Integrated Polarization Image Sensor for Cell Detection

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Abstract: A complete polarization image sensor composed of a 60 by 20 pixel array with on-chip analog processing and integrated with pixel-pitch polymer polarization filter is presented. The image sensor, fabricated in 0.5µm CMOS process, computes the first three Stokes parameters at the focal plane at 30fps with 15mW power consumption. The sensor is used to identify automatically material properties by computing the degree of polarization off chip.

Introduction: CMOS solid state imaging devices have become the prevalent choice in the multi-million dollar industry of digital photography. Consumer demands for high pixel-count imagers have set trends for small pixel-pitch sensors, high signal-to-noise ratios, high dynamic range and better color replication of the imaged scene among others. These trends have resulted in proliferation of imaging sensors in our daily lives that capture two of the three fundamental properties of light: intensity and wavelength [1]. The third fundamental property of light, i.e. polarization, has been ignored by solid state image sensors partially due to the human inability to discriminate polarization information.

Polarization vision contains important information about the imaged environment, such as surface shapes and material properties, which are ignored with traditional image sensors [2]. Previous approaches for integrated polarization sensors have focused on computing only a subset of polarization properties, known as polarization difference imaging (PDI), with large pixel pitch of 50microns [3] and 128microns [4] respectively. The low extinction ratios of ~2 in [3], have limited the precession of the extracted polarimetric information. Typical approaches by the computer vision community toward polarization vision include coupling of power hungry electro/mechanically controlled polarization filters coupled with commercial image sensors and DSP/PCs.

We have developed an imaging system capable of extracting complete polarization information from the imaged environment in real time and in high resolution. This sensory system integrates current mode photo pixels, pixel pitch matched micro polarization array and processing at the focal plane. The paper is organized as follows. In the next section we present theoretical overview of basic polarization properties of light, followed by a discussion on focal plane polarization filters. Measurements and results are presented in the last section.

Theoretical overview of polarization: Polarization is a phenomenon observed in transverse vectorial waves. These are waves that vibrate in a direction perpendicular to their direction of propagation. Since light is a transverse wave, it can be represented as a sum of waves vibrating in (generally partially) random directions perpendicular to the line of propagation. If the vibration is consistently in a particular direction, the light is linearly polarized. Partial polarization of light usually occurs once the unpolarized light is reflected from a given surface or has passed through a polarization filter.

Polarimetric information of partially polarized natural light is described by the first three Stokes parameters. There are different ways to express Stokes parameters, one of which is presented by equation (1), which describe the polarization state of the electric-field vector.

$$S_0 = I_t; \quad S_1 = 2I(0^\circ, 0) - I_t \quad ; \quad S_2 = 2I(45^\circ, 0) - I_t \qquad (1)$$

In equation (1), I_t is the total intensity; $I(0^0,0)$ is the intensity of the e-vector filtered with a 0 degree polarizer and no phase compensation between the x and y components; and $I(45^0,0)$ is the intensity of the e-vector filtered with a 45 degree polarizer and no phase compensation as above. The first three Stokes parameters can be computed with two linearly polarized intensities and the total intensity of the e-field vector. The 4^{th} Stokes parameter is usually ignored for the natural light, since the phase information between the orthogonal polarization components is not readily available for naturally occurring light.

Therefore, in order to fully describe the polarization state of light in nature, for which the phase information between the components is not available, three linearly polarized projections or two non-orthogonal linearly polarized projections in combination with the total intensity are needed.

Image sensor overview: A block diagram of the complete polarization image sensor with the schematic of the pixel is presented in Figure 1. The sensor successfully couples CMOS current mode active pixel imaging elements with pixel-pitch polymer polarization filter array in order to compute the first three Stokes parameters of polarization. The first three Stokes parameters fully describe the polarization of light with two linearly polarized intensities and the total intensity of the light wave. In order to fully describe the polarization state of light in nature, for which the phase information between the components is not available, two linearly polarized projections in combination with the total intensity are needed.

In the image sensor presented in Figure 1, a neighborhood of 2 by 2 pixels is addressed and accessed simultaneously. In the 2 by 2 window of computation, one pixel records the 0 degree projected polarized image (*I(0)*), another records the 45 degree projected polarized image ($I(45^0)$) and two pixels record the unfiltered intensity image (I_t). The polarimetric parameters are estimated by reading out all four pixels in parallel and scaling them individually at the periphery, i.e. away from the imaging array.

The photo pixel is composed of a photodiode and three transistors, reset and two read-out transistors. The switch transistor is eliminated from the pixel and moved to the periphery of the imaging array. The pixel operates in an integrative mode and a linear relationship between light and output current is accomplished by operating the read-out transistors M2 and M3 in the linear regime. Two output currents are provided per pixel in order to access two neighboring pixels per row simultaneously. The access of individual pixels is controlled via an external current conveyor. The read-out current from a single pixel is scaled with digitally controlled analog scaling circuit and merged with the other three scaled currents in the window of computation.

