yet been explored in sensors. The different orientation angles of the grid measure the different polarized light intensities. Extinction ratios of 6.3 and 7.7 have been achieved in the two sense regions of the sensor. The 0º, 45º and 90º polarized light intensities are used to compute the degree of polarization using Stokes parameters. The computational algorithm can be implemented on-chip which would result in miniaturized navigational sensors.

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