Incident Light Angle Detection Technique Using Polarization Pixels

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Abstract—**In this paper we present the design and analysis of a CMOS image sensor pixel capable of detecting the angle of incident light. Determining the angle is of paramount importance in reconstructing the 3D information of the imaged scene. These pixels achieve this by including polarization gratings on top of the photodiodes in each pixel. Three different pixels, each with different grating orientation produce enough information to determine the local incidence angle. Because of the symmetric nature of the response for positive and negative angles, another set of pixels, called the linear quadrature pixel cluster has been included to break the symmetry and provide greater angle resolution. We present the simulation results as well as the design, which is targeted towards GlobalFoundries 65 nm CMOS mixed-signal process.**

Index Terms—**Polarization detection; linear quadrature pixel cluster; angle estimation; CMOS image sensor.**

I. Introduction

3D image capture is considered as the next revolutionary step in the field of image sensors. Research is currently focused on the many methods for capturing 3D images like Time-of-Flight (ToF) [1] and multi-aperture [2] to name a few. These methods either require an active light source or a number of pixels working in cohesion to achieve the objective. Although highly accurate results were demonstrated using some of these methods, they have serious limitations in terms of power consumption, chip area, highly complicated setup and requirement of specialized components. These factors limit their wide scale commercial adaptation.

Recently an on-chip method - one that uses diffraction related Talbot effect to determine the local incidence angle was proposed and demonstrated [3]. Although the results were far from satisfactory and involved complex data processing, the method showed an alternative way for capturing 3D data. It has been demonstrated that by capturing the local incidence angle and intensity of the incoming light, complete 3D information of the imaged scene can be reconstructed. Keeping in line with this latest trend we present yet another alternative method for capturing the 3D data - one that uses polarization.

Polarization imaging has been around for decades and many applications of the technique have been successfully demonstrated. Typical wide scale use of polarization imaging has been limited to applications like reducing the glare of captured image in outdoor settings (notably involving water or hazy atmosphere) [4] and to classify materials based on their reflectivity for applications involving object recognition [5].

The polarization angle detection technique that we present here is generic, in the sense that, along with angle detection we can use the sensor for a variety of applications that depend on polarization information contained in light captured by the sensor. This paper mainly deals with angle detection, which is a pressing problem that has to be solved in order to accurately reconstruct a 3D imaged scene. Integrated solutions such as the Talbot pixels have serious limitations in terms of pixel resolution and sensitivity. The easiest approach to increase the sensitivity is to increase the size of the photodiode. But this leads to lower pixel resolution. The technique that is presented here requires far fewer number of pixels for achieving a wide angle resolution compared to the Talbot pixels, resulting in angle and pixel resolution that are superior to any integrated approach that has been demonstrated so far.

II. Background Information

Light is a transverse electromagnetic wave in which the electric field, magnetic field and the direction of propagation are all orthogonal to each other. Polarization is a phenomenon associated with transverse electromagnetic waves in which the electric field (or magnetic field) of an EM wave shows preference for vibration along a particular direction. If the polarization direction is completely random, then such waves are said to be unpolarized waves or randomly polarized waves. Majority of the naturally available light sources and a large number of manmade light sources are randomly polarized. Polarization is a hidden phenomenon as far as humans are concerned. The human eye is incapable of detecting polarization in light, unlike intensity (which manifests as brightness) and wavelength (which manifests as color).

When introduced to a wire gird polarizer, light with any arbitrary polarization becomes linearly polarized. Earlier, external polarizer's (PVA polymers or aluminium nano wires) were placed on top of the photodiodes to capture the polarization component of light. This required careful alignment and calibration of polarizer's on top of the pixel array. The results were prone to errors arising out of misalignment between polarizer and pixel array, and optical crosstalk between adjacent pixels because of thick polarizer layer on top of them. Because of the advancement in technology, wire grid polarizers can now be fabricated on-chip, right above the photodiodes using any of the routing metal layers. Although this alleviates some of the problems, low light transmittance onto the photodiode and low extinction ratio's are still a concern.

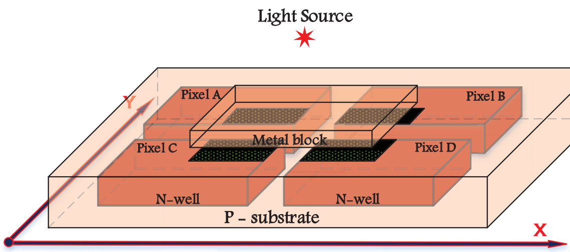


Fig. 1. Physical structure of a quadrature pixel cluster.

