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Acquisition of a full-resolution image and aliasing reduction for a spatially modulated imaging polarimeter with two snapshots

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Abstract

A snapshot imaging polarimeter using spatial modulation can encode four Stokes parameters allowing instantaneous polarization measurement from a single interferogram. However, the reconstructed polarization images could suffer a severe aliasing signal if the high-frequency component of the intensity image is prominent and occurs in the polarization channels, and the reconstructed intensity image also suffers reduction of spatial resolution due to low-pass filtering. In this work, a method using two anti-phase snapshots is proposed to address the two problems simultaneously. The full-resolution target image and the pure interference fringes can be obtained from the sum and the difference of the two anti-phase interferograms, respectively. The polarization information reconstructed from the pure interference fringes does not contain the aliasing signal from the high-frequency component of the object intensity image. The principles of the method are derived and its feasibility is tested by both computer simulation and a verification experiment. This work provides a novel method for spatially modulated imaging polarization technology with two snapshots to simultaneously reconstruct a full-resolution object intensity image and high-quality polarization components.

OCIS codes

(260.5430) Polarization; (120.5410) Polarimetry; (100.3010) Image reconstruction techniques

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1. INTRODUCTION

Polarization is one of the fundamental properties of the light field, together with its frequency and intensity. Imaging polarimetry is used to measure the two-dimensional (2D) distribution of spatial Stokes parameters from a scene. It is a valuable tool in characterizing aerosol size distributions, distinguishing man-made targets from background clutter, and evaluating the distribution of stress birefringence and biological tissues in medical imaging [1–23]. The Stokes parameters contain four elements: S_0 is the intensity image of the object, and S_1 , S_2 , and S_3 are three polarization components of the object.

The spatially modulated snapshot imaging polarimeter (SMSIP) encodes four Stokes parameters allowing instantaneous polarization measurement from a single interferogram [3,4,7]. There are many SMSIPs that use various methods, such as polarization gratings [17], birefringent prisms [3], conventional Savart polariscopes [4,8–10], or modified Savart polariscopes (MSPs) [5,14–16].

Traditionally, SMSIP makes use of a single snapshot to reconstruct the Stokes parameters by the Fourier transform and bandpass filtering. However, this is not always artifact-free because the frequency spectra of the object image (S_0) and interference fringes are superposed. When the object image contains substantial high-frequency components, the cross talk occurs among adjoining channels. If the cross talk is not eliminated, the reconstructed polarization information (S_1 , S_2 , and S_3) will contain false information.

Some polarization imaging methods use different approaches (dual-channel, coded aperture, and polarization gratings) to acquire the polarization information without suffering from the aliasing [18–20]; however, some other polarization imaging methods use different approaches (channeled modulation) to acquire the polarization information with suffering from the aliasing [22,23]. The aliasing artifacts in the polarization channels caused by the high-frequency components of S_0 in SMSIP could be eliminated if the full knowledge of S_0 were available. But the conventional method that uses a single snapshot to reconstruct the S_0 will lead to loss of too much high-frequency information of the S_0 due to low-pass filtering. Thus, the conventional method cannot acquire the full knowledge of S_0 . To achieve this goal, we proposed a method acquiring two anti-phase snapshots. The S_0 reconstruction of full-resolution can be obtained by the sum of the two snapshot measurements first. Then, the high-frequency aliasing can be removed from the interferograms by subtraction of the two snapshots before the reconstruction of higher-order Stokes parameters (S_1 , S_2 , and S_3). Although the measurement of two anti-phase snapshots slightly increases system complexity, it provides a novel means for SMSIP to obtain full-resolution object image (S_0) and high-quality reconstructed polarization information (S_1 , S_2 , and S_3) simultaneously. Furthermore, although the proposed method is tested by a snapshot imaging polarimeter using a modified Savart polariscope (MSPSIP) [6,16] in this work, it is also applicable for other SMSIPs, such as polarization gratings, birefringent prisms, and convention Savart polariscopes.

The principle is given in Section 2. The numerical simulation and the experiment in laboratory are presented in Sections 3 and 4, respectively. Finally, the work is concluded in Section 5.

