Observation of polarization-gate based reconstruction quality improvement during the process of turbidity suppression by optical phase conjugation

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We present experiments that study the impact of polarization selection on the phenomenon of turbidity suppression by optical phase conjugation. Counter to intuition, we discovered that the preferential utilization of multiply scattered light field components over their sparsely scattered counterparts via appropriate polarization selection can lead to better image reconstruction quality. This effect was observed with tissue phantoms and biological tissue sections. The physical origin of this effect and its dependence on scatterer properties are discussed. © 2009 American Institute of Physics. [doi:10.1063/1.3236836]

Elastic optical scattering is typically at least an order of magnitude stronger than absorption in biological tissues[1] and is the dominant effect that obscures light transmission through tissues. Interestingly, the apparent random wavefront is deterministic in nature. We recently showed that an appropriate recording of the transmission, followed by the time reversed playback through reversal of the phase and the propagation direction of the optical wave (optical phase conjugation),[2] can cause the light field to retrace the scattering paths through the tissues and reconstruct the initial input light field.[3] We observed this phenomenon, termed turbidity suppression by optical phase conjugation (TSOPC), by employing a photorefractive crystal[4,5] to generate the time reversed light field. In principle, a complete time reversal requires a phase conjugate mirror (PCM) of constant reflectivity for all input directions and polarizations to capture the entire scattered wavefront.[6] In practice, such a mirror is difficult to achieve and often only a small portion of the wavefront of a single polarization can be captured and time reversed.

This raises two specific considerations regarding our ability to reconstruct the original light field. As a control, consider an input light field consisting of a single Gaussian light spot. First, the reconstruction fidelity, defined as proportion of the light power returning to such a spot, can be expected to drop as a function of turbidity. A second metric of interest, the reconstruction quality, is defined as the ratio of the reconstructed spot size to the original spot size. Interestingly, this quantity can improve with increasing sample turbidity, as shown by previous acoustic time reversal research.[7]

This counterintuitive result can be understood by noting that in the absence of a scattering sample, large angle components of the input field may completely miss the PCM and thus are never recorded or time reversed. The numerical aperture (NA) of the recording and playback process is simply given by the dimensions of the PCM. The absence of these large angle components during playback leads to a poor reconstruction quality. In the presence of scatterers, some large angle components of the input light field may be scattered into the acceptance cone angle of the PCM to be recorded and played back as phase conjugate components. These large angle components can dramatically improve the reconstruction quality. Derode *et al.*[7] reported an observed resolution that is one-sixth of the theoretical limit based on the mirror's aperture.

In this paper, we explore the use of polarization gating to preferentially select the multiply scattered light field component and study its impact on image reconstruction quality in the optical regime. As opposed to the acoustic regime, the availability of optical polarization control allows us to easily select sparsely scattered or multiply scattered light fields during time reversal experiments.

Figure 1 illustrates the experimental schemes: copolarization (a) writing and (b) reading, and cross-polarization (c) writing and (d) reading. We first transmitted a vertically polarized imaging-bearing light field (signal beam) through a scattering medium (in face 1) [Fig. 1(a)] and selectively recorded vertically polarized (copolarization) transmission onto our phase conjugator. Next, we generated and counterpropagated a phase conjugate light field from our phase con-

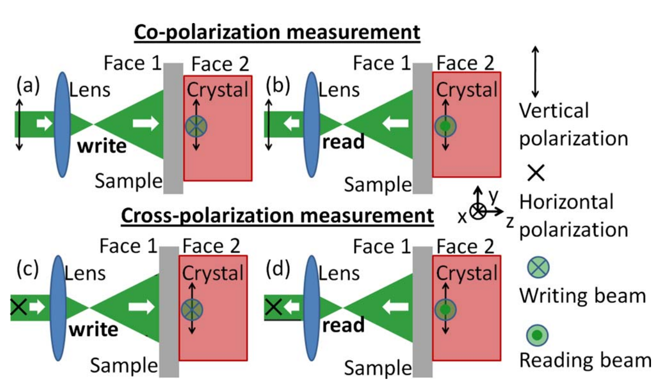

FIG. 1. (Color online) Schematic illustration of copolarization (a) writing and (b) reading and cross-polarization (c) writing and (d) reading. The dark double headed arrow and cross represent the vertical and horizontal polarizations, respectively. The green cross and the green dot with concentric ring represent the directions of the writing and reading beams, respectively.

