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Single-shot time-reversed optical focusing into and through scattering media

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Abstract: Optical time reversal can focus light through or into scattering media, which raises a new possibility for conquering optical diffusion. Because optical time reversal must be completed within the correlation time of speckles, enhancing the speed of time-reversed optical focusing is important for practical applications. Although employing faster digital devices for time-reversal helps, more efficient methodologies are also desired. Here, we report a single-shot time-reversed optical focusing method to minimize the wavefront measurement time. In our approach, all information requisite for optical time reversal is extracted from a single-shot hologram, and hence no other preconditions or measurements are required. In particular, we demonstrate the first realization of single-shot time-reversed ultrasonically encoded (TRUE) optical focusing into scattering media. By using the minimum amount of measurement, this work breaks the fundamental speed limit of digitally based time reversal for focusing into and through scattering media, and constitutes an important step toward high-speed wavefront shaping applications.

Keywords: Wavefront shaping; Optical time reversal; Scattering media; Spatial light modulator; Single-shot detection; Ultrasonically encoded optical focusing.

INTRODUCTION

Complex media with microscopic refractive index inhomogeneity create optical scattering that is highly undesirable in biomedical optical imaging, manipulation, stimulation, and therapy. Emerging wavefront shaping (WFS) modalities, such as feedback-based iterative WFS [1-7], transmission matrix inversion [8-11], and optical time reversal [12-30], have opened new avenues to breaking the optical diffusion limit in these applications. Notable among these modalities, optical time reversal can realize optical focusing through and into complex media with high speed because no iterative controls or measurements are required. Optical time reversal can be implemented through analog optical phase conjugation (AOPC) and digital optical phase conjugation (DOPC). Based on holography in nonlinear optical crystals, AOPC can generate high-fidelity time-reversed foci [12-15]. However, the analog approach suffers from a low energy gain, which has thus far limited its applications. DOPC [16-30] employs a digital camera to capture the phase information of scattered light through interferometry. A spatial light modulator (SLM) is then used to modulate a plane wave as the conjugated wavefront of the scattered light. In this way, DOPC can intrinsically achieve a fluence reflectivity greater than unity. Therefore, it has attracted much more attention than AOPC.

Because living tissues are dynamic, optical time reversal must be completed within the correlation time of the received optical speckles. For DOPC, the system speed depends mainly on the time needed to measure the phase of the scattered light and to update the SLM pattern. A straightforward approach to accelerating a DOPC system is to employ faster cameras and SLMs, as reported in [18, 23]. However, to measure the phase, at least three frames of phase-shifted holograms are generally acquired. The acquisition occupies much of the time-reversal period, especially due to the limited frame rate of the camera. While the technology awaits faster cameras, reducing the required number of holograms would immediately accelerate optical time reversal.

A possible solution is to employ the off-axis interferometry, which enables wavefront measurement from a single hologram [31, 32]. However, this method brings about several intrinsic disadvantages, which hinders its wide applications in practical DOPC systems: (a) The off-axis configuration sacrifices the spatial resolution of wavefront measurement; (b) To ensure successful wavefront retrieval and avoid excessive loss of spatial resolution at the same time, the optimal off-axis angle should be reasonably determined, which depends on the spatial frequency distribution of the scattered beam and thus is sample-dependent. This requirement reduces the versatility of the DOPC system; (c) The wavefront retrieval of off-axis interferometry involves a Fourier transform as well as an inverse Fourier transform of a large matrix, thus it has a significant computational load. Therefore, the on-axis interferometry is still the more desirable method for wavefront measurement in DOPC applications because it does not have these undesirable disadvantages mentioned. To minimize the required number of on-axis holograms for focusing through scattering media, the quasi-single-shot method in Ref. [22] provides a heuristic solution, which uses only two frames of images, i.e., one image of the hologram and one pre-recorded intensity image of the reference beam. Although this method has been widely used in many fast DOPC systems, it requires that the signal beam must be far weaker than the reference beam in intensity, a precondition highly unsatisfactory for practical use. Furthermore, the method fails to work if the goal is to focus light into, instead of through, the scattering medium.

Compared with focusing light through scattering media, focusing light into scattering media is much more useful yet at the same time more challenging. Taking advantage of an ultrasonic guide star, time-reversed ultrasonically encoded (TRUE) optical focusing [13] provides a controllable and non-invasive way to focus into scattering media. When the scattered light passes through an ultrasonic focus, its optical frequency is shifted as a result of the ultrasonic modulation [33]. Using this acousto-optic interaction, TRUE optical focusing detects the frequency-shifted scattered light and time-reverses it to form an optical focus at the ultrasonic focus. However, most realizations of TRUE optical focusing based on DOPC use traditional four-step phase-shifting holography, where four frames of holograms are required. Recently, an endeavor was made to reduce the required number of holograms for TRUE optical focusing to two frames using a complicated optical and electronic setup [18].

Here, we report a single-shot optical time-reversal approach for focusing both into and through scattering media. In our approach, all the information for the optical time reversal is extracted from a single on-axis hologram, and no other measurement is required. This method — simple, stable and powerful — does not have any additional precondition for use, which can be generally used for accelerating digitally based time reversal. Using this novel approach, we demonstrate single-shot TRUE optical focusing into scattering media for the first time.

