# Novel micro-polarizer array patterns for CMOS polarization image sensors


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***Abstract*—In this paper, we present two novel "quasi-Bayer" micro-polarizer (MP) patterns for the polarization imaging based on the division-of-focal-plane polarimeters (DoFP). Compared with the traditional equally-weighted MP pattern with four different micro-polarizers, the "quasi-Bayer" pattern requires less photo-lithography-based selective etching steps, leading to a significant reduction of the MP array's fabrication complexity. In addition, for the mainstream bilinear interpolation algorithm, the proposed "quasi-Bayer" pattern with three micro-polarizers exhibits the lowest mean square error (MSE) of 0.43%. Moreover, the "quasi-Bayer" patterns take advantages not only at the fixed illumination level, but also for different illumination levels. Reported experimental results validate the effectiveness of the "quasi-Bayer" patterns by varying the input light intensity from 13 lux to 213 lux.**


## I. Introduction

Recent years have witnessed the fast development of the polarization imaging based on the focal plane polarimeters with predetermined pattern, which is also known as the division of focal plane polarimeters (DoFP) [1]–[6]. By integrating a layer of pixelated micro-polarizers (MP) on top, traditional monochromatic image sensors photo-sensing pixels are enabled to simultaneously extract the incident lights different polarization components. With high similarity to the color filter array (CFA) widely adopted in the color image sensor, the most classic Bayer pattern for color filter array becomes the primary choice for designing the pattern of micro-polarizers in DoFP [2], [4], [5]. As a result, in most literatures, the micro-polarizers are arranged to a 2×2 periodic pattern, with their local major polarization axes oriented differently [2]–[6]. In the Bayer-pattern-CFA-based color imaging, it is well-known that the spatial resolution is traded-off for the simultaneous extraction of different wavelength channels (i.e. R, G and B), and interpolation algorithms are necessary to compensate the spatial resolution loss, namely demosaicing [7]. The same concept of "demosaicing" applies in the DoFP.

The way of DoFPs demosaicing has been paved by Ratliff *et al* in [8]. Several bilinear interpolation strategies were explored to improve the polarization image quality. These bilinear algorithms were extended to higher order bicubic and bicubic-spline interpolation methods by Gao *et al* in [9]. According to the acquired simulation results, the bicubic-based interpolation algorithms outperform the bilinear-based ones, however, it is at the expense of computational complexity and high cost of the hardware implementation. In order to well-balance the interpolation accuracy and the computational complexity, in [10], Gao *et al* adopted another gradient-based interpolation method. Although a number of interpolation algorithms have been explored and validated, they are all reported for the identical MP pattern, which is presented in Fig. 1(A). This 2×2 pattern include four equally-weighted micro-polarizers with their major polarization axes along 0°, 90°, 45°, 135°, respectively. Nevertheless, this is not the only pattern ever reported for the MPs design/fabrication in the previous literatures. In [2], [4], [5], a "quasi-Bayer" pattern was exploited for the micro-polarizer arrays design and fabrication. As shown in Fig. 1 (B), there are two pixels directly exposed to the incident light without any micro-polarizer applied, which can be used to record the total intensity of the incident light. This "quasi-Bayer" pattern significantly reduces the fabrication complexity of the micro-polarizer array, since only two photo-lithography-based selective etching steps are needed. By contrast, for the most widely adopted pattern in Fig. 1 (a), at least four photo-lithography-based selective etching steps are necessary to form the equally-weighted 0°, 90°, 45°, 135° micro-polarizers. However, up to now, none of the previous literatures has reported any demosaicing or interpolation algorithm tailored for the "quasi-Bayer" pattern, which takes great advantages in terms of the fabrication complexity and cost.

