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ABSTRACT

Focusing light through or inside scattering media by the analog optical phase conjugation (AOPC) technique based on photorefractive crystals (PRCs) has been intensively investigated due to its high controlled degrees of freedom and short response time. However, the existing AOPC systems only phase-conjugate the scattered light in one polarization direction, while the polarization state of light scattered through a thick scattering medium is spatially random in general, which means that half of the scattering information is lost. Here, we propose dual-polarization AOPC for focusing light through scattering media to improve the efficiency and fidelity in the phase conjugation. The motivations of the dual-polarization AOPC are illustrated by theoretical analysis and numerical simulation, and then an experimental system is established to realize the dual-polarization AOPC. By separating and rotating the two orthogonal polarization components of the randomly polarized scattered light, light in all polarization states is recorded and phase-conjugated using the same PRC. Experimental results for focusing through a thick biological tissue show that the intensity of the time-reversed focus from the dual-polarization AOPC can be enhanced by a factor of approximate four compared with the existing single-polarization AOPC.

Focusing light through or inside scattering media is an interesting and demanding research topic with many applications such as biomedical optical imaging, photodynamic therapy, and optical manipulations. However, due to the microscopic refractive index inhomogeneity in scattering media, light is strongly scattered after propagating a distance beyond the optical diffusion limit (typically ∼1 mm in biological tissue),[1] which hampers optical focusing. Several techniques have been developed for optical scattering suppression, such as feedback-based wavefront shaping,[2,3] transmission matrix inversion,[4,5] and optical phase conjugation (OPC).[6–18] The feedback-based wavefront shaping technique rectifies the wavefront of input light iteratively using a spatial light modulator (SLM) until the optimal target focus through the scattering media is achieved. The transmission matrix inversion method calibrates the transmission matrix of a scattering medium (SM) and modulates the incident beam's wavefront according to the desired target output field to obtain a focus through the scattering medium. The optical phase conjugation (OPC) technique generates the optimal wavefront for optical focusing through or inside scattering media by directly playing back a phase-conjugated field of the resultant speckle field. Compared with the feedback-based wavefront shaping and transmission matrix inversion techniques, OPC is a promising method to be employed in *in vivo* applications for its shorter operation time and higher phase conjugation quality.

The OPC can be realized by two different approaches: digital OPC (DOPC)[6–12] and analog OPC (AOPC).[13–18] In DOPC, a digital camera is used to measure the phase information of scattered light through interferometry, and then the conjugated phase map is uploaded to an SLM to modulate a plane wave for generating the conjugated field of scattered light. AOPC directly generates the conjugated field using hologram diffraction in a photorefractive crystal (PRC). Compared with DOPC, AOPC can accomplish the optical focusing fast, depending on the response time of the photorefractive material. Also, it has much higher controlled degrees of freedom (DOF), at least two orders of magnitude more than that of DOPC,[18] resulting in a higher phase conjugation quality. Thus, ever since the first work for focusing through biological samples via AOPC was reported in 2008,[17] AOPC has been studied in terms of improving the phase conjugation speed by different PRCs,[15] focusing inside tissues by combining internal guide stars,[14] and fluorescence-based imaging applications,[18] which improves the potential of AOPC for practical biomedical applications.

In general, the polarization state of scattered light passing through an optically thick scattering medium such as biological tissue is spatially random because of the depolarization effect arising from multiple scattering.[19] Ideally, to realize time reversal of scattered light, all the information including its phase, amplitude, and polarization must be recorded, and then the scattered light must be phase-conjugated with the original position-dependent polarizations. However, the existing AOPC systems for focusing through or inside scattering media only phase-conjugate the scattered light in one polarization direction, which is usually determined by the direction in which the PRC has a prominent electro-optic coefficient. A similar problem is also encountered in DOPC due to the operating principle of the SLM, which has been solved by two sets of DOPC systems to phase-conjugate two orthogonal polarization components separately.[20] Although single-polarization AOPC can achieve partial time reversal for the randomly polarized scattered light, there are strong motivations for us to make use of the information in the scattered field that is not phase-conjugated because of the scrambled polarization.