PRINCIPLE AND METHOD

The experimental setup for single-shot optical time reversal is shown in Fig. 1. It is based on a DOPC system, whose operation contains two steps: a recording step and a playback step. In the recording step [Fig. 1(a)], the system records a single hologram from the interference between the scattered beam and the reference beam via an on-axis Mach–Zehnder interferometric configuration. As shown in Fig. 1(a), the laser (Verdi G5, Coherent) is split into two beams by a polarizing beam splitter (PBS1). The reflected beam after expansion acts as the reference plane wave, while the transmitted beam illuminates the scattering medium (SM). The scattered light is collected by a lens (L1) and recombines with the reference beam at the beam splitter (BS2). Both the scattered and reference beams are reflected by the spatial light modulator (SLM, Pluto-2-VIS, Holoeye) and relayed to the camera plane (PCO.edge 5.5, PCO), where a single-shot hologram is acquired. Note that the SLM and the camera are placed in conjugated positions with a calibrated pixel-matched relationship. In the playback step [Fig. 1(b)], the signal beam is blocked by a shutter, and a proper phase pattern based on the acquired hologram is loaded to the SLM. The SLM modulates the reference beam to produce a time-reversed copy of the scattered field. Thus, the modulated reference beam can retrace its trajectory through the SM, which is verified by detecting a focus on the camera (Grasshopper 3, FLIR) through a lens (L4).

To realize optical time reversal with a single-shot on-axis hologram, the modulation pattern on the SLM must be inferred from the limited information. The interferometric hologram between the scattered beam and the reference beam can be modeled as

$$I = \left|\mathbf{E}_R\right|^2 + \left|\mathbf{E}_S\right|^2 + \mathbf{E}_R^{\,*}\mathbf{E}_s + \mathbf{E}_R\mathbf{E}_s^{\,*}, \tag{1}$$

where $\mathbf{E}_R$ and $\mathbf{E}_s$ are the complex amplitudes of the reference and scattered beams, respectively. It can be seen that the last term on the right of Eq. (1) contains the conjugated scattered field, which can be reconstructed by reading the intensity hologram with a conjugated reference beam, analogous to analog time-reversal approaches based on photorefractive crystals. This fact inspires that it is possible to realize single-shot digital time reversal by mimicking the hologram reading process in analog time-reversal approaches. Motivated by this idea, we can directly display a phase map ϕ_{SLM} on the SLM based on the hologram by the relationship:

$$\phi_{SLM} = 2\pi \cdot I / \max(I), \tag{2}$$

where max(·) denotes the maximum value. We should note that the first three terms in Eq. (1) are not the conjugated field of the scattered light. Playing back these terms would introduce background into the desired conjugated field. To alleviate this effect, we can extract the average of the hologram further before loading the phase map to the SLM. That is,

$$\phi_{SLM} = 2\pi \cdot [I - mean(I)] / \max\{abs(I - mean(I))\}, \quad (3)$$

where $mean(\cdot)$ and $abs(\cdot)$ respectively denote the mean and absolute values. Because the average-subtracted intensity image may have negative values, we choose to normalize to the maximum of its absolute values in Eq. (3) to ensure that the phase is within 2π radians.

Although Eqs. (2) and (3) give two effective ways to extract the playback phase information from a single-shot hologram for optical time reversal, they are based on the full grayscale modulation of an SLM. Some types of SLMs with binary modulation, such as digital micromirror devices and ferroelectric liquid crystal based SLMs, provide much faster response than those with grayscale-modulation. Therefore, the intensity hologram can be binarized to work with such devices. Inspired by Eq. (3), we can directly make a binary version of the average-subtracted hologram:

$$\phi_{SLM} = \begin{cases} 0, & if\ I - mean(I) > 0 \\ \pi, & if\ I - mean(I) \le 0 \end{cases}. \quad (4)$$

A more detailed mathematical description of the proposed single-shot optical time-reversal method above is provided in Supporting Information.

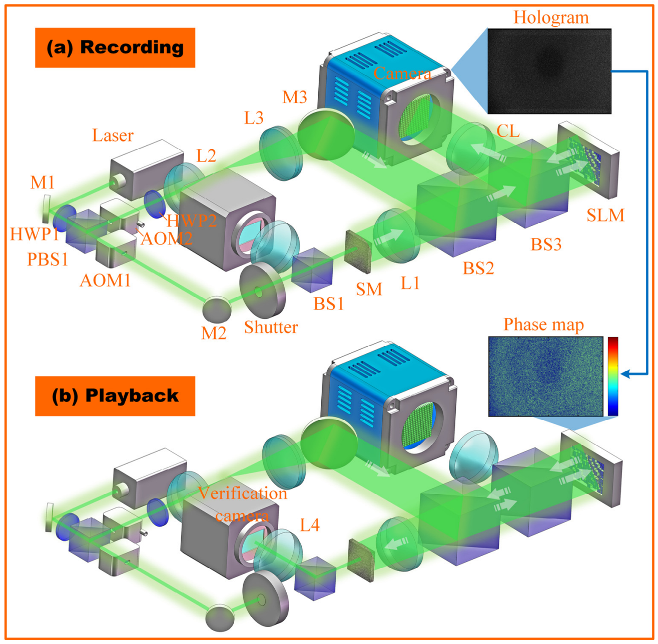

Fig. 1. Schematic of the optical time reversal system used in this work for focusing through scattering media. AOM, acousto-optic modulator; BS, beam splitter (non-polarizing); CL, camera lens; HWP, half-wave plate; L, lens; M, mirror; PBS, polarizing beam splitter; SLM, spatial light modulator; SM, scattering media.