2. PRINCIPLE

Figure 1 shows the optical layout of the MSPSIP. The polarimeter from the object plane (xy plane) to the image plane (CCD plane) consists of a bandpass filter, a MSP, a half-wave plate (HWP) oriented at 22.5° , a second MSP, an analyzer (A) oriented at 45° , and a lens (L). The CCD detector is placed on the focal plane of the imaging lens L. If the quasi-monochromatic source or the broadband light source is to be used, the filter in front of MSP1 can be removed. A common incident ray emitted from the object is sheared by the combination of two MSPs and a HWP into four output rays along the x (y)-axial with intensities proportional to the polarization state of the light. Note that the HWP oriented at 22.5° rotates the electric field vector by 45° , enabling the second MSP to shear the rays that exit from the first MSP. Finally, the analyzer and the imaging lens L combine the four beams to create interference, resulting in spatial modulation on the 2D CCD camera.

Based on the ray-tracing analysis, the light intensity I_{45} in the image plane of the CCD camera distributes as follows [14]:

$$I_{45} = \frac{1}{2}S_0 + \frac{1}{2}S_1\cos(2\pi \times 2\Omega \times x) + \frac{1}{4}|S_{23}|\cos(2\pi \times 2\Omega(y-x) + \left\{\arg[S_{23}]\right\}) - \frac{1}{4}|S_{23}|\cos(2\pi \times 2\Omega(x+y) - \left\{\arg[S_{23}]\right\}), \quad (1)$$

$$S_{23} = S_2 + iS_3; \quad \Omega = \Delta/\lambda f, \quad (2)$$

where “arg” denotes the operator to take the argument of the complex number; and λ are the lateral shearing of a single Savart plate and the wavelength of the incident light, respectively; f is the focal length of the imaging lens; S_0 , S_1 , S_2 , and S_3 represent Stokes parameters distributed in 2D space. After making the Fourier transform of the light intensity I_{45} , there are seven peaks containing different Stokes parameters in the spectrum (Fig. 2). Because of the symmetry of the Fourier transform, the polarization information can be extracted from the channels C_0 , C_1 , and C_{23} in Fig. 2 with 2D bandpass filtering. The inverse Fourier transform can be applied to reconstruct the polarization information of S_0 , S_1 , and S_{23} :

$$\mathfrak{F}(C_0) = \frac{1}{2}S_0, \quad (3)$$

$$\Im(C_1) = \frac{1}{4}S_1 \exp(j4\pi\Omega y), \quad (4)$$

$$\Im(C_{23}) = \frac{1}{8}(S_2 + jS_3) \exp(j4\pi\Omega x) \exp(j4\pi\Omega y). \quad (5)$$

To reconstruct the Stokes parameters of the unknown object, a system calibration can be used to demodulate the phase factors $\exp(j4\pi\Omega x)$ and $\exp(j4\pi\Omega y)$ by measuring the known polarization states as the reference data [17]. The calibration data are taken for two reference targets: (1) a linear polarizer at 0 deg (R1) and (2) a linear polarizer at 45 deg (R2). Here, reference R1 is used to demodulate the phase factors $\exp(j4\pi\Omega y)$ while R2 is used to demodulate the phase factors $\exp(j4\pi\Omega x)$ and $\exp(j4\pi\Omega y)$. After normalization of the measured data for the unknown object and the reference data, the phase factors can be canceled so that the Stokes parameters can be reconstructed as

$$S_{0, \text{object}} = |\Im(C_{0, \text{object}})|, \quad (6)$$

$$S_{1, \text{object}} = R \left[\frac{\Im(C_{1, \text{object}})}{\Im(C_{1, \text{reference}, 0^\circ})} \frac{|\Im(C_{1, \text{reference}, 0^\circ})|}{S_{0, \text{object}}} \right], \quad (7)$$

$$S_{2, \text{object}} = R \left[\frac{\Im(C_{23, \text{object}})}{\Im(C_{2, \text{reference}, 45^\circ})} \frac{|\Im(C_{2, \text{reference}, 45^\circ})|}{S_{0, \text{object}}} \right], \quad (8)$$

$$S_{3, \text{object}} = I \left[\frac{\Im(C_{23, \text{object}})}{\Im(C_{2, \text{reference}, 45^\circ})} \frac{|\Im(C_{2, \text{reference}, 45^\circ})|}{S_{0, \text{object}}} \right], \quad (9)$$