In this paper, we first explore the mainstream bilinear interpolation algorithm for the "quasi-Bayer" pattern with two micro-polarizers [Fig. 1(B)]. Then we propose a novel "quasi-Bayer" pattern with three micro-polarizers. As illustrated in Fig. 1(C), there are three micro-polarizers (i.e. 0°, 90°, 45°) included with one micro-polarizer's weight higher than the other two. The same bilinear interpolation algorithm is applied to the aforesaid three different MP patterns and the corresponding images are compared visually and in term of mean square root (MSE) as well. The rest of this paper is organized as follows: Section 2 illustrates the traditional equally-weighted MP pattern and the principle of bilinear interpolation based on this pattern. Section 3 presents two different "quasi-Bayer" patterns with the first one widely adopted in the experiment due to its simplicity and the second one proposed in this paper. The experimental results and discussions are provided in Section 4, and the concluding remarks are drawn in Section 5.


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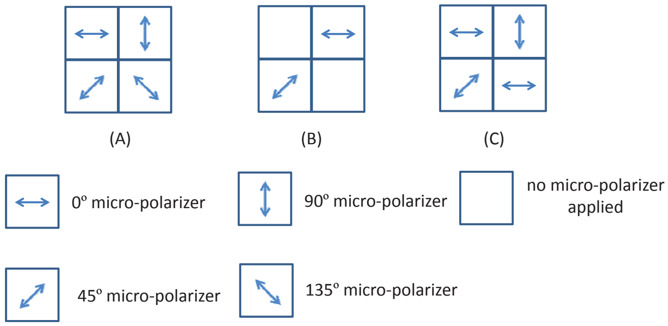


Fig. 1. Different MP patterns: (A) traditional equally-weighted MP pattern with four different micro-polarizers; (B) "Quasi-Bayer" patterns with two micro-polarizers; (C) "Quasi-Bayer" patterns with three micro-polarizers.

## II. The traditional equally-weighted MP pattern with four different micro-polarizers

DoFP based image sensors monolithically integrate the pixelated micro-polarizers on top of an array of photo-sensitive elements. Traditionally, the pixelated micro-polarizers are periodically arranged to 2×2 with their polarization direction oriented at 0°, 90°, 45° and 135°, respectively [3]–[6].

| | | | |
|---|---|---|---|
| $I_0$ (1,1) | $I_{90}$ (1,2) | $I_0$ (1,3) | $I_{90}$ (1,4) |
| $I_{45}$ (2,1) | $I_{135}$ (2,2) | $I_{45}$ (2,3) | $I_{135}$ (2,4) |
| $I_0$ (3,1) | $I_{90}$ (3,2) | $I_0$ (3,3) | $I_{90}$ (3,4) |
| $I_{45}$ (4,1) | $I_{135}$ (4,2) | $I_{45}$ (4,3) | $I_{135}$ (4,4) |

Fig. 2. The traditional equally-weighted MP pattern with the bilinear interpolation algorithm applied.

As shown in Fig. 2, the MPs are labelled with their corresponding coordinates. It is observed that the four different MPs are equally-weighted (each MP's weight is 25%) and the traditional-pattern-based polarization image can be split to four downsampled polarization sub-images. By applying the mainstream bilinear interpolation algorithm, the down-sampled sub-images can be restored to their full resolution. Take the pixel at (3,2) for example, the MP at (3,2) records the intensity of the light after passing through a 90° linear polarizer (i.e. $I_{45}$); while the $I_0$, $I_{45}$ and $I_{135}$ at (3,2) are missing, which can be interpolated through bilinear interpolation algorithm as follows:

$$I_0(3,2) = 0.5 \times [I_0(3,1) + I_0(3,3)] \tag{1}$$

$$I_{135}(3,2) = 0.5 \times [I_{135}(2,2) + I_{135}(4,2)] \tag{2}$$

$$I_{45}(3,2) = 0.25 \times [I_{45}(2,1) + I_{45}(2,3) + I_{45}(4,1) + I_{45}(4,3)] \tag{3}$$