RESULTS

Simulations: We first simulate the proposed single-shot optical time-reversal method using a random scattering matrix [34]. The input field $\mathbf{E}_{in}$ before the SM is assumed to have N spatial modes, which can be denoted as a column vector with N elements. The SM is represented by a random complex matrix $\mathbf{T}$ of size $N \times N$, and each element of $\mathbf{T}$ is drawn from a circular Gaussian distribution. The scattered field can be written as $\mathbf{E}_S = \mathbf{T}\mathbf{E}_{in}$. The field $\mathbf{E}_S$ interferes with a reference plane wave $\mathbf{E}_R$, and the hologram is generated according to Eq. (1). Next, the phases for playing back are determined based on Eqs. (2)–(4). For convenience, we refer to the approaches for generating the phase maps from Eqs. (2) – (4) as Modes 1 – 3, respectively. The optical field of the modulated playback beam becomes $\mathbf{E}_p = \mathbf{E}_R \exp(j\phi_{SLM})$. After the modulated playback beam passes through the SM, we obtain the optical field of the time-reversed focus as $\mathbf{E}_f = \mathbf{T}^T\mathbf{E}_p$, where the superscript "T" represents the matrix transpose. In our simulations, N is set to be 2500, and the middlemost element of $\mathbf{E}_{in}$ is set to 1, while the other elements are set to zeros to simulate a narrow incident beam. The simulated speckle pattern is shown in Fig. 2(a). After the scattered beam interferes with a plane reference beam, a hologram is generated as shown in Fig. 2(b). The phase maps for single-shot optical time reversal from Modes 1 – 3 and their corresponding playback foci are presented in Figs. 2(c)-2(e), respectively. As expected, all three modes can successfully realize single-shot optical time reversal through the SM. The peak-to-background ratios (PBRs) of the time-reversed foci from these three modes are 258±28, 277±25 and 570±25 respectively, based on 100 independent simulations. The PBR from Mode 2 is a little bit higher than that from Mode 1 because the non-conjugated terms in Eq. (1) are rejected to some level by subtracting the average of the hologram. More interesting, the PBR from Mode 3 is the highest. The reason is that the binary operation in Eq. (4) adaptively and effectively divides the phases of the scattered light into two parts according to whether they contribute to constructive interference or destructive interference, as detailed in Supporting Information.

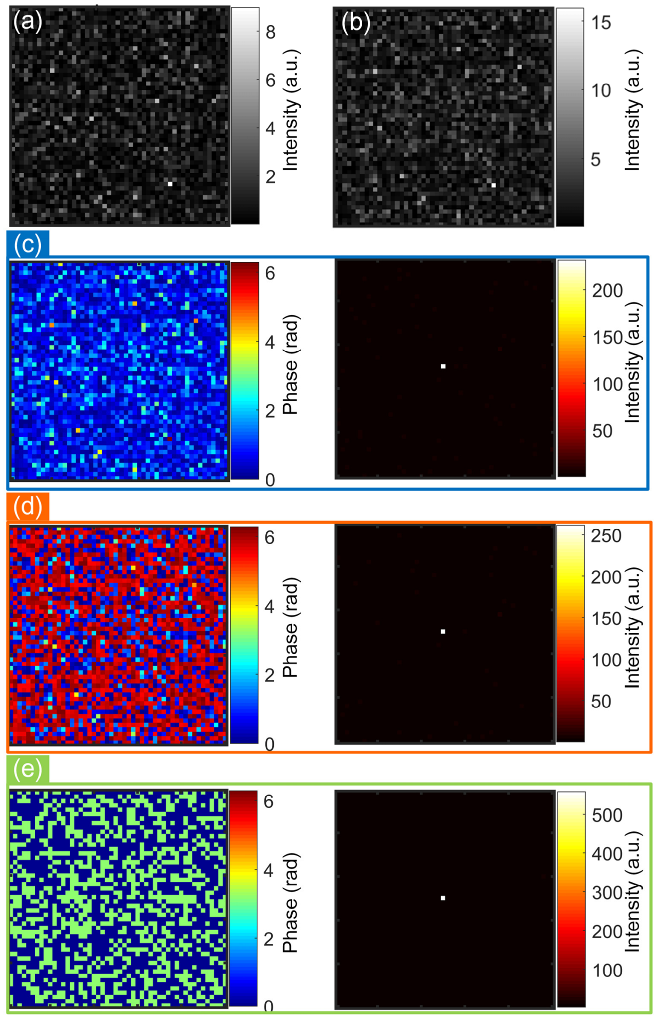

Fig. 2. Simulations of the proposed single-shot time-reversed optical focusing through scattering media. (a) Simulated speckle pattern from a laser beam transmitted a scattering medium; (b) Hologram from the interference between the scattered and reference optical fields; (c)-(e) Phase maps (left) and the corresponding time-reversed foci (right) based on Mode 1, Mode 2 and Mode 3, respectively.

Experiments: We verified the proposed single-shot time-reversed optical focusing through scattering media experimentally, using the setup in Fig. 1. Here, two optical diffusers (DG-220, Thorlabs) are employed as the scattering medium in the experiments for the purpose of demonstration. The experimental results for Mode 1, Mode 2, and Mode 3 are shown in Figs. 3(a)-3(c), respectively. All three modes successfully realize optical time reversal, and the calculated PBRs of the time-reversed foci from these three modes are 9175, 10432, and 23504, respectively.

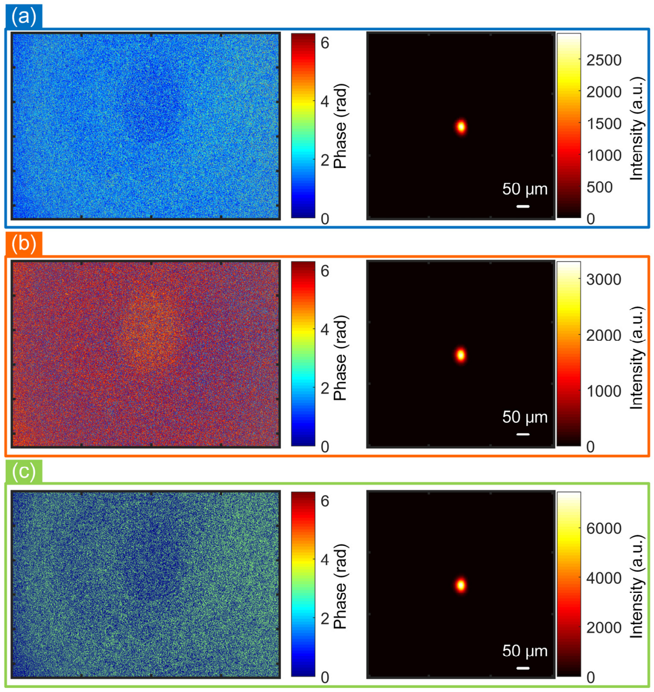

Fig. 3. Experimental verifications for the proposed three modes of single-shot time-reversed optical focusing through scattering media. (a)-(c) Phase maps (left) and the corresponding time-reversed foci (right) for Mode 1, Mode 2, and Mode 3, respectively.

