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Dual-shot approach for polarization retrieval through a scattering medium

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Abstract

A dual-shot technique based on the field basis addition of two statistically independent speckle patterns is developed to recover an input polarization through a scattering layer. It is proposed theoretically, and demonstrated both numerically and experimentally that by tuning the linear polarization orientation of the reference speckle pattern to 0° and 45° w.r.t. the *x*-axis, polarization retrieval of an object beam through a scattering layer can be achieved by measuring the degree of polarization of the superposed speckle pattern. The proposed technique can have a wide range of applications in polarization sensing and biomedical imaging.

Keywords: polarization retrieval, speckle correlation, uncorrelated speckle patterns, Stokes parameters, polarization ellipse, speckle superposition, degree of polarization

1. Introduction

Looking through a random scattering medium, which scrambles the information of an input beam to the generated speckles, has been an area of interest of the science and engineering community for the last few decades. Several techniques, such as, phase conjugation, wavefront shaping, transmission matrix and holography-based approach etc, have been developed to recover the amplitude and phase information of an input beam through a random scatterer [1–4]. Another important aspect of the object information recovery is the retrieval of polarization information though a scatterer.

Similar to the amplitude and phase, the polarization of a beam is also affected by a scattering medium in some cases, and the effect depends on the type of the scatterer, i.e. this effect is determined by the number of scattering events encountered by the light beam while propagating through the scatterer. A depolarizing medium completely depolarizes the input polarization in the far-field, whereas in the case of a scattering layer, the far-field speckle pattern retains the same polarization as that of the input beam [5, 6]. Hence, different approaches are required for polarization recovery through different types of scatterer. A wavefront shaping based approach, where the wavefront of the input beam is modulated, has been recently demonstrated to retrieve the input polarization through a depolarizing medium [7]. The proposed technique in [7] has been further improved for a complete polarization retrieval by modulating both the horizontal and vertical polarization components of the input beam using a single spatial light modulator (SLM) [8]. Cross-correlation of two speckle patterns, where each pattern is generated by rotating

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the input polarization orientation, can be exploited to track the polarization rotation through a multiple scatter [9]. The cross-correlation based approach can also be extended to retrieve the Stokes parameters of an input beam through a similar bulk scattering medium [10].

On the other hand, various efforts have also been reported for polarization sensing through a scattering layer or a weak scattering medium. The Stokes parameters of an input beam can be retrieved from the transmission matrix of the scatterer by exploiting a linear relation between the Stokes parameters of the beam and the generated speckle pattern [11]. A four-shot technique combining the off-axis speckle holography [12] and two-point intensity correlation has been proposed to recover the input polarization through a scattering layer [13]. Recently, non-invasive, real-time tracking of linear polarization rotation through a weak scatterer has been demonstrated using the speckle superposition-based approach [14]. Retrieval of two mutually orthogonal polarization through a weak birefringent scatterer is possible from proper manipulation of the generated speckle pattern [15]. All these reported techniques have several constraints, such as, the technique proposed in [11] requires a large number of data set to construct the transmission matrix of the scatterer. On the other hand, in the case of the approach in [13], apart from four shots, a complex off-axis holography-based setup is required, whereas, the method reported in [15] is applicable only to the linear polarizations.

Here, in this work, a dual-shot approach based on the superposition of two mutually uncorrelated speckle patterns is proposed to recover polarization information through a scattering layer. It is predicted theoretically, and subsequently demonstrated both numerically and experimentally that by modulating the linear polarization orientation of the reference speckle pattern, it is possible to retrieve any polarization though a scattering layer. Here, it is important to mention that similar to the works in [11, 13, 15], the present work does not consider the scenario of multiple scattering of the beam, i.e. the depolarization effect introduced by the scattering medium. The theoretical derivation along with the numerical and experimental results are presented.

2. Theoretical details

As a polarization ellipse is considered to be the generalized representation of polarization of light, let us consider that the object field under consideration is elliptically polarized, and the major axis of the ellipse makes an angle ψ with the x-axis (shown in figure 1) and the phase difference between the x and y component of the field is δ. For simplicity, an auxiliary angle α is introduced for the polarization ellipse and is defined in terms of the x and y component of the amplitude of the field, i.e. E'_x and E'_y, as $\tan\alpha = \frac{E'_y}{E'_x}$.