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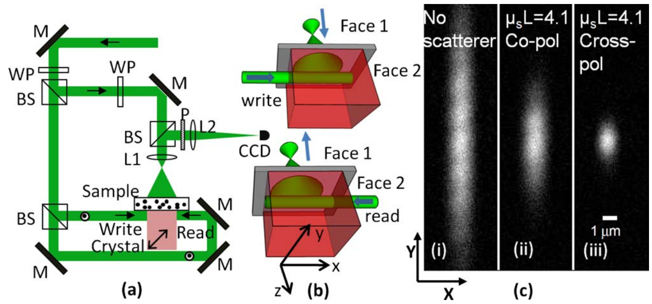

FIG. 2. (Color online) (a) Experimental setup for the polarization gated OPC. M, mirror; BS, beam splitter; P, polarizer; WP, half wave plate (532 m); L1 and L2, lenses. The concentric dark ring and dot represents the vertical polarization of the laser beams. The dark arrow on the crystal represents the *c*-axis of the crystal. (b) Three-dimensional illustration of the recording volume. (c) OPC images reconstructed without scatterers (i) between the point source and the photorefractive crystal and through 1-mm-thick tissue phantoms of $\mu_s L=4.1$ with (ii) copolarization and (iii) cross-polarization measurements.

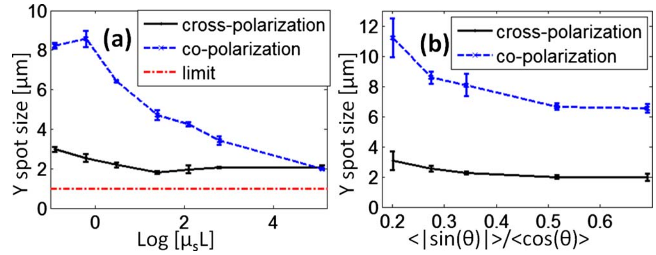

FIG. 3. (Color online) (a) shows the reconstructed spot size dependence on scatter (1 μm bead) concentration. The plotted limit line indicates the ideal spot size if the reconstruction process is perfect. In (b), $\mu_s L$ is fixed at 0.82 and the scatterer size is varied. Mie theory is used to calculate $\langle|\sin(\theta)|\rangle/\langle\cos(\theta)\rangle$, which describes the transverse spreading of the scattered light. In both plots, the error bars represent standard deviation.

jugator through the scattering medium (in face 2 and out face 1) [Fig. 1(b)]. We then passed the result through a vertical polarizer and measured the image reconstruction quality. We expected to preferentially select light components that had experienced few scattering events, as these were more likely to preserve their original polarization. In the second set of experiments, we transmitted a horizontally polarized signal beam and then selectively recorded the vertically polarized (cross-polarization) transmission on the phase conjugator [Fig. 1(c)]. During playback, the phase conjugate light field counterpropagated through the scattering medium [Fig. 1(d)]. We then passed the result through a horizontal polarizer and measured the image reconstruction quality. Here, we preferentially selected multiply scattered light components as they were more likely to become randomly polarized, having a significant vertical polarization contribution. If our conjectures based on Ref. 7 were correct, we expected higher image reconstruction quality in the second set of experiments.

Figure 2(a) shows the experimental setup. A collimated CW laser beam at 532 nm was split into three beams whose polarizations were controlled by half wave plates. One beam (signal beam) was used to illuminate the scattering medium. The transmitted signal was received by a 45° cut Fe-doped $LiNbO_3$ photorefractive crystal and recorded as a hologram by a vertically polarized writing beam with a recording time of ~10 s. After recording, the writing beam was blocked and another vertically polarized beam (reading beam) counterpropagated through the crystal to generate the phase conjugate of the transmitted signal. The reconstructed image was analyzed by a polarizer with transmission axis matched to the signal beam polarization. The transmitted signal and the writing beam interfered to write a diffraction grating along the *c*-axis of the crystal.[4] Due to the nature of interference, only the components of the transmitted signal that shared the same polarization as the writing beam were recorded. Thus, we time reversed only a single polarization transmission component.

To start, we used the setup illustrated in Fig. 2(a) to study the TSOPC reconstruction quality of a single light spot. The signal beam was focused to a diffraction limited round spot (1 μm in diameter) and subsequently expanded to a diverging beam (6 mm in diameter) incident at face 1 of the scattering sample. The writing beam (1 mm in diameter) passed through the photorefractive crystal (10 mm thick), creating a horizontally elongated recording volume as illustrated in Fig. 2(b). As the crystal can only record the signal field at locations where the writing beam is present, this implied a wider recording angle in the horizontal (x) direction than in the vertical (y) direction.

Our first experiment [copolarization configuration, Figs. 1(a) and 1(b)] was performed with a clear sample and a vertically polarized signal beam. The recorded reconstruction is shown in Fig. 2(c)(i). Since the collection-and-playback NA in the x-direction was large, the reconstructed spot is well confined along the x-direction. We measured the full width at half maximum (FWHM) of the reconstructed spot to be 1.1 μm, close to the initial signal beam spot size (1 μm). However, the collection-and-playback NA in the y-direction was small. As such, the reconstructed spot was broad along the y-direction. We measured the FWHM of the reconstructed spot to be 10 μm. This value was consistent with the predicted 9.4 μm when we considered the effective y-axis NA.