As aforementioned, the widely used optical time-reversal method for focusing through scattering media that uses the minimal amount of measurement is the quasi-single-shot method in [22]. We call it "quasi-single-shot" because it requires a pre-recorded intensity image of the reference beam and another single hologram. It would be interesting to compare our "real" single-shot method to the quasi-single-shot approach. While keeping the reference beam constant, we performed focusing-through experiments with different signal beam intensities. Figure 4 shows the calculated PBRs of the time-reversed foci from the different methods, plotted with respect to the mean intensity ratios between the signal beam and reference beam. As can be seen, the proposed Mode 3 outperforms the others in all cases. It is also notable that the proposed Modes 1 – 3 are much more stable than the quasi-single-shot method. Their PBRs are insensitive to the intensity ratio between the signal beam and the reference beam, but the PBR of the quasi-single-shot method drops rapidly when the intensity ratio increases. This behavior is expected because the quasi-single-shot approach requires the intensity of the signal beam to be far less than that of the reference beam. Note that, in general, when the signal intensity is too weak, the low signal-to-noise ratio (SNR) would be detrimental to the PBR. Thus, the PBRs of all these methods rise at the beginning of the curves.

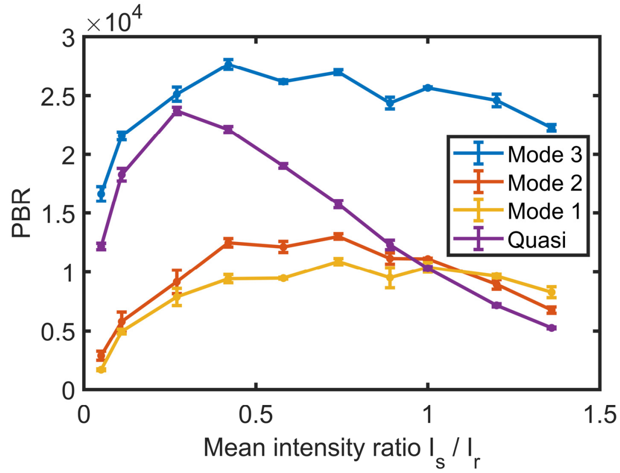

Fig. 4. Experimental PBRs of the proposed three "real" single-shot modes and the current quasi-single-shot method at different mean intensity ratios between the signal beam and the reference beam.

Next, we experimentally demonstrated that, besides good performance for focusing light through scattering media, the proposed method can straightforwardly realize single-shot TRUE optical focusing into scattering media for the first time. Based on the DOPC system in Fig. 1, Fig. 5(a) shows a simplified schematic of the setup for focusing light into a scattering medium comprising two separate samples (SM1 and SM2). In our experiment, an ultrasonic transducer (A381S, Panametrics, USA) is driven by a 3.5 MHz sine wave to generate the focused ultrasonic guide star. At the same time, we set the frequency deviation between the reference beam and the signal beam to 3.5 MHz, by means of two AOMs, shown in Fig. 1. When the signal beam passes through SM1 and the ultrasonic focus, the frequency of the photons modulated by the ultrasonic focus increases by 3.5 MHz. After being scattered by SM2, the frequency-modulated photons can interfere with the reference beam because they have the same frequency. The frequency components in the scattered light that differ excessively from the frequency of the reference beam contribute only to the background of the hologram, because the camera is not fast enough to capture the rapid change of the heterodyne signals. We captured a single-shot hologram and generated the phase map using the proposed single-shot approach (Mode 3). To verify that light was indeed time-reversed to the ultrasonic focus, a beam splitter was inserted between the two scattering media to divert a copy of the playback beam to the verification camera. After the phase map calculated from the single-shot hologram was loaded to the SLM, the TRUE focus was obtained successfully, as shown in Fig. 5(b). The PBR was estimated to be ~17. As a comparison, we also show the experimental result using the quasi-single-shot method in Fig. 5(c). Obviously, no focus can be seen, as expected and also pointed out in [18]. The line profiles of the central rows in Figs. 5(b) and 5(c) are shown in Fig. 5(d) for better comparison. Finally, we conducted a control experiment without the ultrasonic modulation, where no focus was obtained, as shown in Fig. 5(e). We note that Mode 1 and Mode 2 can also experimentally realize single-shot TRUE optical focusing, but with lower PBRs. In addition, the nominal focal size of the ultrasonic transducer we used in this experiment was 0.86 mm. A higher PBR could be realized by using a higher-frequency and larger-NA ultrasonic transducer with a much tighter ultrasonic focus.