In this letter, we demonstrate dual-polarization AOPC for focusing light through scattering media. In our approach, the two orthogonal polarization components of the randomly polarized scattered light are separated and rotated to the desirable direction in which the PRC can realize prominent phase conjugation. In this way, the scattered light in all polarization states is phase-conjugated using the same PRC. Taking advantage of the independent multibeam phase conjugation ability as well as the absolute phase compensation characteristic of PRCs,[21–23] we show experimental focusing through a thick biological tissue. The intensity of the OPC focus from the dual-polarization AOPC can be enhanced by a factor of approximately four compared to the existing single-polarization AOPC, which means higher efficiency and fidelity of the phase conjugation.

Let us first analyze the polarization evolvement in existing single-polarization AOPC experiments, as detailed in Fig. 1. When an incident optical field with vertical polarization ($\mathbf{E}_1$) passes through a thick scattering medium, the resultant field $\mathbf{E}_2$ is generally in elliptical polarization. If expressing $\mathbf{E}_2$ using the Jones vector, we have $\mathbf{E}_2 = (E_{2,x}, E_{2,y})^T$, where $E_{2,x}$ and $E_{2,y}$ are the two orthogonal components in the x-axis and y-axis, and "T" stands for the transpose operator. Assume that the PRC only phase-conjugates the vertical component (y-axis), and the conjugation reflectivity is unity without loss of generality. We will obtain the phase-conjugated field $\mathbf{E}_3 = (0, E_{2,y}{}^*)^T$. Following the time reversal principle, only the phase-conjugated field with the same elliptical polarization as $\mathbf{E}_2$ can be focused through the scattering medium. We can decompose $\mathbf{E}_3$ into two components:

$$\mathbf{E}_3 = \frac{1}{2}\left(E_{2,x}{}^*, E_{2,y}{}^*\right)^T + \frac{1}{2}\left(-E_{2,x}{}^*, E_{2,y}{}^*\right)^T. \quad (1)$$

It can be seen that the first term in Eq. (1) is just the phase-conjugated field of $\mathbf{E}_2$, denoted as $\frac{1}{2}\mathbf{E}_2{}^*$. For convenience, we denote the second term as $\frac{1}{2}\mathbf{E}_2{}^*{}_{,\perp}$. Considering that the polarization of $\mathbf{E}_2$ is spatially random, the energies in the two orthogonal polarizations are approximately equal. Therefore, we can calculate the inner product of the two terms as $\langle \mathbf{E}_2{}^*, \mathbf{E}_2{}^*{}_{,\perp}\rangle = \int\int(-|E_{2,x}|^2 + |E_{2,y}|^2)dxdy \approx 0$. In this sense, the second term can be viewed as the orthogonal field of the first term. The component $\frac{1}{2}\mathbf{E}_2{}^*$ would pass through the scattering medium and form the desired conjugated field $\frac{1}{2}\mathbf{E}_1{}^*$, while the component $\frac{1}{2}\mathbf{E}_2{}^*{}_{,\perp}$ would be scattered randomly by the scattering medium again into a speckle background $\frac{1}{2}\mathbf{E_b}$. From the above illustration and analysis, we can see that, in single-polarization AOPC, only half of the collected scattered light field is phase-conjugated by the PRC. More importantly, among the phase-conjugated field by the PRC, only half of the energy can propagate through the scattering medium to constitute the desired focus. Hence, for single-polarization AOPC, one fourth of the scattered light energy is focused through the scattering medium even for a PRC with a phase conjugation reflectivity of 1. This fact motivates us to make use of the energy in the scattered light that is not phase-conjugated by the PRC and generate its phase-conjugated field as well to improve the efficiency and fidelity of the phase conjugation. Since the phase-conjugated field through the scattering medium has the same polarization state as the incident field, there would be a possibility to obtain a constructively interfered field when both orthogonal polarization components are phase-conjugated. Ideally, this scheme can improve the energy efficiency of the phase conjugation by four times because all the energy of the collected scattered light is phase-conjugated, as will be demonstrated in the simulation and experiment.

