A polarization CMOS image sensor with on-pixel polarizer optimized for microwave electric-field imaging

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Abstract In this study, we designed and fabricated a CMOS image sensor with a dual-layer on-pixel polarizer to improve the performance of electric field imaging using the electro-optic effect. The on-pixel polarizer is composed of the second and third metal wiring layers of a 0.35-µm standard CMOS process. The parameters were optimized to obtain the maximum extinction ratio at a wavelength of 780 nm. 10 GHz electric field imaging performed was improved by using the image sensor with the proposed on-chip polarizers.

Keywords: polarization image sensor, on-pixel polarizer, electric field imaging, electro-optic imaging

1. Introduction

High-frequency electric field measurements are performed using electro-optic (EO) probes based on high-frequency photonics techniques. This EO probe is low-intrusive and has broadband characteristics up to the THz waveband. Furthermore, photonic techniques are suitable for parallel processing. The combination of an image sensor and EO crystals can provide real-time electric field distribution [1,2]. In this method, EO crystals are illuminated with polarized light, and the birefringence index changes by the electric field are measured. Since the change in the birefringent index is very weak, an image sensor highly sensitive to polarization change is required. However, conventional polarization image sensors are not suitable for high-sensitivity measurement. However, the low extinction ratio of on-pixel polarizers and the small pixel size are not suitable for detecting weak signal changes. To solve this problem, we have proposed a method for detecting weak polarization changes by using a signal-selective polarizer directly above the polarization image sensor [1,3].

In this study, we improved the on-pixel polarizers to obtain good performance in the 780 nm band by improving the high-sensitivity polarization image sensor we have developed for electric-field imaging.

2. Highly sensitive polarization-imaging method using a double-polarizer structure

We proposed a highly sensitive polarization-imaging method based on a double-layer polarizer structure that combines a polarization image sensor with an on-pixel polarizer and a signal-selective polarizer, as shown in figure 1[1,3]. The signal-selective polarizer is performed to "improvement of modulation by signal components" while the on-pixel polarizer is performed to "conversion of polarization changes to light intensity." In the proposed method, a polarization image sensor with two types of on-pixel polarizers (0° and 90°) mounted on adjacent pixels was fabricated. The signal selective polarizers are positioned at ±45° to the on-pixel polarizers. The signal selective polarizers are uniform polarizers with a high extinction ratio and are arranged in a crossed-Nicol arrangement with respect to the incident linear polarization. This arrangement significantly reduces the linear incident polarization and provides high transmittance for the polarization-changing component generated by the observed object. As a result, it is possible to enhance the polarization rotation angle while avoiding pixel saturation, and the SNR in polarization change detection is significantly improved.

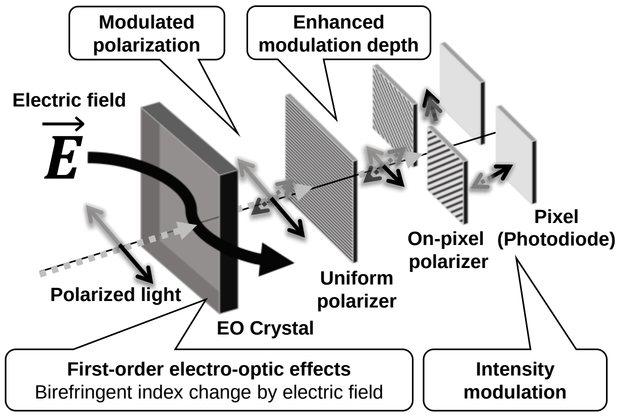

Fig. 1. EO imaging system based on the proposed method.

Table I Image sensor specifications

Technology	0.35-µm 2-poly 4-metal standard CMOS
Pixel size	30 µm × 30 µm
Photodiode size	15 µm × 15 µm
Photodiode	n-well / p-sub
Number of pixels	80 × 60 (40 × 60 set)
On-chip polarizer	Line/Space = 0.7 µm / 0.7 µm (Metal2)
	Line/Space = 0.7 µm / 0.7 µm (Metal3)
	0º or 90º
Extinction ratio	3.28 (0º), 3.30 (90º) at 780 nm

3. Polarization image sensor

A 0.35-µm 2-poly 4-metal standard CMOS process is employed to fabricate the image sensor. Table I lists the specifications of the sensors, and Figure 2(a) shows the pixel

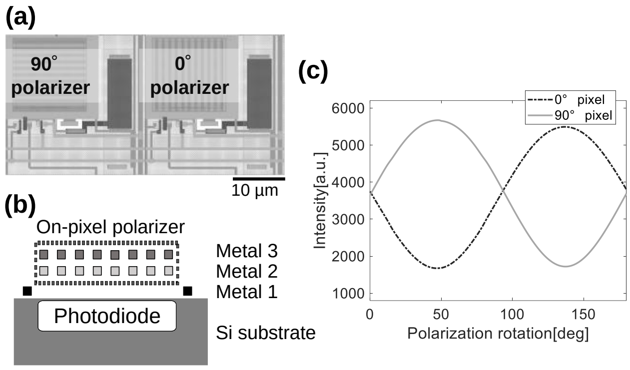

Fig. 2. (a) Layout of the polarization pixel pair. (b) Schematic diagram of the pixel strictures. (c) Pixel output versus incident polarization angle.