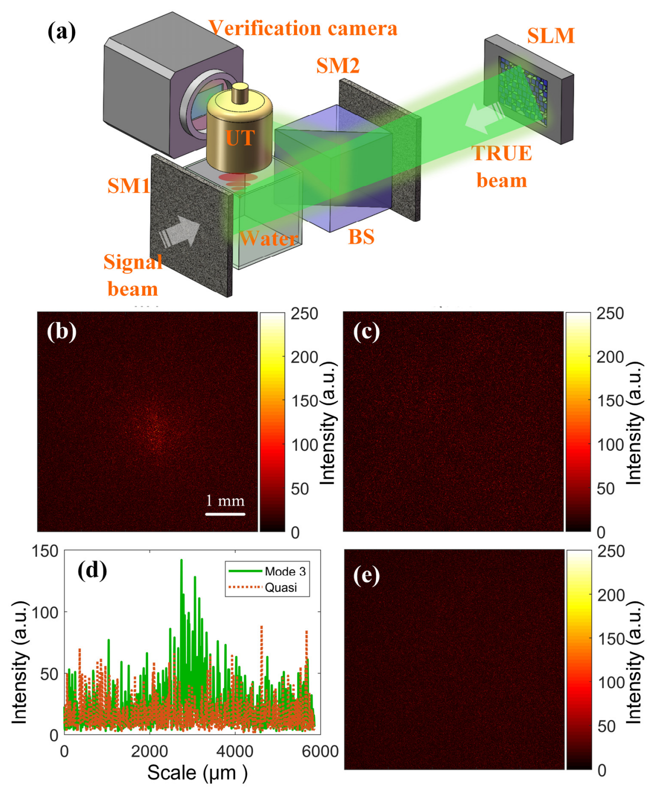

Fig. 5. Experimental results for single-shot time-reversed optical focusing into scattering media. (a) Schematic of TRUE optical focusing; (b) Image of the single-shot time-reversed focus achieved by Mode 3; (c) No focus can be seen by the quasi-single-shot method; (d) Line profiles of the central rows in (b)

and (c); (e) In a control experiment, no time-reversed focus can be seen when no ultrasound is used. UT, ultrasonic transducer.

DISCUSSIONS AND CONCLUSIONS

Increasing the speed of optical time reversal is one of the most pressing issues for focusing into or through scattering media in practical applications. Most efforts have concentrated on using faster digital devices, but the system speed is still limited by the frame rate of the cameras and by the speed of data transfer and processing. Here, we present a single-shot optical time-reversal method that reduces the number of holograms required for the time reversal to the minimum. Thus, the time for data acquisition, transfer, and processing is minimized.

It should be pointed out that although the off-axis interferometry is also possible to measure the wavefront from one hologram, it has many undesirable disadvantages in DOPC applications, such as degradation in spatial resolution, difficulty in determining the optimal off-axis angle, and computational load in data processing, as detailed in the Introduction section. Therefore, the on-axis interferometry is still the main method for wavefront measurement in current DOPC applications. To accelerate optical time reversal based on on-axis interferometry, the quasi-single-shot method was proposed and widely used in many fast DOPC systems for focusing through scattering media. However, this method needs to acquire two images for optical time reversal: one image for the reference beam, and the other one for the interferometric hologram. If the reference beam changes due to laser perturbation or accumulative mechanical drift, the acquisition for the reference beam must be redone. Additionally, the signal beam must be far less intense than the reference beam. Our "real" single-shot method resolves these limitations completely. It can be used without considering the intensity ratio between the signal and reference beams. Furthermore, our new method can achieve a much greater PBR and stability, as experimentally demonstrated in Fig. 4.

Compared with focusing through scattering media, focusing light into scattering media is more challenging. TRUE optical focusing provides a promising solution for controllable and non-invasive focusing into scattering media. However, the existing TRUE optical focusing still depends on multiple frames of holograms. Here, we demonstrate that the proposed method can realize single-shot TRUE optical focusing into scattering media for the first time. The implementation of the method is simple, and hence it can be applied to existing TRUE systems directly to accelerate optical focusing without any change to the system configuration.

Among the three modes of the proposed single-shot optical time-reversal method, we find that Mode 3 performs better compared with the other two. Although we have given some mathematical illustrations in Supporting Information, it may also be helpful to have some intuitive explanations here. Mode 1 and Mode 2 estimate the phase maps by generating full grayscale images of the captured hologram. However, not all the components in these full grayscale images are effective for time reversal because of the existence of the non-conjugated terms in Eq. (1). In other words, lots of the gray levels of the SLM are used to consider the contribution from the non-conjugated terms in Mode 1 and Mode 2, which is a waste of the effective control degrees of freedom. Although Mode 3 is inspired by Mode 2, it tends to approximate the conjugated wavefront itself rather than the accurate hologram intensity. In this way, the influence of the non-conjugated terms is minimized. These may be the intuitive reasons why the binarized phase map from Mode 3 is more effective than the full grayscale phase maps from Mode 1 and Mode 2 for optical time reversal. Because of the better performance and the intrinsic ability to work with SLMs that has very fast response via binary modulation, we recommend Mode 3 in general applications. Even so, we emphasize that Mode 1 and Mode 2 still provide valuable new insights for single-shot optical time reversal.

The experimental results show that the PBR of TRUE optical focusing is several orders of magnitude lower than that of through focusing. This observation can be attributed to two aspects: (1) The number of input speckle modes in TRUE optical focusing is generally several orders of magnitude higher than that in through focusing. According to the general theory of optical time reversal, the PBR of the time-reversed focus is inversely proportional to the number of the input speckle modes; (2) For focusing-through experiments, all the scattered photons incident on the camera can be considered as the signal beam. However, in TRUE optical focusing, only the photons tagged by the ultrasonic transducer and incident on the camera are considered to be the useful signal beam. In fact, an ultrasonic transducer can only tag a small fraction of the scattered photons. Therefore, the signal-to-noise ratio in TRUE optical focusing is also much lower than that in through focusing.

To summarize, the proposed single-shot optical time-reversal method maximizes the speed of focusing into and through scattering media, which is no longer bound by the camera frame rate. Thus, the measurement time is now mainly determined by the exposure time of the camera, which can be well below 1 ms. Also, the method can be straightforwardly combined with the previously reported DOPC systems with faster SLMs to further improve speeds. We anticipate that the presented technique will find ready use in high-speed wavefront shaping applications.

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SUPPORTING INFORMATION

The Supporting Information is available free of charge at https://pubs.acs.org. S1: Mathematical description of the proposed single-shot optical time-reversal method. S2: Supplementary figure.