With the interpolated full-resolution sub-images, it is enabled to calculate the total intensity (Int), the degree of linear polarization (DoLP) and the angle of polarization (AoP) for each pixels by using [11]:

$$Int = 0.5 \times [I_0 + I_{90} + I_{45} + I_{135}] \tag{4}$$

$$DoLP = \frac{\sqrt{(I_0 - I_{90})^2 + (I_{45} - I_{135})^2}}{Int} \tag{5}$$

$$AoP = 0.5 \times \arctan \frac{I_{45} - I_{135}}{I_0 - I_{90}} \tag{6}$$

## III. The "Quasi-Bayer" patterns

### A. "Quasi-Bayer" pattern with two micro-polarizers

In the previous literatures, another non-equally-weighted pattern was widely-adopted for fabricating the MP array. As presented in Fig. 1 (B), there are two diagonal pixels in the 2×2 pattern directly exposed to the incident light without any micro-polarizer applied, the rest two pixels are covered by 0° MP and 45° MP, respectively. With the two diagonal pixels measuring the total intensity, this pattern is quite similar to the Bayer pattern widely-utilized in the color imaging area, namely, "Quasi-Bayer" pattern. From the point view of device fabrication, most MP arrays are fabricated based on the photo-lithography process [refs], and the number of different MPs corresponds to the number of the photo-lithography steps needed. As a result, this "Quasi-Bayer" pattern, having only two micro-polarizers, features much higher simplicity compared to the traditional equally-weighted MP pattern with four different micro-polarizers. By labelling the coordinates

| | | | |
|---|---|---|---|
| $I_{Int}$ (1,1) | $I_0$ (1,2) | $I_{Int}$ (1,3) | $I_0$ (1,4) |
| $I_{45}$ (2,1) | $I_{Int}$ (2,2) | $I_{45}$ (2,3) | $I_{Int}$ (2,4) |
| $I_{Int}$ (3,1) | $I_0$ (3,2) | $I_{Int}$ (3,3) | $I_0$ (3,4) |
| $I_{45}$ (4,1) | $I_{Int}$ (4,2) | $I_{45}$ (4,3) | $I_{Int}$ (4,4) |

Fig. 3. Two MP "quasi-Bayer" pattern with the bilinear interpolation algorithm applied.

for different pixels in the "Quasi-Bayer" patterns with two micro-polarizers, we can spilt the three interlaced sub-images. The pixels without any MP applied, which are denoted as *Int*, have higher weight of 50%. As the above-mentioned, the mainstream bilinear interpolation algorithm is exerted to this "Quasi-Bayer" pattern, and we take the pixel at (3,2) again for describing the detailed interpolation process:

$$I_{Int}(3,2) = 0.25 \times [I_{Int}(2,2) + I_{Int}(3,1) + I_{Int}(4,2) + I_{Int}(3,3)] \tag{7}$$

$$I_{45}(3,2) = 0.25 \times [I_{45}(2,1) + I_{45}(2,3) + I_{45}(4,1) + I_{45}(4,3)] \tag{8}$$

In order to calculate the DoLP and AoP images, we neglect the non-ideal factors of the micro-polarizers and derive the $I_{135}$ using the following equation:

$$Int = I_0 + I_{90} = I_{45} + I_{135} \tag{9}$$

Therefore, with the "quasi-Bayer" pattern, the DoLP and AoP for the interpolated full-resolution sub-images are rewritten as:

$$DoLP = \frac{\sqrt{(2I_0 - Int)^2 + (2I_{45} - Int)^2}}{Int} \tag{10}$$

$$AoP = 0.5 \times \arctan \frac{2I_{45} - Int}{2I_0 - Int} \tag{11}$$

*B. "Quasi-Bayer" pattern with three micro-polarizers*

In this section, we propose a novel "Quasi-Bayer" pattern with three micro-polarizers, that are 0°, 90°, 45° micro-polarizers. With two 0° micro-polarizers placed in the diagonal positions, the proposed pattern with the pixel coordinates is illustrated in Fig. 3. Similar to the above-mentioned two patterns, the bilinear interpolation algorithm for pixel (3,2) is expressed as:

$$I_0(3,2) = 0.25 \times [I_0(2,2) + I_0(3,1) + I_0(3,3) + I_0(4,2)] \tag{12}$$

$$I_{45}(3,2) = 0.25 \times [I_{45}(2,1) + I_{45}(4,1) + I_{45}(2,3) + I_{45}(4,3)] \tag{13}$$