Let us assume that the propagation of this object field through a scattering layer results in an object random field $\mathbf{E}_O(\mathbf{r},t)$. As a scattering layer does not introduce any depolarizing effect to the input polarization, the generated random field, $\mathbf{E_O}(\mathbf{r},t)$ has the same polarization as that of the input beam [5, 6], and can be written as

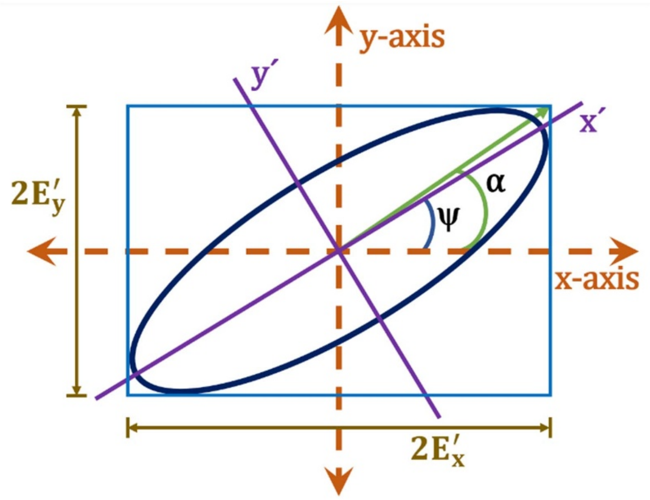

Figure 1. Schematic of a polarization ellipse.

$$\mathbf{E_O}(\mathbf{r},t) = E_\mathrm{O}(\mathbf{r},\ t)\left(\cos\alpha\,\hat{\boldsymbol{x}} + \sin\alpha\,\mathrm{e}^{\mathrm{i}\delta}\,\hat{\boldsymbol{y}}\right) \tag{1}$$

where $E_\mathrm{O}(\mathbf{r},\ t)$ is the amplitude of the object random field, $\mathbf{r}$ is the spatial position vector on the transverse observation plane, and $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are the two mutual orthonormal vectors. Similarly, a linearly polarized reference random field, $\mathbf{E_R}(\mathbf{r},\ t)$, the polarization orientation of which makes an angle ϕ with the x-axis, can be expressed as

$$\mathbf{E_R}(\mathbf{r},t) = E_\mathrm{R}(\mathbf{r},\ t)\left(\cos\phi\hat{\boldsymbol{x}} + \sin\phi\hat{\boldsymbol{y}}\right). \tag{2}$$

As mentioned earlier, here, the superposition of the object and reference random fields are considered, and the superposed random field is written as

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E_O}(\mathbf{r},t) + \mathbf{E_R}(\mathbf{r},t). \tag{3}$$

The spatial degree of polarization (DoP), P($\mathbf{r}$) of a random field can be calculated from its intensity distribution, I($\mathbf{r}$) following the intensity correlation-based approach following [15] as

$$P^2(\mathbf{r}) = 2\times\left.\frac{\langle\Delta I(\mathbf{r}_1)\,\Delta I(\mathbf{r}_2)\rangle}{\langle I(\mathbf{r}_1)\rangle\langle I(\mathbf{r}_2)\rangle}\right|_{\mathbf{r}_1=\mathbf{r}_2} - 1 \tag{4}$$

where $\Delta I(\mathbf{r}) = I(\mathbf{r}) - \langle I(\mathbf{r})\rangle$ is the deviation of intensity from its average value, '$\langle A\rangle$' represents the ensemble average of a variable 'A'. The intensity of the superposed field, $\mathbf{E}(\mathbf{r},\ t)$ can be calculated as

$$\begin{aligned} I(\mathbf{r}) = \;& I_\mathrm{O}(\mathbf{r}) + I_\mathrm{R}(\mathbf{r}) + \left[E^*_\mathrm{O}(\mathbf{r})E_\mathrm{R}(\mathbf{r}) + E_\mathrm{O}(\mathbf{r})E^*_\mathrm{R}(\mathbf{r})\right] \\ & \times\cos\alpha\cos\phi + \left[E^*_\mathrm{O}(\mathbf{r})E_\mathrm{R}(\mathbf{r})\,\mathrm{e}^{-\mathrm{i}\delta}\right. \\ & \left. + E_\mathrm{O}(\mathbf{r})E^*_\mathrm{R}(\mathbf{r})\,\mathrm{e}^{\mathrm{i}\delta}\right]\sin\alpha\sin\phi \end{aligned} \tag{5}$$

where $I_\mathrm{O}(\mathbf{r})$ and $I_\mathrm{R}(\mathbf{r})$ is the intensity of the object and reference random field, respectively. The average intensity of the superposed field can be written as

$$\langle I(\mathbf{r})\rangle = \langle I_\mathrm{O}(\mathbf{r})\rangle + \langle I_\mathrm{R}(\mathbf{r})\rangle. \tag{6}$$