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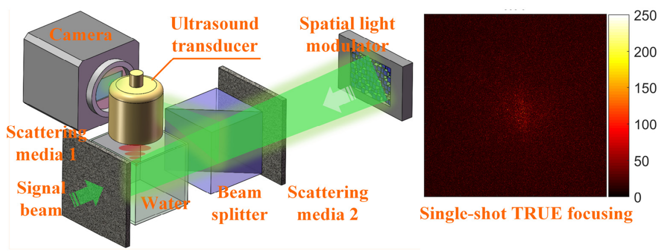
Single-shot time-reversed optical focusing into and through scattering media

Zhongtao Cheng, Jiamiao Yang, and Lihong V. Wang*



Brief synopsis: An optical time-reversal method is proposed which enables optical focusing both into and through scattering media based on a single-shot hologram.

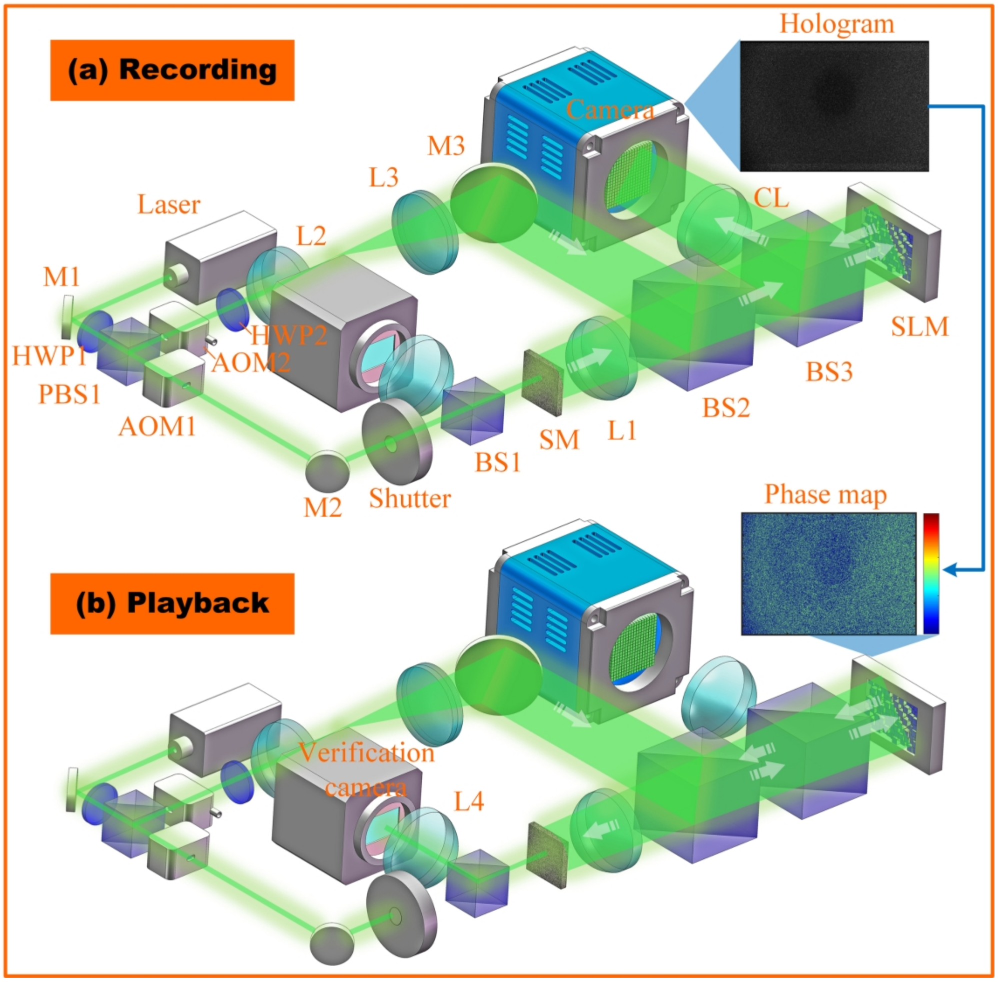


Fig. 1. Schematic of the optical time reversal system used in this work for focusing through scattering media. AOM, acousto-optic modulator; BS, beam splitter (non-polarizing); CL, camera lens; HWP, half-wave plate; L, lens; M, mirror; PBS, polarizing beam splitter; SLM, spatial light modulator; SM, scattering media.

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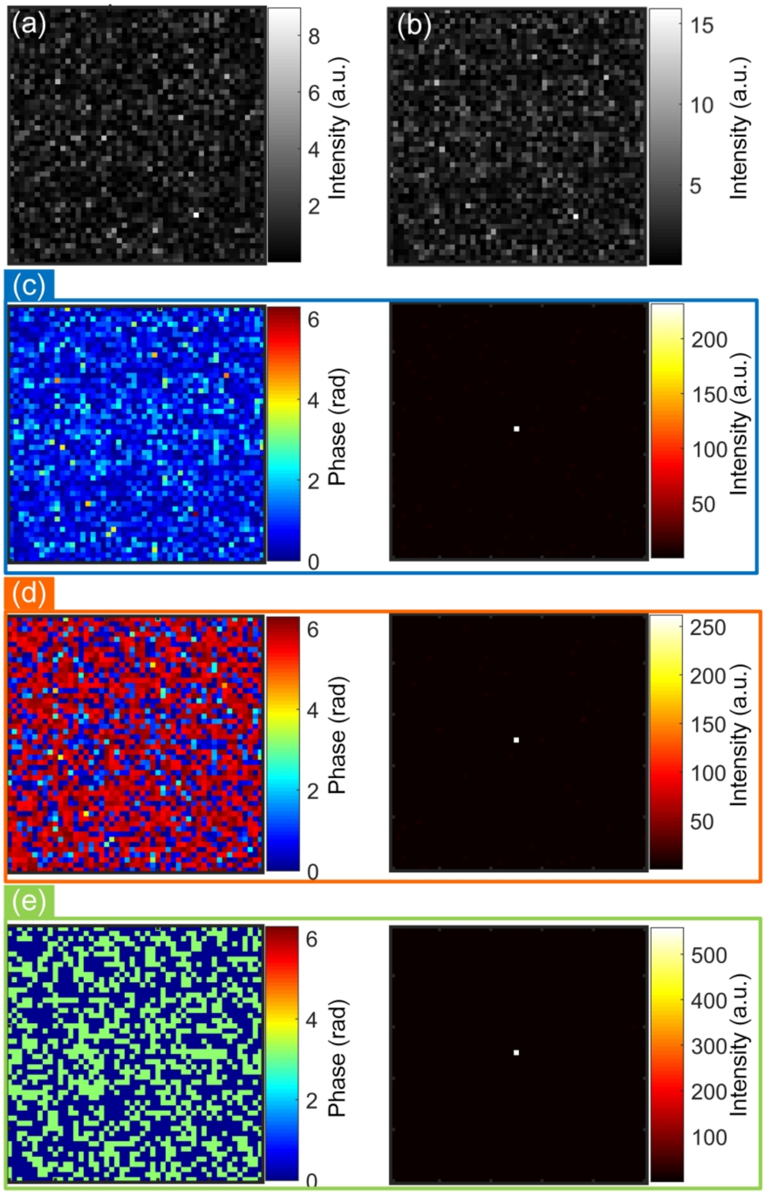