where R and I represent taking the real or imaginary parts of the expression, respectively, and $\Im$ denotes a Fourier transformation. The Stokes parameters (S_1 , S_2 , and S_3) can be perfectly reconstructed by Eqs. (6)–(9), if the data in the channels (C_1 and C_{23}) only contain the information for the corresponding polarized components. However, the high-frequency components of S_0 inevitably extend into the channels C_1 and C_{23} , as shown in Fig. 2, thus leading to the false information in the reconstructed Stokes parameters, i.e., the aliasing problem. These false signatures can be reduced if the high-frequency components of S_0 can be removed before reconstruction. This cannot be accomplished with a single-snapshot measurement in current techniques, because the conventional method that uses a single

snapshot to reconstruct the S_0 will lead to loss of too much high-frequency information of the S_0 due to low-pass filtering. However, if another measurement is made with the analyzer oriented vertically (135°), the interferogram produced by the system is then given by [14]

$$I_{135} = \frac{1}{2}S_0 - \frac{1}{2}S_1\cos(2\pi \times 2\Omega \times x) \quad (10)$$

$$- \frac{1}{4}|S_{23}|\cos(2\pi \times 2\Omega(y-x) + \left\{ \arg[S_{23}] \right\})$$

$$+ \frac{1}{4}|S_{23}|\cos(2\pi \times 2\Omega(x+y) - \left\{ \arg[S_{23}] \right\}).$$

Equation (10) shows a 180° carrier frequency phase shift relative to Eq. (1). This enables removal of S_0 from the interferograms when the two measurements are subtracted, which leads to the pure interference fringes:

$$I_{135} - I_{45} = S_1\cos(2\pi \times 2\Omega \times x) \quad (11)$$

$$+ \frac{1}{2}|S_{23}|\cos(2\pi \times 2\Omega(y-x) + \left\{ \arg[S_{23}] \right\})$$

$$- \frac{1}{2}|S_{23}|\cos(2\pi \times 2\Omega(x+y) - \left\{ \arg[S_{23}] \right\}).$$

Equation (11) does not contain S_0 and indicates that aliasing artifacts produced by the presence of S_0 can be removed before the reconstruction of polarization components.

On the other hand, the addition of two interferograms leads to elimination of S_1 , S_2 , and S_3 and a full-resolution intensity image S_0 can be obtained directly in the image domain:

$$I_{135} + I_{45} = S_0. \quad (12)$$

This is equivalent to that MSP1, HWP, MSP2, and A are not placed in the optical system and a full-spatial-resolution image S_0 does not need to be reconstructed using the C_0 channel of the interferogram.

The above system analysis indicates the full-resolution intensity image and the pure interference fringes can be simply obtained from the summation or the difference of the two interferograms. After their addition, there is only the S_0 component left, i.e., the pure image of the object without the polarization components. Note that the intensity of the S_0 component increases twice of that in each original interferogram. After subtraction between the two interferograms, the S_0 image vanishes and the pure interference fringes are left. Again, the intensity of the pure interference fringe also increases twice of that in each original interferogram.

3. NUMERICAL SIMULATION

In this section, computer simulations were used to demonstrate the feasibility of the proposed method. The configuration of the MSPSIP system is as follows: f is 100 mm, the resolution of the CCD is 1024×1024 , the pixel size is $12 \mu\text{m}$, the thickness of the MSP is 4.25 mm, $n_e = 1.48956$, $n_o = 1.66527$, and the monochromatic light source has a wavelength $\lambda = 632.8 \text{ nm}$.

A. Simulation Result

The spatial output of a vortex pattern retarder was simulated (Fig. 3). The different retardancies between S_1 , S_2 , and S_3 lead to the rotation of the vortex pattern. S_1 , S_2 , and S_3 have an interesting radial distribution of their spatial frequencies from the center to the edge: high frequencies near the center and low frequencies near the edge. The interference pattern shown in Figs. 4(a) and 5(b) is the simulated image of Eqs. (1) and (10), respectively. Figure 5(a) is the reconstructed S_0 images from Fig. 4(a) by the conventional low-pass reconstruction (from C_0 channel). Figure 5(b) is the full-resolution target image (S_0) by the sum between Figs. 4(a) and 4(b). Figure 6 shows the image of the difference between Figs. 4(a) and 4(b), which is the pure interference fringes where S_0 has been removed and there is only the information of S_1 , S_2 , and S_3 . Figures 7(a) and 7(b) are S_1 , S_2 , and S_3 reconstructed from Figs. 4(a) and 6, respectively, by the bandpass reconstruction (from C_1 and C_{23} channels).