layout, where the pixel size is 30 µm. A pair of pixels with 0° and 90° polarizers are arrayed in the sensor. The pMOS capacitors are placed in the guard ring of the n-well and connected to the PDs. By increasing the pixel capacitance, the light saturation limit is increased, and the maximum SNR is improved. Figure 2(b) shows the cross-section of the pixel structure. The on-pixel polarizer comprises the second and third metal wiring layers of the CMOS process. The line and space of the wire grids are both 0.7 µm. The double polarizers are arranged in aligned. The parameters are optimized to obtain the maximum extinction ratio at a wavelength of 780 nm.

The on-pixel polarizer characteristics were measured as a function of the incident linear polarization angle, as shown in Figure 2(c). The extinction ratios were measured to be 3.28 for the 0° pixel and 3.30 for the 90° pixel. We also built a polarization imaging system using the proposed method. This imaging system was used to estimate the angle of polarization change using a sensor with an improved on-pixel polarizer structure. A film polarizer with an extinction ratio of approximately 800 was used as a signal-selective polarizer. The maximum error was 4.6×10^{-4}° in a 50 × 50 pixel average and a 96 frame average in a range of ±0.3°, which is better than the previous study [1].

4. EO imaging demonstration

Figure 3(a) shows a schematic diagram of the fabricated electric field imaging system. In this system, a microstrip line fabricated on a high permittivity substrate as a device under test (DUT), shown in Figure 3(b), was modulated with a frequency f_{RF} = 10 GHz + 90 Hz component, and the electric field in the near field was imaged. The EO crystal used was a (100)-ZnTe crystal. By modulating the crystal at f_{LO} = 10 GHz and using the electro-optic crystal as a mixer for optical heterodyne, the polarization image sensor images the electric field distribution on the DUT at an intermediate frequency of f_{IF} = 90 Hz. The imaging frame rate was set to 360 FPS, and the intermediate frequency components were extracted from 10000 frames by Fast Fourier transform to obtain the intensity and phase distributions shown in Figure 3(c,d). The (100)-ZnTe crystal is sensitive to the electric field vertically from the DUT [4]. Therefore, the electric field intensity on the microstrip line is high, and the phase distribution shows a phase difference of π rad between above and around the line. Detection of the intermediate frequency was performed by post-processing. In the future, it is expected to be possible to perform detection of the intermediate frequency in the chip by installing two capacitors in the pixel and performing detection by swinging the capacitor transfer [5].

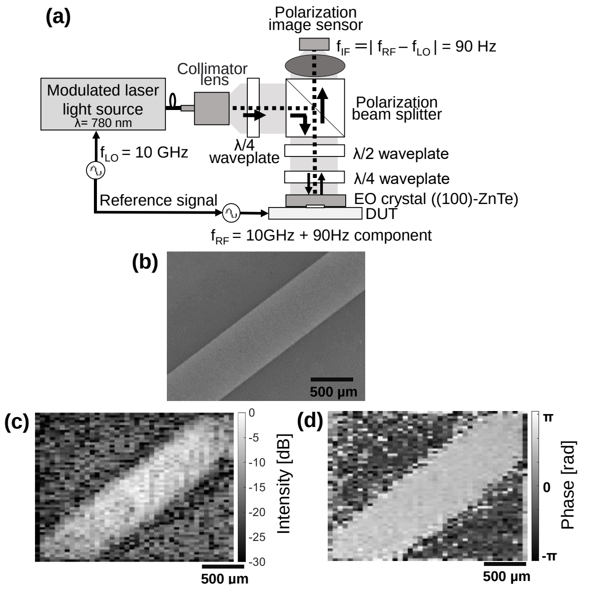

Fig. 3. (a) Experimental setup of RF electric field measurements. (b) Optical image of DUT. Electric field images of (c) intensity and (d) phase at 10 GHz.

5. Conclusion

In this study, we designed and fabricated a CMOS image sensor with a dual-layer on-pixel polarizer to improve the performance of electric field imaging using the electro-optic effect. The extinction rate at 780 nm was improved to 3.28 for the 0° pixel and 3.30 for the 90° pixel, using the second and third metal wiring layers in the polarizer structure. By installing this polarization image sensor into a polarization imaging system based on the proposed method, the measurement accuracy was confirmed to be 4.6×10^{-4}° within a range of ±0.3°. Also, we built an EO imaging system based on the proposed method using the fabricated polarization image sensor and successfully demonstrated electric field imaging at 10 GHz.

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