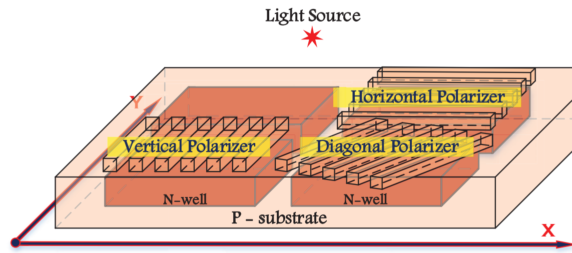


Fig. 2. Physical structure of a group of polarization pixels with different polarizer orientations.

Wire grid polarizers absorb EM wave components that have the same orientation as the wire grid. EM wave components that are orthogonal to the wire grid orientation passes through. For the wire gird polarizer to work efficiently, the pitch 'd', of the wire grid should be lesser than the lowest wavelength, 'λ', that has to be detected, i.e., $d<\lambda/2$ [6]. The visible spectrum range is roughly from 300 nm to 700 nm. Modern CMOS fabrication processes are capable of having smaller metal pitches that make detecting light at the lower end of the visible spectrum feasible. In 65 nm CMOS process the lowest width of metal 1 is 90 nm. For 50% duty cycle, using metal 1 for constructing the wire grid polarizer, we could achieve a minimum pitch of 180 nm.

III. Angle Detection

Earlier work related to Talbot effect based pixels showed that the response produced by diffraction grating is sensitive to changes in the incidence angle. Because of the inherent periodicity of the response produced by such pixels, large number of pixels were required to unambiguously determine incident light angles. Furthermore, the range of angles that could be detected were quite small. Our previous work [7] attempted to solve some of these problems by introducing additional set of pixels, called the quadrature pixel cluster (QPC), which was based on the metal-shading principle. The QPC produced a coarse linear response proportional to the angle variations. Although the combination produces fairly accurate results, it requires a fair bit of post processing to estimate angles because of multiple Talbot response periods within any given angle range.

In this work we extend our previous approach, that is, we combine the linear quadrature pixel cluster response along with the response produced by the polarization pixels to accurately determine the angles. The response produced by polarization pixel is sensitive to the incidence angle, but it exhibits a symmetry around 0°. That is, the positive and negative angles produce the same response. We use the pixels of linear quadrature pixel cluster to break the symmetry thereby allowing unambiguous resolution of positive and negative angles.

Fig. 1 shows the physical structure of a quadrature pixel cluster. The QPC consists of four photodiodes with a metal block on top of it. The shadow produced by the metal block on photodiodes vary based on the incidence angle, producing a change in the pixel response. Pair of adjacent pixels could be used for determining the angle variation along a particular direction. For example, in order to determine the angle variations along the horizontal direction (x-axis) the difference response produced by either pixels A, B or C, D could be used. The response produced by these kind of pixels are linear (within a range), but have low sensitivity making detection of very closely spaced angles difficult.

Fig. 2 shows the physical structure of a group of polarization pixels along with an intensity pixel without any polarizer on top of it. The three polarization pixels have horizontal, vertical and diagonal polarizer orientation on top of the photodiode. In ideal situations, if the light is completely unpolarized, the response produced by a polarizer with arbitrary grating orientation would suffice for estimating the angle. But if the light is polarized with the same orientation as the grating, very little light passes through the grating making the detection process difficult. A solution to this is to have two pixels with their gratings aligned orthogonal to each other (For example, horizontal and vertical polarization pixels in Fig. 2). In this case if the input light has a polarization component with the same orientation as one of the gratings, the other pixel with the orthogonal grating captures enough information so as to make angle detection feasible. By averaging the output response of both these pixels we can capture angle information for light polarized in any arbitrary direction.

IV. Pixel Design

The polarization pixels considered for analysis in this work consist of polarizers with pitch, d = 200 nm, duty cycle = 50% and are made up of metal 1. The QPC on the other hand makes use of metal 5 as the shadow inducing layer. Three different polarizer orientations have been implemented - 0°, 45° and 90°. Only two of these polarizers (0° and 90°) are sufficient for angle detection. The third polarizer (45°) could be used for calculating Stokes parameters that come in handy while determining the polarization information for some special applications.