Comparing the reconstructed Stokes parameter images (Figs. 5 and 7) with the original input image (Fig. 3), the difference is mainly in two aspects. First, Fig. 5(a) is very different from the true S_0 in Fig. 3. This difference can be explained by Fig. 8, which is composed of three parts: the frequency spectrum of the interferogram [Fig. 4(a)], the frequency spectrum of the object image (S_0 in Fig. 3), and the frequency spectrum of interference fringes (Fig. 6). In other words, the frequency spectrum of the interferogram equals the sum of the frequency spectrum of the object image and the frequency spectrum of interference fringes. Note that the high frequency of the object image S_0 [Fig. 8(b)] spreads all over the frequency space, which contaminates the C_1 and C_{23} channels of the interference fringes [bright spots in Fig. 8(c)]. Figure 5(a) is reconstructed from Fig. 4(a) by the frequency domain low-pass filtering, as shown by the green rectangle in Fig. 8(a). From Fig. 8(a), it is clear that Fig. 5(a) only conveys the low-frequency information (inside the green rectangle) of the true S_0 in Fig. 3 and the rich high-frequency information is lost due to the low-pass filtering. Thus Fig. 5(a) is very different from the true S_0 in Fig. 3. On the other hand, Fig. 5(b) is the sum of Figs. 4(a) and 4(b) and contains all high-frequency and low-frequency information of the true S_0 , thus resembling the closest to S_0 in Fig. 3. Second, Fig. 7(a) reconstructed from Fig. 4(a) is tarnished by stripe artifacts, while Fig. 7(b) reconstructed from Fig. 6 is relieved from these artifacts. From Fig. 8(a), it can be seen that Fig. 7(a) suffers from the contamination of the high-frequency components of S_0 within the red and blue rectangles. However, it can be seen that Fig. 7(b) does not contain any frequency information of S_0 because Fig. 6 is the pure interference fringes [that result in Fig. 8(b)], where S_0 has been eliminated and only the information of S_1 , S_2 , and S_3 retains. The numerical simulation demonstrates that the full-resolution intensity image can be obtained from the addition of the two interferograms and

the pure interference fringes can be obtained from the subtraction of two interferograms, as indicated by the “Principle” part.

B. Image Quality Evaluation

Generally, the structural similarity index (SSIM) and peak signal-to-noise ratio (PSNR) are used as the image quality metrics [24,25]. The SSIM is a perception-based model that considers image degradation as perceived change in structural information, while also incorporating important perceptual phenomena, including both luminance masking and contrast masking terms. The PSNR is mainly used to estimate the absolute errors. Herein, the PSNR and SSIM were utilized to evaluate the reconstructed image quality.

The SSIM index characterizes the similarity between the reference image and the reconstructed image. The value of the SSIM is in [0,1], where the larger the SSIM is, the higher the degree of the similarity between two images will be. The value 1 of the SSIM index denotes that two images are identical.

In Table 1, the SSIM values of the proposed method are generally higher than 0.95, which indicates that the proposed method can reconstruct the Stokes parameters with high accuracy. On the other hand, the conventional method suffers badly on this quantitative criterion as the high-frequency component of S_0 is lost in the reconstruction of S_0 and severely contaminates the reconstruction of S_1 , S_2 , and S_3 . Note that the SSIM index of S_0 reconstructed with the proposed method is 1, which indicates a perfect reconstruction of S_0 .