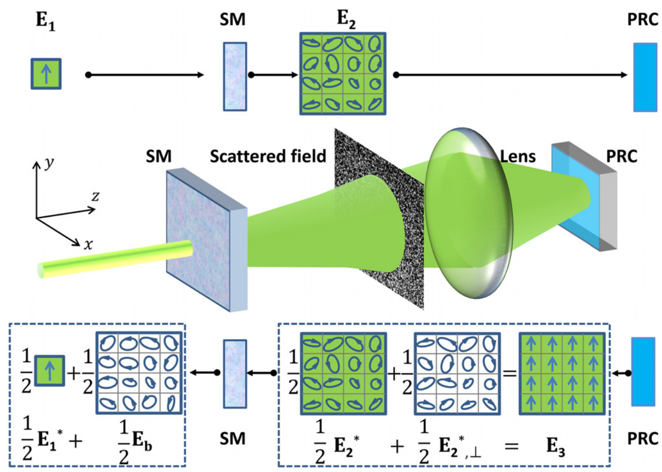

FIG. 1. Illustration and analysis about the polarization evolvement in the existing single-polarization AOPC. When a beam with vertical polarization ($\mathbf{E}_1$) passes through a thick scattering medium, the resultant field $\mathbf{E}_2$ is in elliptical polarization. If the PRC only phase-conjugates one polarization component (e.g., the vertical component), the phase-conjugated field $\mathbf{E}_3$ would not be an accurate conjugation of the input field $\mathbf{E}_1$. $\mathbf{E}_3$ can be decomposed into two orthogonal components, i.e., $\mathbf{E}_2{}^*$ and $\mathbf{E}_2{}^*{}_{,\perp}$. Only $\mathbf{E}_2{}^*$ is the actual conjugation of $\mathbf{E}_1$, which can be focused through the scattering medium. $\mathbf{E}_2{}^*{}_{,\perp}$ results in a speckle background $\mathbf{E_b}$. PRC, photorefractive crystal; SM, scattering medium.

In Fig. 1, we presented an analytical illustration about the motivations to phase-conjugate the dual polarization components in AOPC. Now, we would like to provide a different and more comprehensive view from numerical simulations based on the random matrix theory.[24] Specifically, the input field $\mathbf{E}_1$ is assumed to have N spatial modes, and thus, $\mathbf{E}_1$ can be denoted as a column vector with $2N$ elements, in which the first N elements represent the horizontal polarization of the N spatial modes while the second N elements represent the vertical polarization of the N spatial modes. The scattering medium is represented by a random complex matrix $\mathbf{T}$ with size $2N \times 2N$, and each element of $\mathbf{T}$ is drawn from a circular Gaussian distribution. Thus, the scattered field through the scattering medium can be obtained as $\mathbf{E}_2 = \mathbf{T}\mathbf{E}_1$. In the case of single-polarization phase conjugation, the phase-conjugated field is simulated as $\mathbf{E}_3 = (0, E_{2,y}{}^{*})^T$, i.e., the PRC only phase-conjugates the vertical polarization component, and the horizontal component is lost. In the case of dual-polarization phase conjugation, we have $\mathbf{E}_3 = \mathbf{E}_2{}^{*}$. The resultant field back through the scattering medium becomes $\mathbf{E}_4 = \mathbf{T}^{\mathrm{T}}\mathbf{E}_3$. Summing up the intensities of the horizontal components and vertical components of $\mathbf{E}_4$ yields the focusing-through pattern. In our simulation, N is set to be 2500, and the middlemost element of the vertical polarization components of $\mathbf{E}_1$ is set to 1, while the other elements are set to zeros to simulate a narrow vertically polarized beam. The scattered intensity patterns of the vertical and horizontal components through the scattering medium are shown in Figs. 2(a) and 2(b), respectively. It can be seen that, because of polarization scrambling by the scattering medium, the scattered field contains the vertical and horizontal polarization components with nearly equal intensity. The polarization states of the scattered field can also be calculated from its Jones vectors. Figure 2(c) shows the polarization states of the central nine pixels in the scattered field. Obviously, all of them are in elliptical polarization, as generally expected. The focal patterns back through the scattering medium from the single-polarization AOPC and dual-polarization AOPC are presented in Figs. 2(d) and 2(e), respectively. For the sake of clear comparison, the central line profiles of these OPC foci along the horizontal axes are given in Fig. 2(f). The peak intensity of the focus from the dual-polarization AOPC is 3.99 ± 0.08 times that from the single-polarization AOPC based on 20 simulations, which agrees with the conclusion predicted in the analysis of Fig. 1.