Fig.3 shows the pixel-unit-cell comprising of an intensity pixel, three polarization pixels and a quadrature pixel cluster (which in turn comprises of four pixels). The figure shows the pixel schematic along with the physical photodiode structure. Each pixel is made up of five transistors and a photodiode. Out of the five transistors, 1 is for pixel reset, 2 for the source follower stage and 2 more for a transmission gate, which aids in pixel selection. The photodiode is made up of n-well/p-sub depletion region and has two guard rings surrounding it - one p+ guard ring for isolation against stray holes and one n+ guard ring for isolation against stray electrons. Signal from pixels pass through a switched capacitor amplifier and a global

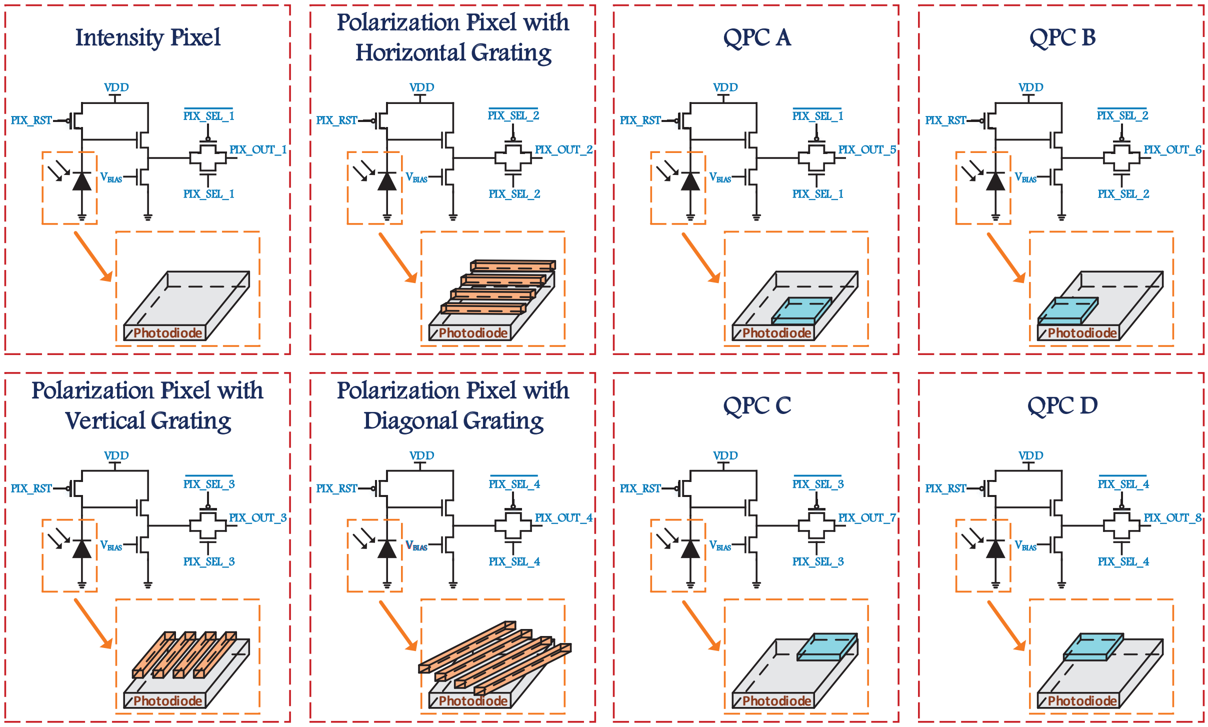


Fig. 3. Pixel-unit-cell comprising of an intensity pixel, three polarization pixels and a quadrature pixel cluster.

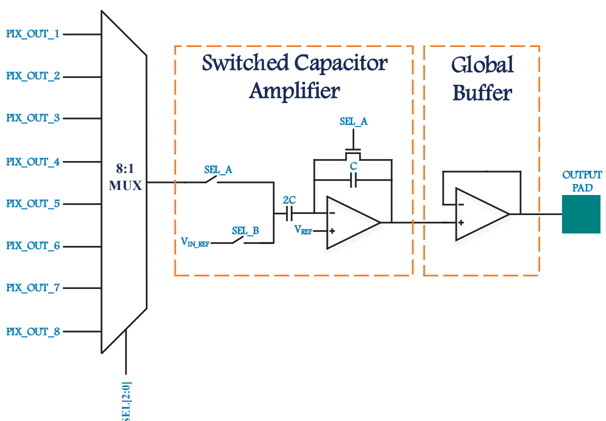


Fig. 4. Figure illustrating signal data path to the output pad.