The PSNR is the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation. In general, a higher PSNR indicates that the reconstruction is of higher quality. We have presented in Table 2 the response of the inversion methods (conventional method and proposed method) with respect to three different intensity values of added white noise. The SNRs of three different intensity values are 20 dB, 25 dB, and 30 dB, respectively [24]. It is obvious from Table 2 that PSNR values of the proposed method are generally higher than those of the conventional method, which indicates that the proposed method can reconstruct the Stokes parameters with high quality. On the other hand, the conventional method suffers badly on this quantitative criterion as the high-frequency component of S_0 is lost in reconstruction of S_0 and severely contaminates the reconstruction of S_1 , S_2 , and S_3 .

C. Accuracy Evaluation of Polarization Measurement

In order to evaluate the accuracy of the polarization measurement by the proposed and the conventional methods, the linear equation between the reconstructed Stokes parameters (S_{rec}) and the input Stokes parameters (S_{inp}) can be obtained using least-square fitting and expressed as

$$S_{\text{rec}} = k_s * S_{\text{inp}} + b_s, \quad (13)$$

where k_S and b_S , respectively, are the slope and intercept of the fitted curve. In addition, the coefficient of determination (R^2) has also been given to estimate the measure of goodness of fit [26]. Statisticians often define R^2 using the residual variance from a fitted model:

$$R^2 = 1 - SS_{\text{resid}}/SS_{\text{total}}. \quad (14)$$

SS_{resid} is the sum of the squared residuals from the regression, SS_{total} is the sum of the squared differences from the mean of the dependent variable (total sum of squares) [26].

These parameters (k_S , b_S , and R^2) are used to evaluate the accuracy of the polarization measurement between the reconstructed and input Stokes parameters, and were obtained and listed in Tables 3, 4, and 5, respectively.

The least-square fitting has the advantage of evaluating precision; the smaller the value of $|k_S - 1|$ and $|b_S|$, the higher the polarization measuring accuracy. From Tables 3 and 4, the accuracy of the polarization measurement of the proposed method is remarkably higher than that of the conventional single-snapshot method. Above all, $|k_S - 1|$ and $|b_S|$ of S_0 reconstructed by the proposed method are both 0. This indicates that S_{rec} equals S_{inp} from Eq. (16). Thus, the proposed method can perfectly measure S_0 . One measure of goodness of fit is the coefficient of determination (R^2). It can be used to estimate how well a reconstructed method can acquire the data, and falls between 0 and 1. The higher the value of R^2 , the better the reconstructed model is at acquiring the data. R^2 is shown in Table 5. From Table 5, the numerical value of R^2 of the proposed method is remarkably higher than that of the conventional single-snapshot method. This indicates that the reconstructions of S_0 , S_1 , S_2 , and S_3 by the proposed method are much better than those by the conventional single-snapshot method.

4. EXPERIMENTAL VERIFICATION

Figure 9 is a schematic diagram of the experimental setup. In this experiment, we used the optical elements that we had available in our laboratory. The halogen tungsten lamp is used as the light source, and the optical filter's central wavelength is 632.8 nm.

The size of the MSP is 25 mm × 25 mm × 8.5 mm (the thickness is 4.25 mm). The focal lengths of L1 and L2 are $f_1 = f_2 = 100$ mm. The resolution of the detector is 1024 × 1024, and the pixel size is 12 μm × 12 μm. A transparent film was used as the imaging object.

The transparent plastic film with some texts, numbers, and scratches is the probed object and it is illuminated by the light source through a linear polarizer shown in Fig. 9. Figures 10(a) and 10(b) are the interferograms obtained from the experimental MSPSIP system with the analyzer A oriented at 45° and 135°, respectively. The interference fringes superposed on the object image can be seen in the magnified part of the images, indicating that the polarization information of the object has been coded to the image through the MSPSIP system. The normalized S_0 component (i.e., the object image) reconstructed from Fig. 10(a) by low-pass filtering is shown in Fig. 11(a), while the corresponding component reconstructed by the

proposed method [using the sum of Figs. 10(a) and 10(b)] is shown in Fig. 11(b). It can be seen that in Fig. 11(b) the edges (the scratches) are much sharper than those in Fig. 11(a), indicating a higher spatial resolution offered by the proposed method. Figure 12 shows the difference image between Figs. 10(a) and 10(b), and the magnified interference fringes (left), respectively. The scratches in Fig. 11(b) and the interference fringes in Fig. 12 are very clear. This indicates that beam deviation caused by the two-snapshot image has no distinct effect on the experiment result. Figure 12 contains only the modulation terms without the S_0 component of the object. Figures 13(a)–13(c) are the polarized components reconstructed from Fig. 12.