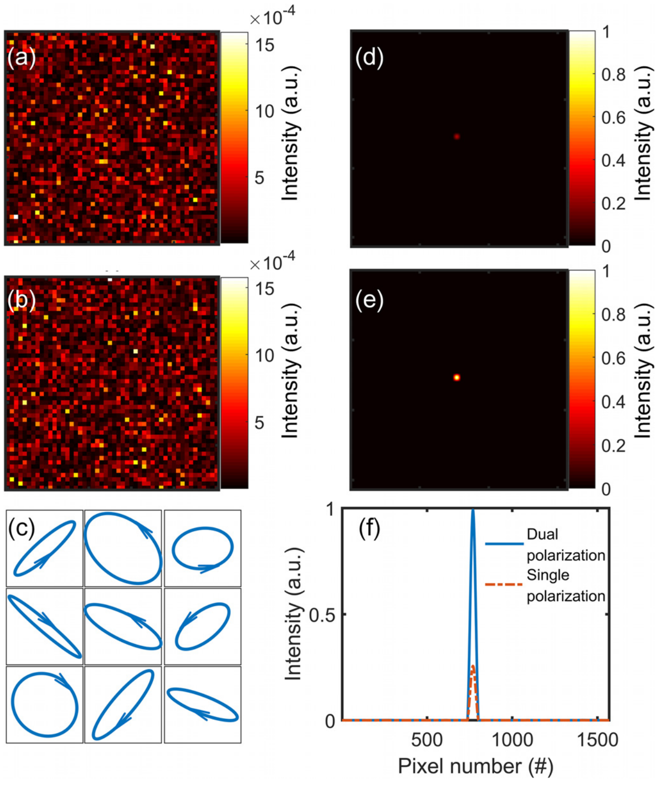

FIG. 2. Simulations of the single-polarization OPC and dual-polarization OPC based on the random matrix theory. (a) and (b) are the intensity patterns of the vertical polarization components and horizontal polarization components of the resultant scattered field, respectively, when a vertical polarization beam passes through a thick scattering medium. (c) The polarization states of the central nine pixels calculated from the Jones vectors of the scattered field. (d) The OPC focus back through the scattering medium if only one polarization component is phase-conjugated, as is done in the existing AOPC experiments. (e) The OPC focus back through the scattering medium when both two polarization components are phase-conjugated. (f) The central line profiles of the OPC foci in (d) and (e) along the horizontal axes.

We use the experimental setup shown in Fig. 3 to demonstrate the dual-polarization AOPC for focusing through scattering media. The vertically polarized laser beam (Verdi V-10, Coherent) is split into the reflection and transmission beams after passing through a mirror (M1), a half-wave plate (HWP1), and a polarizing beam splitter (PBS1). The reflected beam, subsequently modulated by an acousto-optic modulator (AOM) and expanded by a beam expander comprising two lenses and a pinhole, is directed to the photorefractive crystal by mirror 6 (M6) and mirror 7 (M7) to act as the reading beam (R^*). The transmitted beam from PBS1 propagates through an AOM and an HWP2 and is then further split by PBS2. Herein, the function of HWP1 and HWP2 is to control the optical powers of the split beams flexibly, and the two AOMs are used as optical shutters. The reflected beam from PBS2 acts as the reference beam (R) for hologram recording in the PRC, which is expanded to the same diameter as that of the R^* beam and carefully aligned to propagate collinearly with the R^* beam. As such, the R beam and R^* beam constitute a pair of conjugated plane waves in the PRC. The transmitted beam from the PBS2 illuminates the scattering medium. We adopt a 2-in.-diameter (5.08 cm) lens (L1) with a focal length of 60 mm to collect the scattered light passing through the scattering medium as much as possible. In