buffer before reaching the output pad (Fig.4). The SC amplifier amplifies signals at its input by a factor of 2. The signal at the output is given by:

$$\mathrm{V_{OUT}} = \mathrm{V_{REF}} - \frac{2\mathrm{C}}{\mathrm{C}}(\mathrm{V_{IN\_REF}} - \mathrm{V_{PIXEL\_VAL}}) \qquad (1)$$

Fig.5 shows the microphotograph of the pixel array along with the layout of polarization and QPC pixels.

V. Results and Discussion

Simulations were performed using a commercially available software that performs finite difference time domain (FDTD) simulations. All simulations were performed at a wavelength of 500 nm.

Fig. 6(a) and Fig. 6(b) show the response produced by vertical (90°) and horizontal (0°) polarization pixels as a

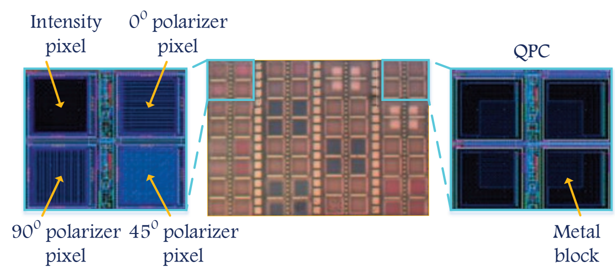
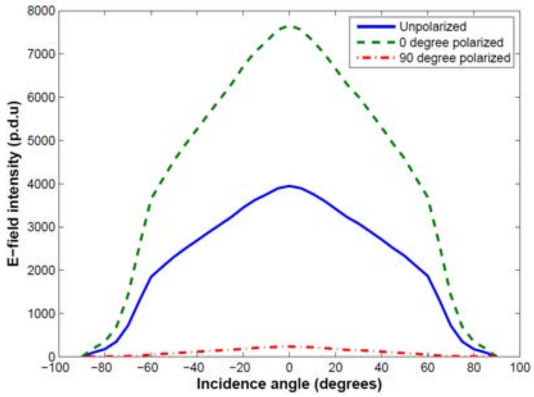


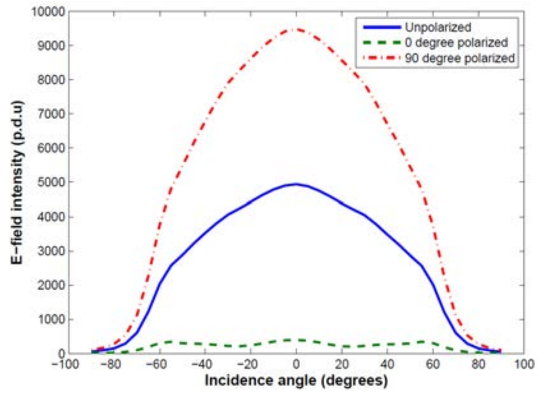
Fig. 5. Microphotograph of the pixel array along with the layout of polarization and QPC pixels.

function of incidence angle. As can be seen from both the plots, the response produced by both the pixels are similar in case of unpolarized light, whereas when light is polarized along a particular orientation, the orthogonal counterpart of the pixel produces a strong response. Hence the average response of both the pixels have to be considered for unambiguously determining the angles.

Fig. 6(c) shows the plot of Talbot effect based pixel response [3] along with the QPC response. As can be seen, in order to achieve a desirable angle resolution (say from -65° to +65°) a number of Talbot response periods have to be considered. This increases the constraints on the QPC response and requires it to have high sensitivity. Sensitivity primarily depends on the area of the photodiode used in the QPC along with a number of other minor parameters. Hence, in order to achieve good sensitivity, a QPC with a large photodiode area is desirable. Add to this a number of Talbot pixel groups with different grating orientation and grating offsets. This reduces the overall pixel resolution for simultaneous intensity and angle detection. QPC response is linear only in the range from -65° to +65° and this limits the total angle range. To increase linearity beyond



(a)