Fig. 2. Simulations of the proposed single-shot time-reversed optical focusing through scattering media. (a) Simulated speckle pattern from a laser beam transmitted a scattering medium; (b) Hologram from the interference between the scattered and reference optical fields; (c)-(e) Phase maps (left) and the corresponding time-reversed foci (right) based on Mode 1, Mode 2 and Mode 3, respectively.

166x259mm (300 x 300 DPI)

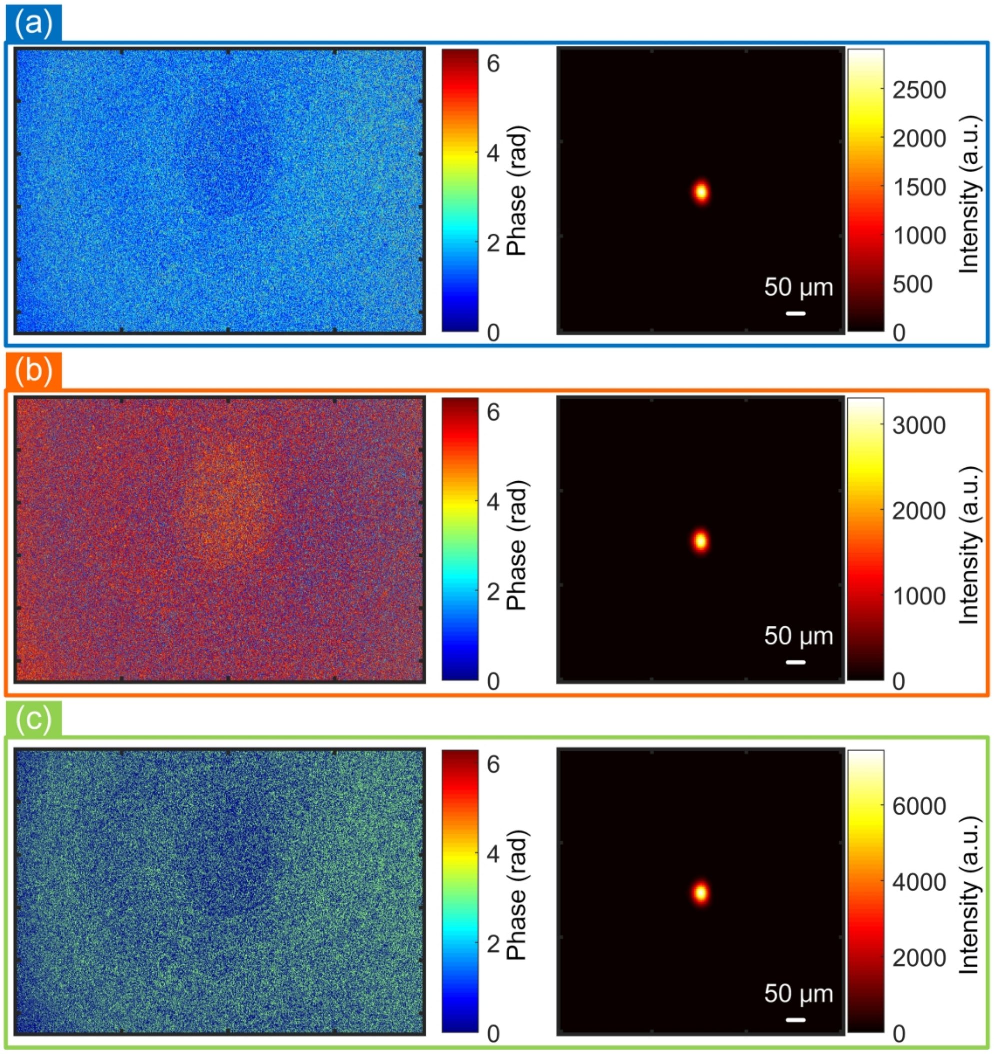

Fig. 3. Experimental verifications for the proposed three modes of single-shot time-reversed optical focusing through scattering media. (a)-(c) Phase maps (left) and the corresponding time-reversed foci (right) for Mode 1, Mode 2, and Mode 3, respectively.