In the present work, the object and reference random fields are generated from two statistically independent scatterers and hence, $\langle E_O^*(\mathbf{r}) E_R(\mathbf{r})\rangle$ and $\langle E_O(\mathbf{r}) E_R^*(\mathbf{r})\rangle$ can be taken as zero. This assumption is used to derive equation (6) from equation (5). The numerator part of the intensity correlation in equation (4) is calculated using equations (5) and (6) as

$$\begin{aligned}\langle \Delta I(\mathbf{r}_1)\Delta I(\mathbf{r}_2)\rangle|_{\mathbf{r}_1=\mathbf{r}_2} = {} & \langle I_O(\mathbf{r})\rangle^2 + \langle I_R(\mathbf{r})\rangle^2 \\ & + 2\langle I_O(\mathbf{r})\rangle\langle I_R(\mathbf{r})\rangle \left[\cos^2\alpha\cos^2\phi \right.\\ & + \sin^2\alpha\,\sin^2\phi + 2\cos\alpha\cos\phi \\ & \left.\times \sin\alpha\sin\phi\cos\delta\right]. \end{aligned} \tag{7}$$

For simplicity, the average intensities of the object and reference random fields are taken as equal, i.e. $\langle I_O(\mathbf{r})\rangle = \langle I_R(\mathbf{r})\rangle = \langle I_E(\mathbf{r})\rangle$. Under this assumption, the above equation can be simplified as

$$\begin{aligned}\langle \Delta I(\mathbf{r}_1)\Delta I(\mathbf{r}_2)\rangle|_{\mathbf{r}_1=\mathbf{r}_2} = {} & \langle I_E(\mathbf{r})\rangle^2 [3 + \cos 2\alpha\cos 2\phi \\ & + \sin 2\alpha \sin 2\phi\cos\delta]. \end{aligned} \tag{8}$$

The DoP of the superposed random field is determined from equation (4) using equations (6) and (8), and is found to be

$$P^2 = \frac{1}{2}(1 + \cos 2\phi\cos 2\alpha + \sin 2\phi\sin 2\alpha\cos\delta). \tag{9}$$

It can be observed that proper manipulation of equation (9) can lead to the retrieval of polarization of the object field, i.e. the values of α and δ. Here, this is achieved by tuning the polarization orientation of the reference random field, i.e. ϕ and by estimating the corresponding DoP of the superposed random field. As we have two unknown variables in equation (9), i.e. α and δ, only two values of ϕ are sufficient to retrieve the unknown polarization of the object field. Here, we have taken ϕ as 0° and 45°, and the values of α and δ can be estimated from the corresponding DoP, denoted as P_0 and P_{45}, respectively, as

$$\alpha = \cos^{-1}(P_0) \tag{10}$$

$$\delta = \cos^{-1}\left(\frac{2P_{45}^2 - 1}{2P_0\sqrt{1 - P_0^2}}\right). \tag{11}$$

The orientation of the major axis of the ellipse w.r.t. the x-axis, ψ can be determined from the values of α and δ following [16] as

$$\psi = \frac{1}{2}\tan^{-1}(\tan 2\alpha\cos\delta). \tag{12}$$

Hence, it can be observed that using the proposed technique, it is possible to retrieve the incident polarization state of the object beam through a scattering medium by taking only two shots. However, a closer look at equation (11) can reveal that for $P_0 = 1$, the value of δ is undefined. This indicates that in the case of a horizontally polarized object beam, the retrieved values of α and δ are zero and undefined, respectively. The undefined value of δ does not restrict the proposed technique, as $\alpha = 0$ is possible only in the case of a horizontally polarized beam.

