A Polarization Contrast Retina That Uses Patterned Iodine-Doped PVA Film

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Abstract

We present the design of a 1D polarization contrast retina. The retina employs two parallel, linear arrays of 29 photodiodes as sensing elements. Polarizing material is placed on the focal plane so that each array of photodiodes receives linearly polarized light whose e-vector components are orthogonal. On chip analog subthreshold MOS circuit computes the polarization contrast. We also discuss how we can process iodine-doped poly(vinyl alcohol) linear polarizers using standard microfabrication lithographic techniques to delineate features with resolution comparable to pixel sizes of standard imagers.

1. Polarization Vision

The retinae of most insect[1] and certain vertebrate[2,3] species are sensitive to polarization in their environment, but humans are blind to this property of light. Currently, scientists use polarization information to perform difficult computer vision tasks, such as image segmentation, object orientation, material classification,[4] and atmospheric and solar research.[5] Biologists use polarimeters to investigate behaviors of animals – vis-à-vis polarization – in aquatic habitats.[6]

Complex vision tasks are made tractable with polarization vision techniques because polarization is a more general descriptor of light and contains physical information about reflecting objects in a scene that traditional intensity based sensors ignore. The electric field (e-vector) of light can be expressed as the superposition of two orthogonal components, E_x and E_y, and can be written as

$$\vec{\mathbf{E}} = \hat{x} A e^{-j(\omega t - kz + \phi_a)} + \hat{y} B e^{-j(\omega t - kz + \phi_b)}, \qquad (1)$$

where ω is angular frequency, k is the wave-vector, and ϕ is phase. Polarized light results when the phase between orthogonal components is deterministic. In the case of 0° phase difference, light is linearly polarized; in the case of non-zero phase difference, light is elliptical polarized. While polarized light sources are rare in nature, almost all reflected light is partially linearly polarized, which means that reflected light consists of an unpolarized

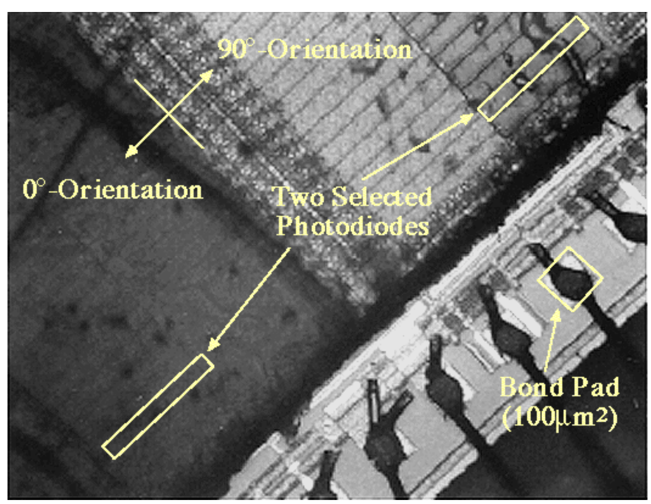

Fig 1 *Photomicrograph of the 1D PCR taken through a polarizer oriented at 90°. Photodiodes under the 90°-orientation film are visible; photodiodes under the 0°-orientation film are blocked by the canceling effect of two orthogonal polarizers.*

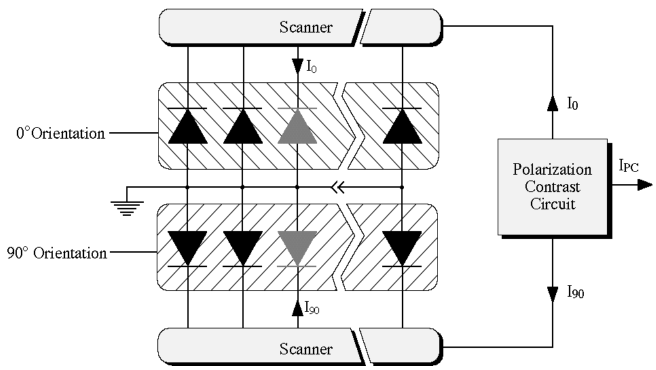

Fig 2. *Architecture of PCR. Two photodiodes selected in a scan are highlighted.*

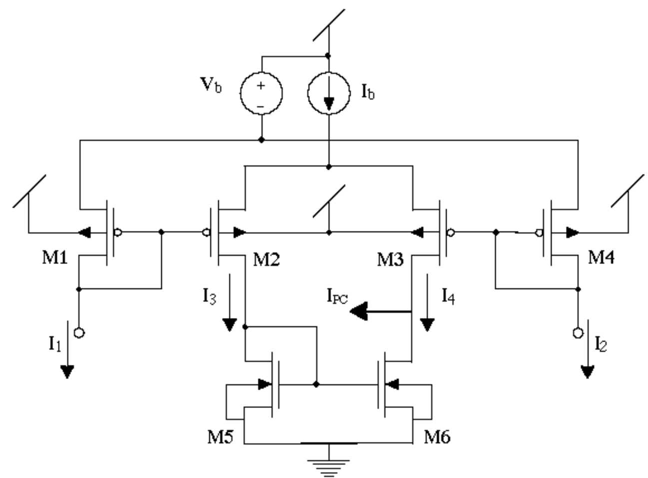

Fig 3 *Polarization contrast circuit. Transistors were drawn with square dimensions: W=L=16µm.*

component and a polarized component that is linearly polarized.