Using the same configuration, we replaced the sample with a scattering medium of thickness $L=1$ mm and scattering coefficient (the probability of light scattering per unit path length)[8] $\mu_s=4.1$ mm^{-1}. The scatterers were uniform polystyrene beads (1 μm in diameter) with a refractive index contrast (scatter:matrix) of 1.19; these scatterers were suspended in polyacrylamide and the volume concentration was 0.088%. Figure 2(c)(ii) shows that the reconstructed spot along the y-direction was reduced. Consistent with our predictions, the reduction was even more dramatic [Fig. 2(c)(iii)] if we employed a horizontally polarized signal beam and time reversed the vertically polarized transmission [cross polarization, Figs. 1(c) and 1(d)]. Two-dimensional Gaussian fitting showed that the vertical (y) spot size was reduced by a factor of 2.7 using the cross-polarization configuration (preferentially selecting multiply scattered light) versus the copolarization configuration (preferentially selecting unscattered and sparsely scattered light).

Our next experiment examined the impact of increasing turbidity on the reconstruction quality. In this experiment, we increased the concentration of scatterers and measured the reconstructed spot size along the y-direction. The results are shown in Fig. 3(a). We found that the spot size in the cross-polarization measurement decreased initially and quickly reached a constant value, while the spot size in the copolarization measurement started at a much larger value and decreased until it reached the same value as the cross-polarization measurement. Reduced ballistically propagating light with increased scattering contributed to the spot size variation in the copolarization measurement, while the ballistic component was blocked in the cross-polarization measurement. The trend clearly shows that the cross-polarization configuration allowed us to more effectively expand the collection NA of our system than copolarization as cross polarization allowed us to preferentially select multiply scattered light.

In the next experiment, $\mu_s L$ was fixed at 0.82 and the scatterer size was varied. Scattering from large particles tends to be both forward directed and polarization preserving, while the reverse is true for small particles. By fixing $\mu_s L$, we were effectively controlling the total number of scattering events within the medium (a reasonably valid statement for highly forward scattering particles and thin media). Therefore, this experiment allowed us to directly investigate the impact of the angular scattering profile on the reconstruction quality. We performed this experiment with scatterers ranging in size from 0.35 to 10 μm. To characterize the transverse spreading of the scattered light, we used Mie theory to calculate $\langle|\sin(\theta)|\rangle/\langle\cos(\theta)\rangle$ for each scatterer size, where θ is the scattering angle and $\langle\ \rangle$ represents weighted averaging. The larger $\langle|\sin(\theta)|\rangle/\langle\cos(\theta)\rangle$, the more isotropic the scattering profile of the scatterer. The results in Fig. 3(b) show that scatterers of greater $\langle|\sin(\theta)|\rangle/\langle\cos(\theta)\rangle$ yielded smaller reconstructed spot sizes. This finding is consistent with the fact that large angle multiple scattering tends to depolarize light more effectively than small angle scattering.

We performed the polarization gated OPC experiment with chicken tissues to illustrate the applicability of our experimental findings beyond ideal scattering media. A USAF target was placed at the focal plane of lens L1 in Fig. 2(a). A second lens was inserted before the beam splitter in front of the charge coupled device (CCD) to expand the laser illumination on the USAF target. The target was replaced with a compensation glass slide following holographic recording. Phase conjugate images of the USAF target reconstructed through 0.5 and 1-mm-thick chicken tissues are shown in Fig. 4, with the images on the left and right sides acquired with cross polarization and copolarization, respectively. The vertical lines were well resolved in all four images while the horizontal lines were blurrier with copolarization than with cross polarization. Comparing the top two images with the bottom two images, we further find that the phase conjugate images reconstructed through thicker samples were improved. Both observations are consistent with the findings

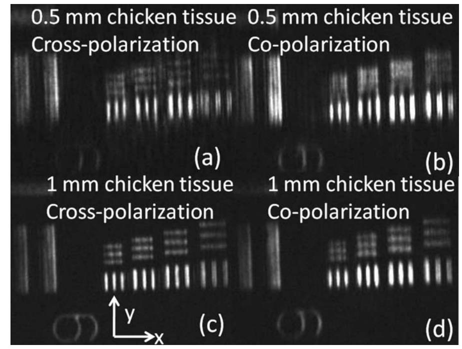

FIG. 4. (a) and (b) are OPC images reconstructed through 0.5-mm-thick chicken tissues. (c) and (d) are reconstructed through 1-mm-thick chicken tissues. (a) and (c) are recorded with cross polarizations, and (b) and (d) are recorded with copolarizations. The line density of the smallest group of the USAF target is 228 lines/mm.

from our point source illumination experiment.

In conclusion, we enhanced OPC reconstruction quality by selecting for multiply scattered light via polarization gating in both tissue phantoms and chicken tissues. Multiple scattering randomizes and spatially redistributes the input wavefront, widening the effective NA of the OPC mirror. Our experimental results suggest that combining a random scattering medium with an OPC mirror of small NA and selectively time reversing the multiply scattered wave may yield a much greater effective NA, significantly improving the time reversal reconstruction quality. The use of cross polarization allows preferential selection of multiply scattered light over ballistically propagating light, consistently improving the reconstruction quality. Finally, we found that scattering media, in which the average scattering angle per scattering event is large, more effectively randomize polarization and lead to better TSOPC reconstruction.

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