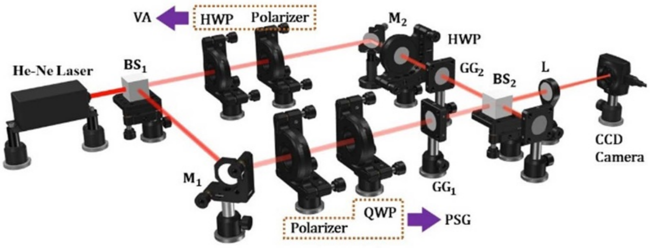

Figure 2. The schematic diagram of the experimental setup.

3. Results and discussion

3.1. Experimental

For the experimental validation of the proposed technique, a Mach–Zehnder interferometer (MZI) is constructed, as shown schematically in figure 2. A beam of horizontally polarized light from a He–Ne laser source with a wavelength of 632.8 nm is made to propagate through the MZI formed by beamsplitters BS_1, BS_2 and mirrors M_1, M_2. The light reflected from BS_1 and M_1 is passed through a scattering layer, here a ground glass plate (GGP), GG_1. The speckles generated by GG_1 form the object arm of the MZI and are referred as object speckles. Different polarization is introduced to the object speckles using a polarization state generator, PSG, which consists of a polarizer and a quarter-wave plate, QWP. On the other hand, the light transmitted through BS_1 and reflected from mirror M_2 is propagated through another GGP, GG_2, which forms the reference arm of the MZI. The speckles generated by GG_2 are referred as reference speckles. A half-wave plate, HWP is placed after M_2 to introduce the required polarizations to the reference speckles, as required in equations (10) and (11). The average intensities of the object and reference speckles are matched using a variable attenuator, VA in the reference arm of the MZI, where the VA consists of a HWP and a polarizer, to satisfy the condition mentioned before equation (8). The object and reference speckle patterns are superposed using beamsplitter BS_2, and the far-field superposed speckle pattern is recorded using a charge coupled device (CCD) camera employing a Fourier arrangement. In this Fourier arrangement, the GGPs and the CCD camera are placed at the front and back focal plane of a lens, L of focal length of 200 mm, respectively. The CCD camera (DCU224M, Thorlabs) has 1024 × 1280 pixels with a pixel pitch of 4.65 μm. Here, it is also important to mention that the assumed conditions for the two scatterers (GG_1 and GG_2) used in the experiment, i.e. they are statistically independent and do not introduce any depolarizing effect in the far-field, are already experimentally verified and reported in [5].

Different polarizations are introduced to the object beam by controlling the fast-axis and pass-axis of the QWP and polarizer of the PSG, respectively. At first, linear polarizations with the polarization vectors oriented at an angle of 30° and 60° w.r.t. the x-axis are introduced. Subsequently, circular, on-axis elliptical and rotated elliptical polarizations are also introduced to the object beam. For any input object polarization, the

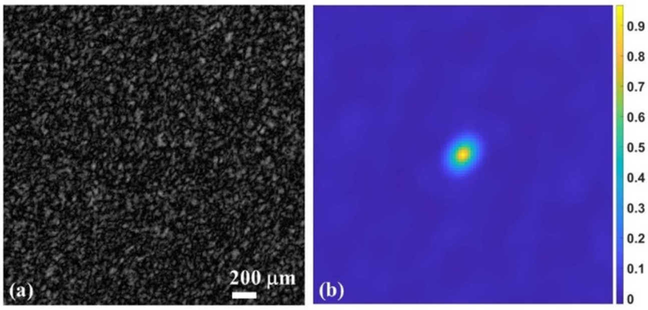

Figure 3. (a) The recorded superposed speckle pattern for $\alpha = 30°$, $\delta = 0°$ and $\phi = 45°$, and (b) the corresponding intensity correlation function.

Table 1. Experimental results.

