

Angular-spectrum modeling of focusing light inside scattering media by optical phase conjugation: supplementary material

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This document provides supplementary information to “Angular-spectrum modeling of focusing light inside scattering media by optical phase conjugation,” <https://doi.org/10.1364/OPTICA.6.000250>. It includes a detailed description of the angular-spectrum method, the single-shot focusing-through DOPC experimental system, and the preparation of the dynamic scattering medium.

1. ANGULAR-SPECTRUM METHOD

The angular-spectrum method is widely used to trace an optical field inside homogeneous media without approximations [1–3]. As shown in Fig. S1, to propagate an optical field from the source plane to the destination plane, the optical field $E_S(x, y)$ on the source plane is decomposed into a series of plane waves with different propagation directions using the two-dimensional (2D) Fourier transformation:

$$\widehat{E}_S(k_x, k_y) = \frac{1}{2\pi} \iint E_S(x, y) \exp[-i(k_x x + k_y y)] dx dy. \quad (\text{S1})$$

Here, $\widehat{E}_S(k_x, k_y)$ is the complex amplitude of a plane wave, where k_x and k_y are the spatial frequencies in the x and y directions. Upon propagation from the source plane to the destination plane with a distance d , the plane wave $\widehat{E}_S(k_x, k_y)$ experiences a phase change:

$$\widehat{E}_D(k_x, k_y) = \widehat{E}_S(k_x, k_y) \exp \left[i n d \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - k_x^2 - k_y^2} \right]. \quad (\text{S2})$$

where n is the refractive index of the medium, and λ is the optical wavelength. By superimposing the destination plane wave $\widehat{E}_D(k_x, k_y)$ with all spatial frequencies using the 2D inverse Fourier transformation, the optical field $E_D(x, y)$ on the destination plane can be obtained as

$$E_D(x, y) = \frac{1}{2\pi} \iint \widehat{E}_D(k_x, k_y) \exp[i(k_x x + k_y y)] dk_x dk_y. \quad (\text{S3})$$

Taking advantage of the fast Fourier transformation algorithm [4], the propagation of the light field can be calculated efficiently.

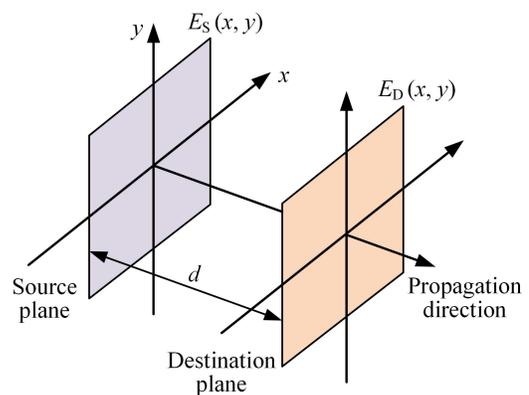


Fig. S1. Angular-spectrum method to trace an optical field between two planes.

2. SINGLE-SHOT FOCUSING-THROUGH DOPC SYSTEM

Figure S2 sketches the single-shot focusing-through DOPC experimental system. A collimated light beam with a wavelength of

532 nm was generated from a continuous-wave laser source (Verdi V5, Coherent). It was subsequently split into a reference beam and a sample beam by a variable attenuator, which was composed of a half-wave plate (HWP1) and a polarizing beam splitter (PBS1). After passing through a lens pair (L1 and L2), the reference beam was expanded to fully illuminate the surface of the SLM (Pluto-2-VIS, HOLOEYE). A shutter was utilized to control the on or off state of the sample beam. A lens L3 with a focal length of 40 mm was utilized to collect the scattered light passing through the scattering medium. The two beams were combined through a beam splitter (BS2), and their interference pattern was formed on the surface of the SLM. Then, a camera lens (CL) was used to relay the SLM plane to the camera (PCO.edge 5.5, PCO) plane and match their pixel sizes with a 1:1 ratio.

In the experiments, the intensity of the reference beam $I_R(x, y)$ was much greater than that of the scattered light $I_S(x, y)$. $I_R(x, y)$ was measured ahead by blocking the sample beam with the shutter. To measure the binary phase map of the scattered light, the hologram, interfered by the scattered beam and the reference beam, was recorded as $I_{\text{holo}}(x, y)$:

$$I_{\text{holo}}(x, y) = I_S(x, y) + I_R(x, y) + 2\sqrt{I_S(x, y)I_R(x, y)}\cos[\varphi_S(x, y) - \varphi_R] \approx I_R(x, y) + 2\sqrt{I_S(x, y)I_R(x, y)}\cos[\varphi_S(x, y) - \varphi_R]. \quad (\text{S4})$$

where $\varphi_S(x, y)$ is the phase distribution of the scattered light, and φ_R , approximated as a constant, is the phase of the reference beam. Thus, the binarized phase map of $\varphi_S(x, y)$ was obtained as [5]

$$\varphi'_S(x, y) = \begin{cases} 0, & \text{if } I_{\text{holo}}(x, y) \geq I_R(x, y) \\ \pi, & \text{if } I_{\text{holo}}(x, y) < I_R(x, y) \end{cases} \quad (\text{S5})$$