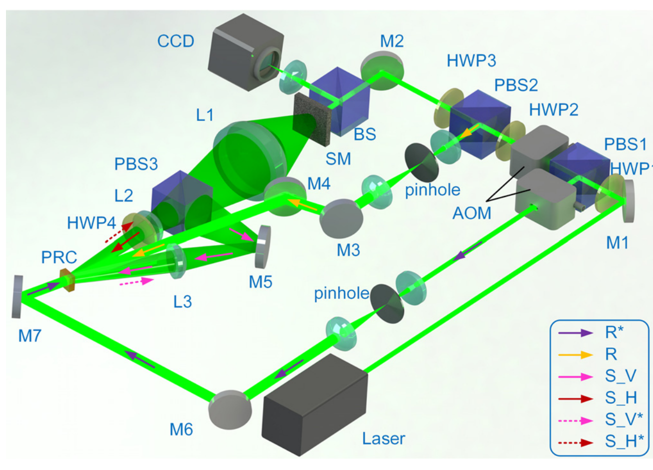

FIG. 3. Schematic of the experimental setup for dual-polarization AOPC. AOM, acousto-optic modulator; BS, beam splitter (nonpolarizing); CCD, charge-coupled device camera; HWP, half-wave plate; L, lens; M, mirror; PBS, polarizing beam splitter; PRC, photorefractive crystal; R, reference beam; S_V, vertically polarized signal beam; S_H, horizontally polarized signal beam; SM, scattering medium.

our configuration, the vertical component of the scattered light is in the preferential polarization direction of the PRC, while the horizontal component experiences nearly no phase-conjugated reflectivity. To realize dual-polarization AOPC, we separate the scattered field into its vertical and horizontal polarization components intentionally using a PBS3 and rotate the horizontal polarization into vertical polarization by the HWP4. In this way, all of the scattered light is in the preferential polarization direction of the PRC and can be phase-conjugated by the same PRC. Note that, in order to obtain similar phase conjugation reflectivity for the two polarization components, we should arrange them with the same angle of incidence. The two phase-conjugated beams would retrace their trajectories through the scattering medium, and a bright focus can be obtained by inserting a 50/50 nonpolarizing beam splitter (BS) to pick up the phase-conjugated field for observation on the charge-coupled device camera (CCD).

In our experiment, we use a $Bi_{12}SiO_{20}$ (BSO) crystal ($10 \times 10 \times 4\,mm^3$) to act as the PRC for the purpose of demonstration. A piece of chicken breast tissue with a thickness of 4 mm is employed as the scattering medium. With a vertically polarized illumination light power of 25 mW incident on the chicken tissue, the optical power values for the vertically and horizontally polarized beams in the scattered light after PBS3 are measured to be 0.256 mW and 0.235 mW, respectively. It can be calculated that the ratio between the vertical and horizontal components is about 1.09:1, which demonstrates that the chicken tissue scrambles the polarization of the incident light nearly completely. After aligning the system as indicated in Fig. 3, the images of the foci through the scattering tissue are obtained, and the results are shown in Fig. 4. Figures 4(a)–4(c) present the original images of the foci captured by the CCD when only the vertical polarization component, only the horizontal polarization component, and both components are phase-conjugated, respectively. The peak intensities of these three foci are 55, 44, and 180, respectively, as quantified by the gray levels of the CCD images. The line profiles of the foci along the central rows of Figs. 4(a)–4(c) are presented in Fig. 4(d). Obviously, the focus from the dual-polarization AOPC is approximately four times as bright as that achieved from the single-polarization AOPC, which agrees well with the analytical and simulation results shown in Figs. 1 and 2, respectively. We also checked the polarization states of these foci by placing a polarizer in front of the CCD and found that all these foci are in the vertical polarization, the same as that of the incident laser beam, which is also consistent with the analytical conclusion from Fig. 1.