Intensity based sensors lump the orthogonal e-vector components into one intensity term by summing the energies of E_x and E_y. Polarization sensors, on the other hand, use these components to extract important physical features such as specularities, occluding contours, and material properties.

We describe a 1D polarization retina that can be used as a polarimetric sensor for real-time, automated vision tasks. Our *polarization contrast retina (PCR)* uses linear polarizers on the focal plane and on-chip analog, subthreshold circuitry to compute polarization contrast.

2. 1D Polarization Contrast Retina

Polarization contrast measures relative polarization phase and partial polarization in a scene.[7,8] We define polarization contrast using the following equation:

$$\textit{polarization contrast} = \frac{TR_{90} - TR_0}{TR_{90} + TR_0}, \quad (2)$$

where TR_0 and TR_{90} represent the transmitted radiance through orthogonal polarizers.

The 1D PCR uses linearly polarizing film that consists of two orthogonally polarizing regions placed directly over two parallel arrays of photodiodes (Figure 1). Linear polarizers cannot distinguish between linear and elliptical polarization; therefore, the PCR cannot distinguish between elliptically and linearly polarized light.

The arrays are addressed such that the current outputs of two photodiodes that lie across from each other under different polarizers are routed to an analog circuit that computes polarization contrast (Figure 2). The circuit operates on the two currents, which are proportional to the transmitted radiance through the 0°-orientation and 90°-orientation polarizers, and produces one output current that represents the polarization contrast, I_{PC}.

An analog, current-mode circuit computes polarization contrast (Figure 3). The circuit is implemented in subthreshold MOS. Ideally, when MOS transistors are used in the subthreshold region, drain current is exponential with V_{gs}. Using this property of transistors in subthreshold and the translinear principle,[9] we can write

$$V_{gs_1} + V_{gs_3} = V_{gs_2} + V_{gs_4} \qquad I_1 I_3 = I_2 I_4. \quad (3)$$

Since the MOS transistors share common substrate and source terminals, the translinear behavior of this circuit is exact.[10] Kirchoff's current law gives us the following additional equations:

$$I_{PC} = I_4 - I_3, \quad (4)$$

$$I_b = I_4 + I_3. \quad (5)$$

We solve for I_{out}, and find that

$$I_{PC} = I_b \frac{I_2 - I_1}{I_2 + I_1}, \quad (6)$$

which is a scaled version of the polarization contrast, since the currents I_1 and I_2 are directly proportional to the transmitted radiance, TR_0 and TR_{90}, through the orthogonal linear polarizers.

Figure 4 shows the response of the PCR. We placed a linear polarizer in front of the PCR and rotated it 180° while measuring I_{PC} every 5°. The angular measure, θ, of the linear polarizer is given with respect to the 0°-orientation of the polarizing film on the chip. Since the transmitted radiance of linearly polarized light through a linear polarizer varies sinusoidally with the polarizer angle, the expected current output from the photodiodes is:

$$I_1 \sim 1 - Cos(2\theta) \qquad (7)$$

$$I_2 \sim 1 + Cos(2\theta). \qquad (8)$$

Substituting into Equation 6 yields

$$I_{PC} \sim Cos(2\theta), \qquad (9)$$

which is shown as the solid curve in Figure 4. Our data shows that the 1D PCR can perform low-power focal-plane computation of useful polarization information using subthreshold CMOS circuits.

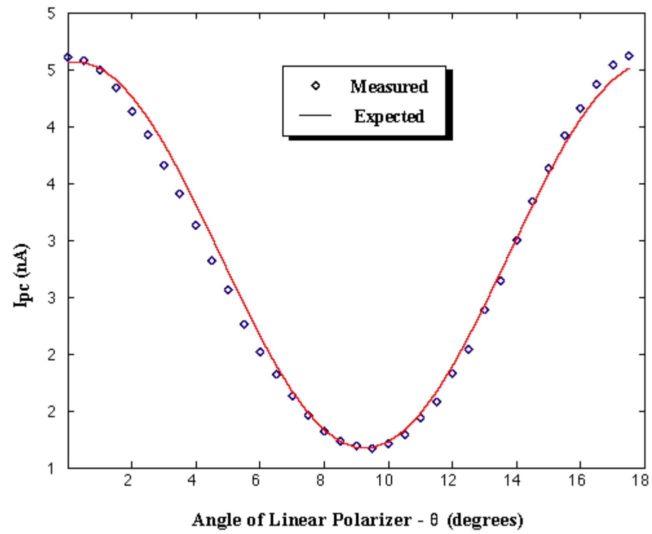

Fig 4. *Response of polarization contrast retina to a rotating linear polarizer.*

3. High-Resolution Linear Polarizers

The 1D PCR uses commercially fabricated polarizers on the focal plane. Unfortunately, commercial techniques for making the high-resolution polarization masks required for a 2D PCR do not exist. The bulk nature of polarizing-film production prevents definition of pixel-sized areas of linear polarization in a 2D array. However, we can adapt modern lithographic techniques used in CMOS circuit fabrication to create custom linearly polarizing filters that we can place on the focal plane of a high-density photoreceptor array.