In the playback step, $\varphi'_S(x, y)$ was displayed on the SLM. The sample beam was blocked by the shutter, while the reference beam was modulated by the SLM upon reflection. After propagating through the scattering medium again, the playback beam became a collimated beam, which was then focused by a lens L4 and observed by a verification camera (CMLN-13S2M-CS, Point Grey).

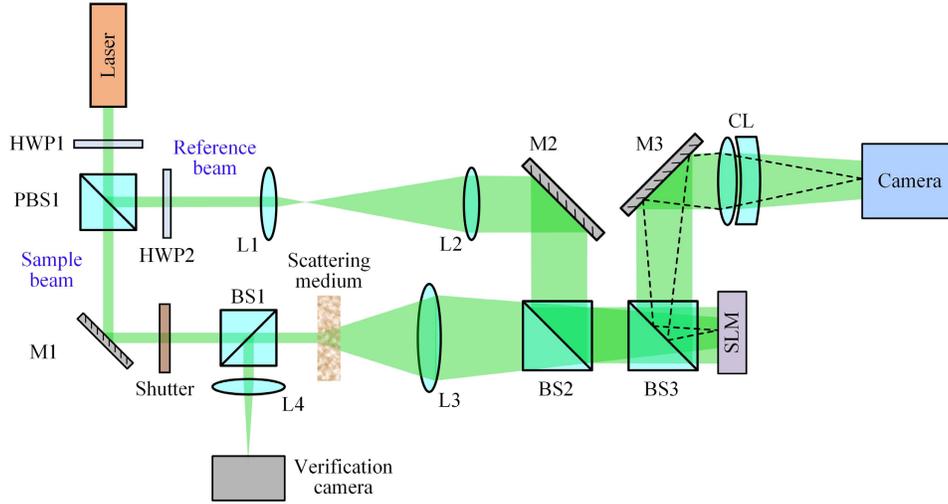


Fig. S2. Schematic of the single-shot focusing-through DOPC system. HWP, half-wave plate; PBS, polarizing beam splitter; L, lens; M, mirror; CL, camera lens; BS, beam splitter; SLM, spatial light modulator.

3. PREPARATION OF THE DYNAMIC SCATTERING MEDIUM

Figure S3 shows the preparation of the dynamic scattering medium, which was composed of two pieces of 1-mm thick 1% intralipid-gelatin phantoms and a tube filled with 1% intralipid solution. The cross-section of the tube was a $1 \times 2 \text{ mm}^2$ rectangle, and the tube was sandwiched between the phantoms with a gap of 2 mm. A syringe pump was used to drive the intralipid solution inside the tube with a specific speed v_s . The decorrelation time of the dynamic scattering medium can be controlled by adjusting the driving speed of the syringe pump.

To measure the decorrelation time of the dynamic scattering medium, the flow of the intralipid solution inside the tube was controlled at a specific speed by the syringe pump. The camera in the DOPC system worked with a region of interest of 400×200 pixels and a frame rate of 200 Hz. The speckle correlation coefficient at time t_m was calculated as the correlation between two speckle images captured at $t = 0$ and $t = t_m$. By fitting the speckle correlation coefficients with the function of

$\alpha_{\text{cor}} = A \exp(-2t/\tau_c) + B$, where A and B are constants, the decorrelation time τ_c can be obtained, which corresponds to the speckle correlation coefficient decreased to $1/e^2 + B$.

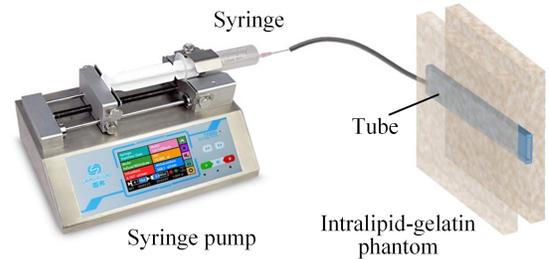


Fig. S3. Dynamic scattering medium preparation. The tube was sandwiched between two 1% intralipid-gelatin phantoms with a gap of 2 mm.

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