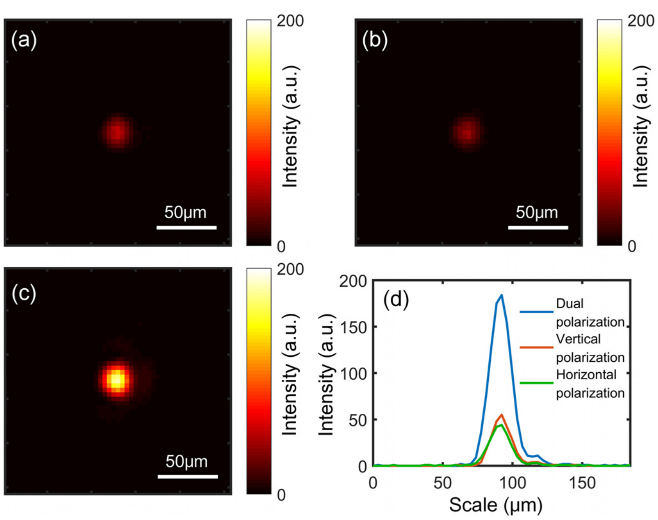

FIG. 4. Experimental results of focusing through a piece of thick chicken tissue. (a)–(c) are images of the foci captured by the CCD when only the vertical polarization component, only the horizontal polarization component, and both components are phase-conjugated, respectively. (d) The line profiles of the foci along the central rows of (a)–(c).

The intensity-enhanced focus of the dual-polarization AOPC results from a constructive interference of the two single-polarization phase conjugated foci. In perfect AOPC, the phase-conjugated field negates all wavefront distortions and spatially uniform phase shifts due to the path delays experienced by the signal light. More specifically, the phase ϕ_c of the ideal conjugated field in the interaction volume of the PRC can be expressed as[25]

$$\phi_c = \phi_0 + \phi_R + \phi_{R^*} - \phi_s, \qquad (2)$$

where ϕ_R, ϕ_{R^*}, and ϕ_s are the phases of the reference beam, reading beam, and signal beam in the interaction volume of PRC, respectively; ϕ_0 is a constant depending on the material parameters of the PRC. In the dual-polarization AOPC system, the two single-polarization phase-conjugated fields are generated through the same reference beam and reading beam, and thus, their foci on the CCD should be strictly in-phase. In practice, we cannot produce a perfectly conjugated pair of reference and reading beams because of the alignment error and the aberration of optics. Therefore, the experimental intensity enhancement factor of the dual-polarization AOPC is slightly less than the theoretically expected value that is four times that of the single-polarization AOPC. Nonetheless, we find that the proposed approach can still bring about considerable improvement on the efficiency and fidelity of phase conjugation based on the results in Fig. 4.

In conclusion, we developed a dual-polarization AOPC technique to focus coherent light through scattering media. In contrast to the existing AOPC that just conjugates one polarization component of the scattered light, the proposed approach can realize the phase conjugation of two orthogonal polarization components simultaneously using the same PRC. Thanks to the intrinsic ability of the PRC for independent optical phase conjugation of multiple beams and absolute phase compensation, the obtained foci from the two polarization components constructively interfere. The intensity of the focus can be enhanced nearly four times, meaning a higher efficiency and fidelity of the phase conjugation. This approach is useful for focusing through thick biological tissues in which the depolarization effect is severe. Working with internal guide stars such as ultrasonic focus,[14] the proposed approach may also obtain the same improvement of phase conjugation quality for focusing inside scattering tissues.

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