The manufacturing process for a widely used polarizing material (H-sheet) dissolves potassium-iodine solution into a sheet of poly(vinyl alcohol)

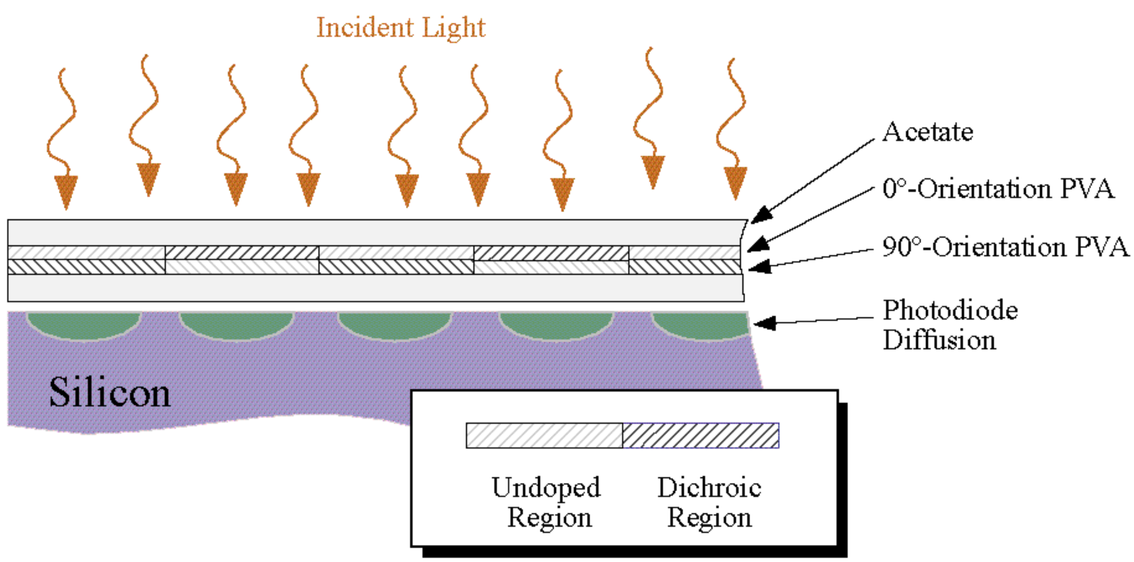

Fig 5. Schematic diagram of 2D high-resolution focal-plane linear polarizer.

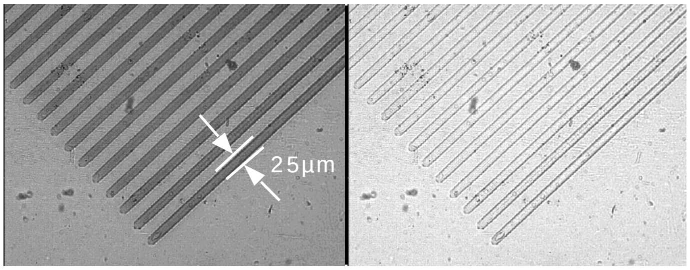

Fig 6. Photomicrograph of processed 0°-phase polarizing film with orthogonal (left) and parallel (right) polarized light. Line widths are 25µ.

(PVA).[11] If the iodine-doped PVA is stretched, the polymer chains of PVA are axially coordinated along the stretching direction. Stretching of the PVA film causes an abundance of polyiodine complexes of I_3^- and I_5^- to form in linear chains that lie parallel to the polymer molecules. These conducting complexes form a light-absorbing axis in the film along the stretching direction, imparting dichroism to the otherwise transparent polymer sheet.

We use masking and etching steps similar to the ones used in CMOS silicon fabrication processes to *undope* iodine selectively in regions of PVA. Removing the iodine from the polymer sheet destroys the dichroic effect of the iodine complexes. Hence, we can define lithographically patterns of polarizing and nonpolarizing areas of PVA. By stacking linearly polarizing sheets whose optical axes are oriented at various phases, we can create linearly polarizing filters tailored to match photoreceptor size and pitch requirements (Figure 5). With this technique, we are currently capable of fabricating linear polarizers with 25µm features.(Figure 6).

4. Conclusions

Polarization sensing offers physical cues about objects to which intensity and color-based vision systems are blind; for example, differentiating specular reflections and areas of high brightness in an image. We have made a fully functioning, 1D PCR that computes polarization contrast in a scene. The PCR uses polymer-based, linear polarizers on the focal plane; on-chip, subthreshold CMOS circuitry computes polarization contrast. The 1D PCR can be used in a mechanical scanning mode to extract polarization features in a scene, much like the visual apparatus of the mantis shrimp, which contains polarization sensitive ommatidia arrayed in a narrow strip along the retina.[12] We have also shown that CMOS fabrication techniques can be used in the processing of linearly polarizing film to create a high resolution, two-dimensional polarization contrast retina.

5. Acknowledgment

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