A polarisation-analysing CMOS image sensor for sensitive polarisation modulation detection

R. Okada,1 H. Tashiro,2 and J. Ohta1
1Division of Materials Science, Graduate School of Science and Technology, Nara Institute of Science and Technology, 8916-5 Takayama, Ikoma, Nara, Japan
2Department of Health Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka, Japan
✉Email: sasagawa@ms.naist.jp

In this study, a polarisation-analysing CMOS image sensor is fabricated for sensitive polarisation modulation detection. Although the image sensor with on-pixel polarisers can image the incident polarisation collectively, its sensitivity to a weak polarisation change is not high. With the proposed method, an external polariser is used to enhance the polarisation modulation sensitivity with a polarisation image sensor. The performance of this highly sensitive polarisation image sensor and imaging experiments are evaluated using a flow channel.

Introduction: Polarisation is a fundamental property of light and is useful for sophisticated imaging applications. Polarisation imaging is expected to be used for calculating normal vectors to the surfaces [1], enhancing the contrast under hazy conditions [2]; non-contact fingerprint pattern detection [3]; material classification [4]; and the discrimination of optical isomers of chemical substances [5, 6], among other uses.

An image sensor with an on-pixel polariser structure, in which polarisers are placed directly above the image sensor, as shown in Figure 1(a). Of these on-pixel polarisers, those in the horizontal direction are orthogonal to each other on the image sensor, as shown in Figure 1(a). This linearly polarised light is rotated by the observation target, and the light enters the sensor. First, the external polariser reduces the linearly polarised light component orthogonal to the external polariser. Thus, the total light intensity is reduced and the pixel saturation can be avoided. Common mode noise is removed by acquiring the difference between orthogonal pairs of polarisers on the chip. These structures make it possible to measure polarisation changes with high sensitivity. The details of this method will be reported elsewhere.

Figure 2 show schematic diagrams of the proposed method. In the figure, the boundary of pixel saturation is indicated by a circle. The incident light is shown as a vector along the $\gamma$-axis. In this case, the polarisation to be measured is the red vector. This vector is larger than the pixel saturation, and thus it cannot be measured. Therefore, the incident linear polarisation component is reduced by an external polariser. As a result, the $x$-axis component of the incident light is reduced, and pixel saturation can be avoided. Furthermore, because the polarisation component generated by the measurement object passes through, only the polarisation component parallel to the incident light is reduced. The reduced power is compensated by increasing the incident light intensity. Thus, the ratio of the rotated component is increased and the SNR is improved.

After passing through the external polariser, the polarisation is analysed by the wire grid polariser on the pixel. Figure 3(a) shows the simulation results of the 0° and 90° pixel outputs. The polariser on the pixel shifts the minimum point, resulting in a difference in output. Figure 3(b) shows a plot of the difference between the two outputs. This difference in value corresponds to the change of the polarisation angle from the reference. The amount of change is almost linear within the range where the sine function is linearly approximated. By normalising this value, the change in polarisation can be estimated from the sensor output signal. In addition, because the difference in value is obtained, the common mode noise component can be reduced.
Table 1. Specifications of fabricated CMOS image sensor chip

| Parameter          | Value                      |
|--------------------|----------------------------|
| Technology         | 0.35-μm 2-poly 4-metal standard CMOS process |
| Polariser [μm]     | Line/space = 0.5:0.45       |
| Pixel size [μm²]   | 15 × 15                    |
| PD size [μm²]      | 11.2 × 12.0                |
| Array size         | 160 × 120 (80 × 60 set)    |
| Supply voltage [V] | 3.3                        |
| Chip size [mm²]    | 2.700 × 2.645              |

Fig. 4 Polarisation measurement CMOS image sensor. (a) Block diagram. (b) Micro-photograph of full chip and pixel layout. (c) Circuit diagram of differential circuit

Polarisation imaging CMOS sensor overview: In this study, we designed and fabricated the sensor using a 0.35-μm 2-poly 4-metal standard CMOS process. Table 1 shows the specifications of the sensor. Figure 4(a) shows a block diagram of the prototype sensor, and Figure 4(b) shows a micro-graph of the sensor and its pixel layout. Figure 4(a) shows a block diagram of the prototype sensor, and Figure 4(b) shows a micrograph of the sensor and the layout of the pixels. The size of the pixels is 15 × 15 μm and the sensor has a pixel resolution of 160 × 120. Because the orthogonal pixels are arranged next to each other, a polarisation image with a pixel resolution of 80 × 120 pixels can be acquired. In this sensor, an operation for taking the difference between orthogonal pairs of polarisers was created using a CMOS circuit. Figure 4(c) shows the circuit. By installing a differential amplifier in each of two columns, the difference can be taken in parallel, and the process of image acquisition can be omitted, enabling real-time measurements. An external ADC with a resolution of 14-bit was used to digitise the output signal.