The polymer polarization array is fabricated separately by an optimized procedure for manipulating Polyvinyl Alcohol (PVA) thin film [5]. The final pixel-pitch polarization filter is composed of two individually patterned layers of PVA, offset by 45 degrees and merged together via UV activated transparent epoxy. The pattern of the micropolarization array is similar to the Bayer pattern used in color imaging and the integration of the PVA filter with the CMOS image sensor is presented in Figure 3. The “Bayer” polarization pattern, provides individual pixels with polarization sensitivity. The total height of a single (two) layer(s) is 10 (~25) microns, with 18 micron square structured filters. The array of regularly patterned single PVA layer can be observed from the SEM image in Figure 2. The measured extinction ratio, defined as the ratio of the maximum to the minimum transmission, is 50 at 620nm wavelength.

The performance of the polarization image sensor is evaluated under uniformly linearly polarized light. The degree of polarization of the incident light is changed between 0 and 180 degrees in increments of 10 degrees while the intensity remains constant. The response of three neighboring pixels is presented in Figure 4 and they are normalized with respect to reference pixels without any filters. The maximum response of the 0 and 45 degree polarization filtered pixels is 33% and 28% of the total incident intensity, respectively. The standard deviation of the polarization response is 1.8% before calibration and 0.9% after off-chip calibration. The variation between various polarization filters is predominantly due to the difference in the height of the polymer filter. The unfiltered pixel has maximum transmission of 44%, which is due to light absorption in the epoxy layers between the two PVA layers and the interface with the CMOS image sensor. The angle of polarization, defined as $\sqrt{S_1^2 + S_2^2} / S_0$ is computed off chip and presented in Figure 4. A linear fit error of 2.2% was achieved.

A sample image obtained from the image sensor is presented in Figure 5. The intensity image presents two objects, a CD and a plastic cover against a black diffusive background. The degree of polarization, computed off-chip as $0.5 * \arctan(S_2 / S_1)$, has strong correlation with the material properties of the imaged objects. The diffusive black background does not polarize reflected light and the degree of polarization is around 0 for this region. Light reflected from the CD has a degree of polarization of around 25 degrees, while the plastic cover creates a 35 degree of polarized light. The specular reflection in the corner of the CD creates a maximum degree of polarization at the Brewster angle of reflection.

A summary of the image sensor performance is provided in Table 1. The integrated polarization sensor computes the first three Stokes parameters in parallel at 30fps and consuming 15mW of power. The polarization extinction ratios of 50 can be used to automatically detect materials of the imaged objects.

References:

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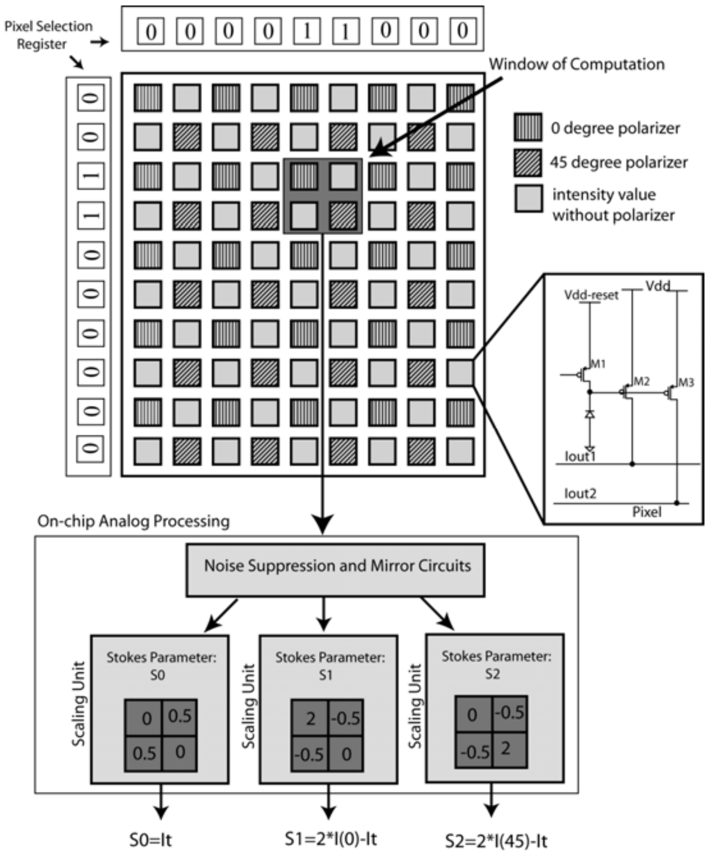