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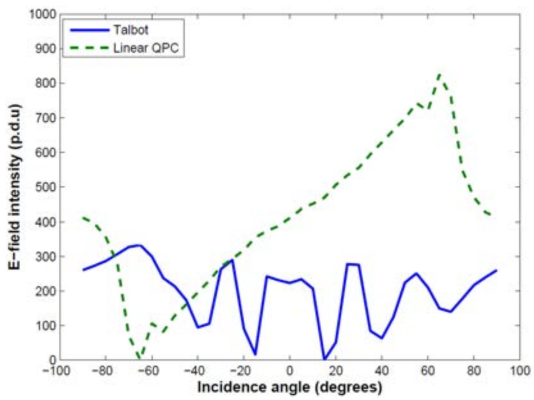
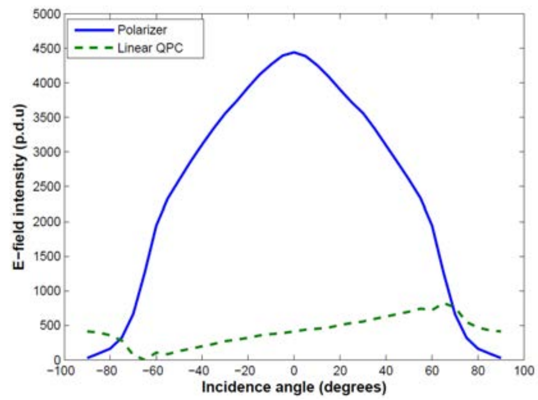


(c)



(d)

Fig. 6. Simulation results. (a) Vertical polarization pixel response as a function of incidence angle for different polarization states of light source. (b) Horizontal polarization pixel response as a function of incidence angle for different polarization states of light source. (c) Talbot pixel response and QPC response as a function of incidence angle for an unpolarized light source. (d) Polarization pixel response and QPC response as a function of incidence angle for an unpolarized light source.

this limit, bigger photodiodes and large separation between adjacent photodiodes is required.

Fig. 6(d) shows the response of one of the polarization pixels along with QPC response. An unpolarized light source was considered for this illustration. Based on the plot, angles anywhere in the range from -65° to +65° can be unambiguously determined. The main limitation here is the linearity of the QPC response.

VI. Conclusion

The paper presented a new technique for determining the angle of incident light. The technique can unambiguously determine angles in the range from -65° to +65°. This range is primarily limited by the linearity of quadrature pixel cluster response which has been used in conjunction with the polarization pixels to break the inherent symmetry in the polarization pixel response. Compared to the conventional Talbot pixel response, the response produced by the polarization pixels are stronger, enabling the use of low sensitivity photodiodes. Also, the number of pixels required to simultaneously resolve incidence angles and intensity is way lower than that required by the Talbot pixels. We hope that by adopting this technique, the angle detection process will become simpler, enabling high resolution 3D image capture. We will report further results once the chip is tested with real imaging scenes.

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References

[1] S.-J. Kim, S.-W. Han, B. Kang, K. Lee, J. D. K. Kim, and C.-Y. Kim, "A Three-Dimensional Time-of-Flight CMOS Image Sensor With Pinned-Photodiode Pixel Structure," *Electron Device Letters, IEEE*, vol. 31, no. 11, pp. 1272–1274, 2010.

[2] K. Fife, A. El Gamal, and H.-S. Wong, "A Multi-Aperture Image Sensor With 0.7μm Pixels in 0.11μm CMOS Technology," *Solid-State Circuits, IEEE Journal of*, vol. 43, no. 12, pp. 2990–3005, 2008.

[3] A. Wang and A. Molnar, "A Light-Field Image Sensor in 180 nm CMOS," *Solid-State Circuits, IEEE Journal of*, vol. 47, no. 1, pp. 257–271, 2012.

[4] Y. Schechner, S. Narasimhan, and S. Nayar, "Instant dehazing of images using polarization," in *Computer Vision and Pattern Recognition, 2001. CVPR 2001. Proceedings of the 2001 IEEE Computer Society Conference on*, vol. 1, 2001, pp. I–325–I–332 vol.1.

[5] L. Wolff, "Polarization-based material classification from specular reflection," *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, vol. 12, no. 11, pp. 1059–1071, 1990.

[6] E. Hecht, *Optics*, 4th ed. Addison Wesley, 2002.

[7] V. Varghese, X. Qian, S. Chen, S. ZeXiang, T. Jin, L. Guozhen, and Q. J. Wang, "Track-and-Tune Light Field Image Sensor," *Sensors Journal, IEEE*, vol. PP, no. 99, p. 1, 2014.