Polarization of object beam	Input polarization parameters		Measured degrees of polarization		Retrieved polarization parameters	
	α in degree	δ in degree	P_0 (standard deviation)	P_{45} (standard deviation)	α in degree (standard deviation)	δ in degree (standard deviation)
Linear	30	0	0.870 (0.003)	0.963 (0.0001)	29.58 (0.32)	4.01 (2.93)
	60	0	0.517 (0.002)	0.971 (0.001)	58.87 (0.11)	1.18 (4.34)
Circular	45	90	0.704 (0.016)	0.718 (0.024)	45.24 (1.35)	88.26 (4.14)
On-axis ellipse	30	90	0.877 (0.0008)	0.688 (0.014)	28.72 (0.09)	93.72 (2.63)
Rotated ellipse	37.89	48.35	0.790 (0.006)	0.898 (0.005)	37.78 (0.57)	50.73 (1.66)

polarization orientation of the reference speckles is switched to 0° and 45°, and the superposed speckle pattern is recorded in each case. The recorded superposed speckle pattern for $\alpha = 30°$, $\delta = 0°$ and $\phi = 45°$, and the corresponding estimated two-point intensity correlation function are presented in figures 3(a) and (b), respectively.

The DoP of a recorded superposed speckle pattern is determined following the two-point intensity correlation-based approach discussed in equation (4), where the ensemble average is replaced with spatial average under the assumptions of spatial stationarity and ergodicity of the recorded pattern. The estimated DoPs for $\phi = 0°$ and 45° are then utilized to retrieve the polarization information of the object beam using equations (10) and (11). Moreover, in the case of a rotated elliptical polarization, the unknown polarization parameters of the input beam (before GG_1) are measured from the Stokes parameter-based approach [16] to compare with the retrieved parameters. The polarization parameters of the object beam, the experimentally measured values of P_0 and P_{45}, and the retrieved polarization parameters along with the standard deviations in the experimental results are presented in table 1.

3.2. Simulation

A numerical simulation identical to the discussed experiment is also performed following [17] to further validate the proposed approach. For the numerical simulation, two statistically independent scatterers are generated using two independent sets of random numbers. Light beam with wavelength same as that of the experiment, i.e. 632.8 nm is used to illuminate these two scatterers, and a Fourier transformation based approach is utilized to superpose the scattered fields from these scatterers in the far-field. For these simulations, the polarization of the object beam is controlled only by tuning α and δ of equation (1). Similar to the experiment, the linear polarization of the reference speckle pattern is changed to 0° and 45°, and the superposed speckle patterns are analyzed to determine P_0 and P_{45}, which are then used to retrieve the values of α and δ of the input object beam following equations (10) and (11). The results obtained by this numerical simulation are presented in table 2.

The observed excellent match between the input polarization parameters and the experimental results, in both the tables, validates the applicability of the proposed approach. It can also be observed from the presented results that the retrieved values of α is more accurate than δ, which is due to the presence of the quadratic terms of P_0 and P_{45} in equation (11). A slight deviation of the experimental results from the theoretical expectation gets amplified due to these quadratic terms, which leads to slightly larger differences in the retrieved values of δ. The errors in the experimental results, quantified by standard deviation in table 1, appear due to the power fluctuation of the laser, noise of the camera and the imperfection of the optical components. The errors in the experimental results are minimized

Table 2. Numerical simulation results.

Polarization of object beam	Input polarization parameters		Measured degrees of polarization		Retrieved polarization parameters	
	α in degree	δ in degree	P_0	P_{45}	α in degree	δ in degree
Linear	30	0	0.872	0.974	29.35	0
	60	0	0.501	0.974	59.91	0
Circular	45	90	0.712	0.690	44.61	92.78
On-axis ellipse	30	90	0.872	0.697	29.35	91.87
Rotated ellipse	30	40	0.872	0.912	29.35	39.08

by taking multiple measurements and can be further reduced by using a laser with better power stability and a camera with lower noise. On the other hand, the imperfection in generating the scatterers can be a source of error in the simulation results.

4. Conclusion

In this work, we have developed and demonstrated a dual-shot technique based on the superposition of two independent speckle patterns to recover polarization information through a scattering layer. It is shown that by tuning the linear polarization orientation of the reference random field in two particular directions, the polarization of an object beam can be retrieved only by two shots. Apart from being a dual-shot approach, another advantage of the proposed technique is that it does not require a complex off-axis holography-based measurement, as needed in [13], making this technique much easier to implement. This approach can be extended to recover any spatially varying polarization distribution as well. This developed technique may have potential applications in polarization sensing and biomedical imaging, where utilizing the polarization information of light has been reported to be useful for obtaining more detailed information about the samples under investigation [18–20].

Data availability statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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A R and R P have contributed equally to this work and should be considered equal first authors.

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