Figure 1: Image sensor overview

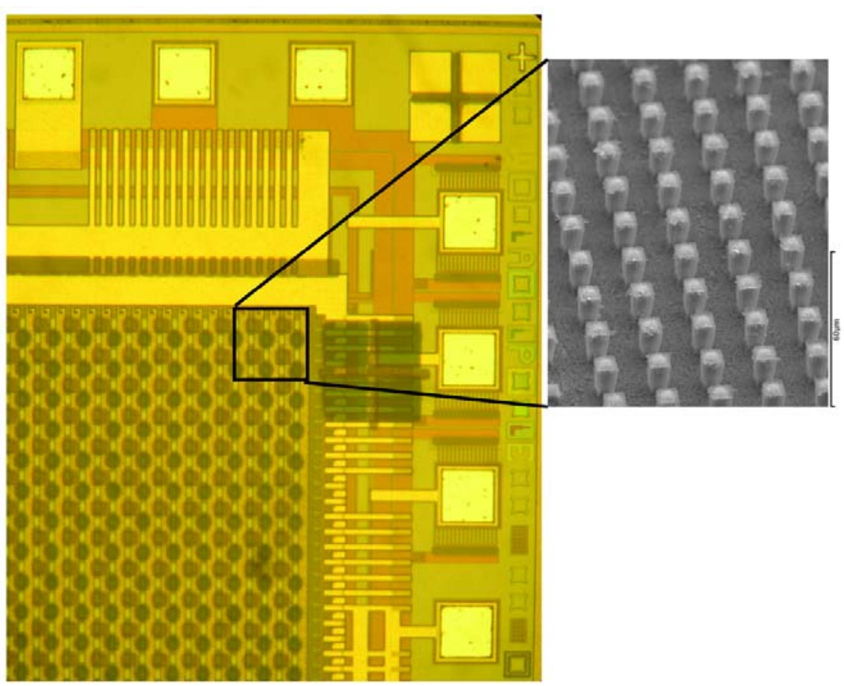
Figure 2: CMOS image sensor merged with polymer micro polarization array and an SEM image of the top layer of the filter array

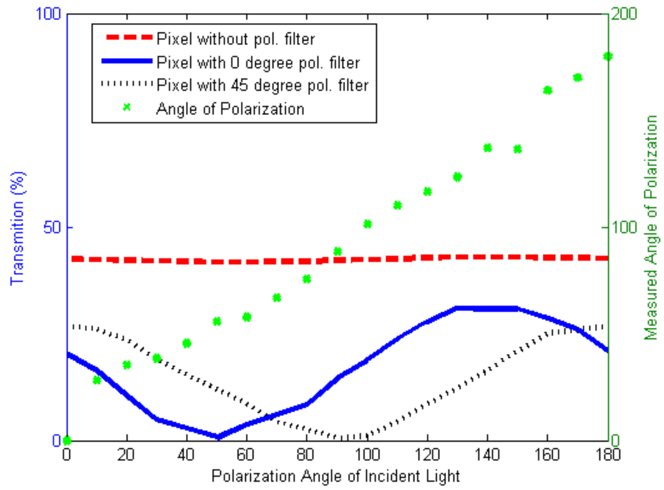

Figure3: Polarization response of three individual pixels with two different polarization filters offset by 45 degrees and one without a filter and the computed angle of polarization of linearly polarized incident light.

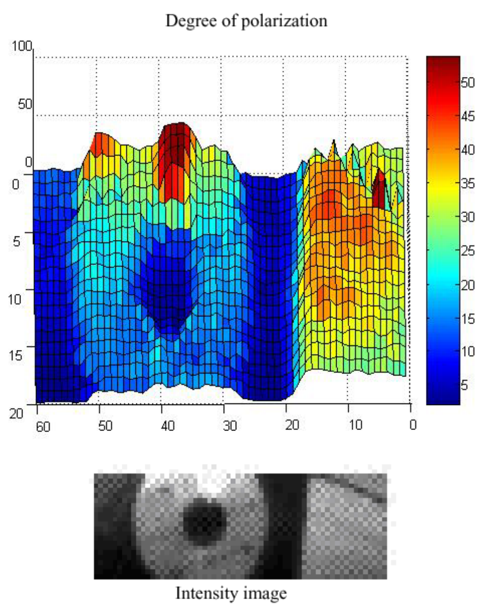

Figure 4: Intensity image provided from the image sensor and the computed degree of polarization presented in color. The color presents the degree of polarization and indicative of the material properties of various object.

Technology	0.5µm CMOS (3M,2P)
Array Size (Pixel Size)	60 x 20 (18µm x18µm)
Fill Factor	40%
FPN	1.2% of saturated level before DDS 0.4% of saturated level after DDS
Frame Rate	30fps
Micropolarization array material	Polyvinyl Alcohol (PVA)
Number of PVA layers	Two layer offset by 45 degrees
Thickness of final (single) filter	~25 µm (10µm)
Extension Ratios at 620nm	50
Power Consumption	15mW

Table: Image sensor performance summary