After the interpolation process, we can have the complete set of the 0°, 90°, 45° micro-polarizers for each pixel. By adopting the same assumption as earlier, we can calculate the DoLP and AoP for the full-resolution sub-images:

$$DoLP = \frac{\sqrt{(I_0 - I_{90})^2 + (2I_{45} - I_0 - I_{90})^2}}{I_0 + I_{90}} \tag{14}$$

$$AoP = 0.5 \times \arctan \frac{2I_{45} - I_0 - I_{90}}{I_0 - I_{90}} \tag{15}$$

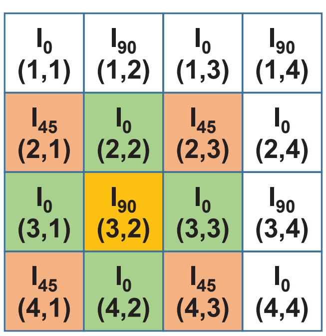


Fig. 4. Three MP "quasi-Bayer" pattern with the bilinear interpolation algorithm applied.

## IV. Experimental results and discussions

In order to evaluate the different MP patterns with the same interpolation algorithm, we took a set of polarization raw images by placing a rotating linear polarization filter in front of a grey-scale CCD camera. The original image resolution is 960×1080 and the sub-images for different patterns are generated as follows:

1) For the traditional equally-weighted MP pattern with four different micro-polarizers, the four polarization sub-images are recorded with the linear polarizer rotated at 0°, 45°, 90° and 135° orientations, respectively. Then the four polarization sub-images are down-sampled by 25% with their origins aligned according to the pattern illustrated in Fig. 2: 0° sub-image's origin aligned to (1, 1), 90° sub-image's origin aligned to (1, 2), 45° sub-image's origin aligned to (2, 1) and 135° sub-image's origin aligned to (2, 2).
2) For the "Quasi-Bayer" patterns with two micro-polarizers, the first polarization sub-image is recorded without linear polarizer applied then down-sampled by 50% with its origin aligned to (1, 1), as illustrated in Fig. 3. The other two polarization sub-images are recorded with the linear polarizers oriented at 0° and 45°, respectively, and down-sampled by 25% with their origins aligned to (1, 2) and (2, 1), respectively.
3) For the "Quasi-Bayer" patterns with three micro-polarizers, the first polarization sub-image is recorded with the linear polarizer oriented at 0° then down-sampled by 50% with its origin aligned to (1, 1), as illustrated in Fig. 4. The other two polarization sub-images are recorded with the linear polarizers oriented at 90° and 45°, respectively, and down-sampled by 25% with their origins aligned to (1, 2) and (2, 1), respectively.

As above-mentioned, the different down-sampled sub-images are interlaced according to the pattern design, which well-mimics the polarization image taken by the DoFP. In addition, we apply the bilinear interpolation algorithm to the test images with aforesaid different MP patterns and visually compare the corresponding grey intensity images, DoLP images and AoP images. As shown in Fig. 5, the first column represents the grey intensity image for different MP patterns, the second column represents the DoLP images for different MP patterns, and the third column represents the AoP images for different MP patterns. It is indicated that the details regarding the imaged object are well-disclosed in the DoLP image and AoP image.

In order to quantitatively compare the accuracy of bilinear interpolation algorithm applied on different MP patterns, we choose to calculate mean square error (MSE) between the original raw image and the interpolated image. The MSE definition is expressed as:

$$MSE = \frac{1}{MN} \sum_{1 \le i \le M} \sum_{1 \le j \le N} (I_{raw}(i,j) - I_{interpalated}(i,j))^2 \tag{16}$$