The difference circuit is based on a switched capacitor circuit. First, Set-SW is turned on and the output of Pixel-OUT-A is sampled. Then, Set-SW is turned off and Sample-SW is turned on. By doing so, the difference in potential between V Pixel-OUT-A and V Pixel-OUT-B can be obtained.

\[
\Delta V_{\text{Pixel-OUT}} = V_{\text{Bias}} + \frac{C_1}{C_2} \times (V_{\text{Pixel-OUT-A}} - V_{\text{Pixel-OUT-B}})
\]

In the designed switched-capacitor amplifier, capacitors are provided to double the amplification factor. In addition, 80 differential amplifiers are installed as column amplifiers, and the output column of the differential amplifier can be selected by select-SW.

Measurement results and imaging experiments: To evaluate the function of the sensor, measurements were made by changing the linear polarisation. A red high-intensity LED with a peak wavelength of 633 nm was used as the incident light source. The polariser used to generate the linear polarisation was a high extinction ratio polariser with an extinction ratio of 10³:1. For the external polariser on the extinction ratio sensor, a wire grid polariser film with an extinction ratio of approximately 500:1 was used. The linear polarisation incident on the sensor was varied within the range of ±0.5°. In the measurement, we averaged 60 × 60 pixels and 96 frames. Figure 5(a) shows the result of this measurement. Figure 5(b) shows the result of the normalisation within the range of ±0.5°.

The output from the difference amplifier changes linearly with the change in polarisation. In this case, the error was calculated as 2.5 × 10⁻³° within the range of ±0.5°, as shown in Figure 5(c). This value includes the mechanical error of the polariser holder that changes the linear polarisation, and the measurement accuracy of the sensor itself is estimated to be higher than this.

For the polarisation imaging experiments, we set up an experimental system, as shown in Figure 6(a). A channel of 1.2 mm wide and 1.4 mm thick was fabricated and placed on the sensor. The image of the change in polarisation was obtained by comparing the flow of L-menthol and D-menthol with the flow of ethanol as the reference image in the unpolarised state. The L-menthol solution was prepared by dissolving 4.5 g of L-menthol with 10 mL of ethanol, and the D-menthol solution was prepared by dissolving 1.5 g of D-menthol with 10 mL of ethanol. Figure 6(b) shows the change in polarisation when the L-menthol solution flowed into the channel, and Figure 6(c) shows the polarisation change when the D-menthol solution flowed into the channel. For the polarisation angle calculation, a calibration curve was created from the previous experiment, and the output value of the sensor was calculated to the polarisation angle from the calibration curve.

The analysed polarisation is opposite for the L-menthol and D-menthol solutions. In fact, a change in polarisation opposite to the concentration of menthol solutions. In fact, a change in polarisation opposite to the concentration of menthol solutions.
Fig. 6 Experimental set up and the imaging results. (a) Experimental set up. (b) Image showing change in polarisation when L-menthol flows. (c) Image showing change in polarisation when D-menthol flows

Fig. 7 Time change of polarisation change when L-menthol and D-menthol are passed through the flow path

Figure 6(b,c). The spikes in the plot are caused by air bubbles that are introduced when the liquid flowing in the channel is changed and they pass through the channel.

Conclusion: We fabricated a polarisation-analysing CMOS image sensor for sensitive polarisation modulation detection. The proposed method avoids the limitations of polarised image sensors such as a pixel saturation and low extinction ratio of on-chip polarisers, and realises a highly sensitive imaging of changes in polarisation. In addition to the flow path imaging demonstrated in this paper, the proposed approach is expected to be applied to real-time high-frequency electric field imaging based on the electrooptic effect [14].

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