194x206mm (300 x 300 DPI)

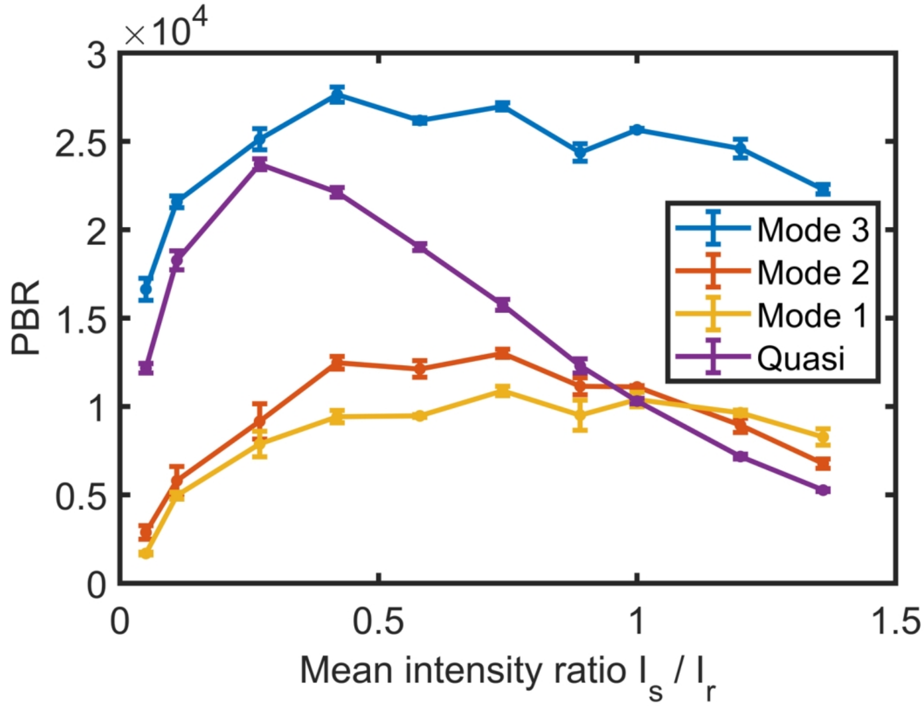

Fig. 4. Experimental PBRs of the proposed three "real" single-shot modes and the current quasi-single-shot method at different mean intensity ratios between the signal beam and the reference beam.

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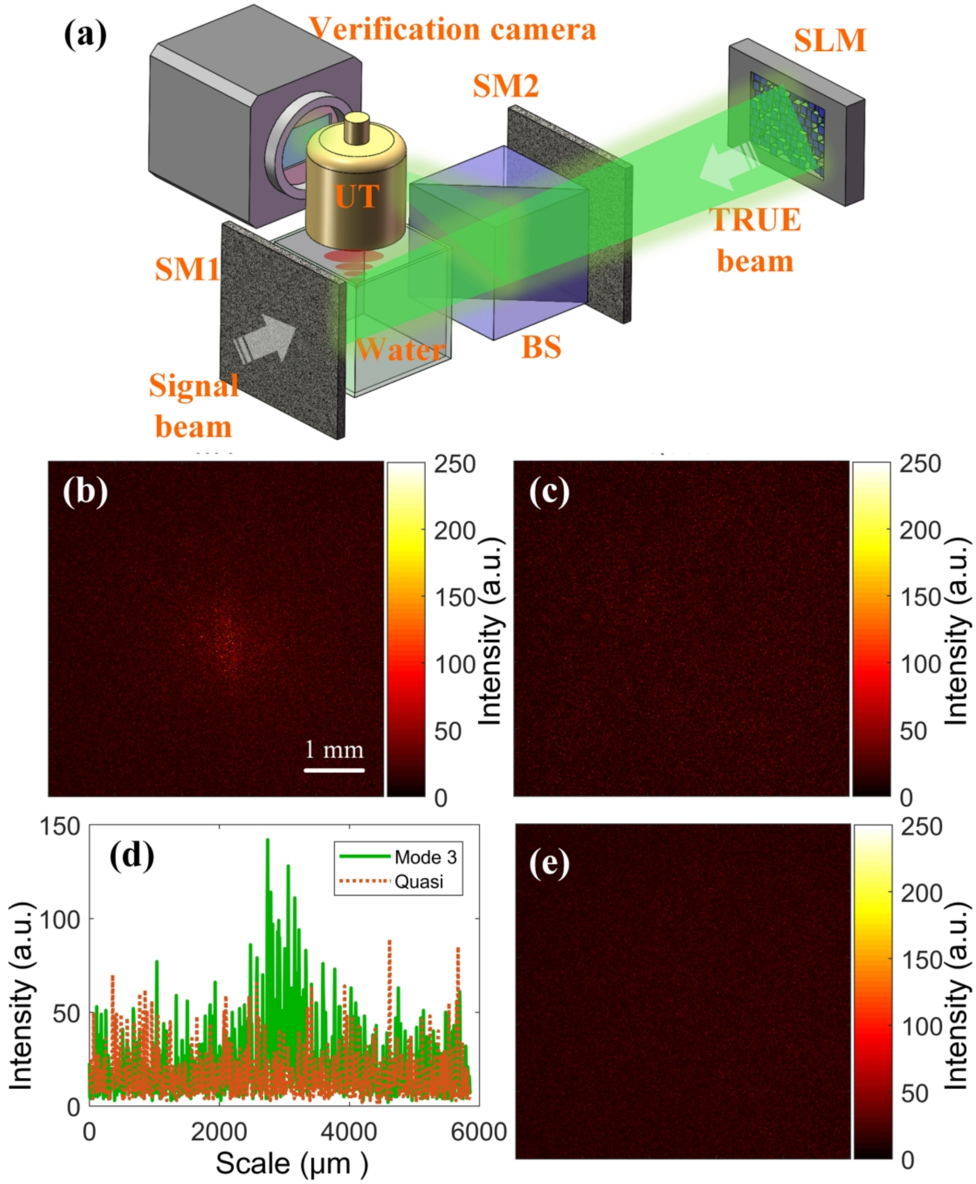

Fig. 5. Experimental results for single-shot time-reversed optical focusing into scattering media. (a) Schematic of TRUE optical focusing; (b) Image of the single-shot time-reversed focus achieved by Mode 3; (c) No focus can be seen by the quasi-single-shot method; (d) Line profiles of the central rows in (b) and (c); (e) In a control experiment, no time-reversed focus can be seen when no ultrasound is used. UT, ultrasonic transducer.

186x223mm (300 x 300 DPI)