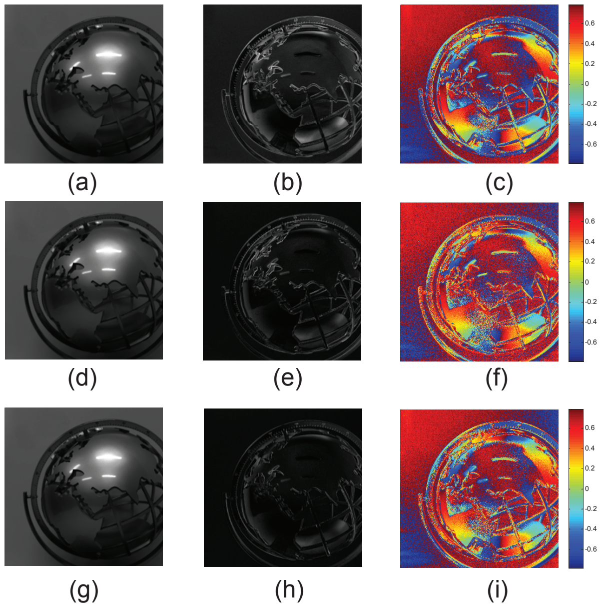


Fig. 5. Visual comparison of the bilinear interpolation algorithm applied to different MP patterns: (a) grey intensity image of the traditional equally-weighted MP pattern with four different micro-polarizers; (b) DoLP image of the traditional equally-weighted MP pattern with four different micro-polarizers; (c) AoP image of the traditional equally-weighted MP pattern with four different micro-polarizers;(d) grey intensity image of the "Quasi-Bayer" patterns with two micro-polarizers; (e) DoLP image of the "Quasi-Bayer" patterns with two micro-polarizers; (f) AoP image of the "Quasi-Bayer" patterns with two micro-polarizers; (g) grey intensity image of the "Quasi-Bayer" patterns with three micro-polarizers; (h) DoLP image of the "Quasi-Bayer" patterns with three micro-polarizers; (i) AoP image of the "Quasi-Bayer" patterns with three micro-polarizers.

where $I_{raw}(i, j)$ is the pixel value of the original raw images as above-mentioned, and $I_{interpolated}(i, j)$ is the interpolated pixel value. $M \times N$ is the array size of the test image. Fig. 6 illustrates the results for the experiment carried out with the input intensity varied from 13lux to 213lux. It can be observed that for the test image taken under the intensity of 213lux, the "quasi-Bayer" pattern based MP array exhibits the lowest normalized MSE of 0.43%, which is almost the half of the traditional equally-weighted pattern based MP array. The reason is that for "quasi-Bayer" patterns, one sub-pixel is sampled twice, which corresponds to a weight of 50%. However, for the traditional equally-weighted MP pattern with four different micro-polarizers, each sub-pixel is only sampled once, which corresponds to a weight of only 25%. Consequently, the MSE is higher for the interpolated sub-pixel channel with lower weight.

## V. Conclusion

In this paper, novel "quasi-Bayer" MP patterns for the DoFP-based polarization imaging are demonstrated. Compared with the traditional widely adopted MP pattern, the "quasi-Bayer" MP patterns feature less photo-lithography-based selective etching steps, and greatly simplifies the MP array's fabrication process. Additionally, with the reported "quasi-Bayer" pattern having three micro-polarizers, the interpolation's MSE is minimized for different illumination levels. As a result, the "quasi-Bayer" MP patterns are more suitable for the previous low-cost DoFP implementations, which can be combined with the commercial intensity/color image sensor to enable the promising on-chip polarimetric image sensing and processing.

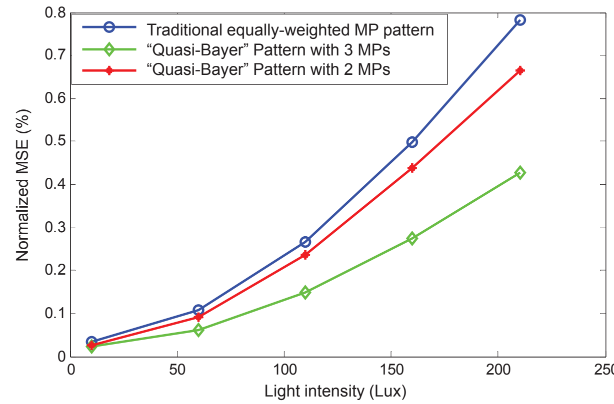


Fig. 6. The normalized MSE for different MP patterns.

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