5. CONCLUSIONS

In this work, we propose a method with two snapshots to recover the full-resolution intensity image of the object and to eliminate its cross talk on polarization components. In addition to the theoretical derivation, the feasibility of the method was verified by both computer simulation and the laboratory experiment. The proposed method has significant advantages over the conventional method: (1) the full-resolution image of the object can be obtained by adding anti-phase interferograms together, and (2) the polarized components are reconstructed from the difference of anti-phase interferograms without the contamination from the S_0 component. Although MSPSIP was used as a testing platform in this work, this novel method can also be applied to other snapshot imaging polarimeters using spatial modulation to get the full-resolution image of the objective and high-quality polarization components. This work provides an optimal method for spatially modulated imaging polarization technology with two snapshots to simultaneously reconstruct a full-resolution object intensity image and high-quality polarization components.

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Fig. 1.
Optical layout of the MSPSIP.

Fig. 2. Schematic diagram of the filter channels for the Stokes parameters in frequency (Fourier) space.

Fig. 3.
The input Stokes object.

Fig. 4. Simulated image. (a) Simulated image of the Stokes object using Eq. (1); (b) simulated image of the Stokes object using Eq. (10).

Fig. 5.

(a) Reconstructed S_0 from Fig. 4(a) by the conventional low-pass reconstruction (from C_0 channel); and (b) the full-resolution S_0 [the sum of Figs. 4(a) and 4(b)].

Fig. 6.
Difference between Figs. 4(a) and 4(b).

Fig. 7.

(a) Reconstructed $S_{1\sim3}$ images from Fig. 4(a); and (b) reconstructed $S_{1\sim3}$ images from Fig. 6.

Fig. 8.

Composition of the interferogram in the frequency domain: (a) frequency spectrum of the interferogram, (b) frequency spectrum of the object image (S_0), and (c) frequency spectrum of interference fringes.

Fig. 9.
Schematic diagram of the experimental MSPSIP.

Fig. 10.

(a) Raw image (interferogram) of a transparent plastic film for the 45° analyzer and (b) that for the 135° analyzer, and their magnified interference fringes (middle), respectively.

Fig. 11.

(a) Normalized S_0 reconstructed images from the singlesnapshot method; and (b) normalized S_0 reconstructed images from the sum of Figs. 10(a) and 10(b).

Fig. 12. Normalized difference image between Figs. 10(a) and 10(b), and the magnified interference fringes (left), respectively.

Fig. 13.
Stokes component images reconstructed from Fig. 12: (a) S_1/S_0 , (b) S_2/S_0 , and (c) S_3/S_0 .

Table 1

Structural Similarity (SSIM) Index

	SSIM			
	S_0	S_1	S_2	S_3
Conventional method	0.020	0.5631	0.4187	0.4120
Proposed method	1.000	0.9624	0.9595	0.9565

Table 2

Peak Signal-to-Noise Ratio (PSNR)

PSNR(dB)					
	White noise (dB)	S_0	S_1	S_2	S_3
Conventional method	20	1.3480	19.2256	18.2382	18.1431
	25	1.3492	19.3906	18.7579	18.7042
	30	1.3496	19.4609	18.9316	18.8715
Proposed method	20	20.0865	28.6320	26.3899	25.9850
	25	25.0872	29.3232	28.4479	27.7004
	30	30.0973	29.6247	29.2912	28.4544

Table 3

Slope of the Fitted Line

	k_S			
	S_0	S_1	S_2	S_3
Conventional method	1.0236	0.9647	0.9599	0.9576
Proposed method	1.000	1.0048	1.0039	1.0047

Table 4

Intercept of the Fitted Line

	b_s			
	s_0	s_1	s_2	s_3
Conventional method	-0.0232	-0.0007	0.0004	0.0002
Proposed method	0	-0.0004	0.0004	0.0002

Table 5Coefficient of Determination (R^2) of the Fitted Line

	R^2			
	S_0	S_1	S_2	S_3
Conventional method	0.0175	0.9527	0.95354	0.9467
Proposed method	1	0.9963	0.9965	0.9953