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Implementing transmission eigenchannels of disordered media by a binary-control digital micromirror device

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ABSTRACT

We report a method for measuring the transmission matrix of a disordered medium using a binary-control of a digital micromirror device (DMD). With knowledge of the measured transmission matrix, we identified the transmission eigenchannels of the medium. We then used binary control of the DMD to shape the wavefront of incident waves and to experimentally couple light to individual eigenchannels. When the wave was coupled to the eigenchannel with the largest eigenvalue, in particular, we were able to achieve about two times more energy transmission than the mean transmittance of the medium. Our study provides an elaborated use of the DMD as a high-speed wavefront shaping device for controlling the multiple scattering of waves in highly scattering media.

1. Introduction

Light waves propagating through disordered media undergo a complicated multiple scattering process. This causes two major detrimental effects for optical techniques—the distortion of waves and the attenuation of wave intensity. In recent years, various studies were conducted in which the deterministic nature of the scattering process was made use of for resolving these effects. For example, wavefront shaping techniques were used to generate a sharp focus at the opposite side of a scattering medium [1–7], and wavefront sensing techniques were used to image objects hidden behind scattering layers [8–11].

Studies concerning wave transmission through a disordered medium have also drawn broad attention. In these studies, an interesting physical property of a disordered medium—the existence of transmission eigenchannels [12]—has been explored. Vellekoop and Mosk indirectly demonstrated the existence of the open eigenchannel, which is the eigenchannel of unity transmission, by analyzing transmission enhancement as a consequence of single-point optimization process [13]. Popoff et al. measured a transmission matrix of a scattering medium and analyzed the statistical properties of the transmittance of eigenchannels [14]. And our group conducted an experiment to couple incident waves to individual transmission eigenchannels of a disordered medium. In the previous study, we identified transmission eigenchannels by recording the transmission matrix of the medium [15].

All the previous studies dealing with transmission eigenchannels used a liquid-crystal-based spatial light modulator (LC-SLM) either for wavefront shaping or wavefront sensing. In the present study, we considered a digital micromirror device (DMD) consisting of a large number of micromirrors as an alternative to the LC-SLM in studying transmission eigenchannels of a disordered medium. Although each micromirror in a DMD is only capable of binary amplitude control, not phase control, the refresh rate (23 kHz) is much higher than that of an LC-SLM (typically 60 Hz) [16]. Therefore, the DMD offers a high-speed wavefront-shaping opportunity, which can be critical in various applications. In fact, the DMD was previously used to generate a focus at the opposite side of a scattering medium [5,6]. In these implementations, mainly two types of wavefront shaping methods have been developed. One is to selectively turn on the micromirrors that increase the intensity of a target output channel with adaptive feedback control. The other is to make use of multiple micromirrors to form a diffraction grating, with which the phase of the wave is controlled in a way that pre-compensates the phase distortion and makes constructive interference at a single output point. Akbulut et al. demonstrated focusing through scattering media for the first time in using a DMD by the first method [5]. Later, Conkey et al. employed the phase-control method based on a DMD to generate a focus [6].

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In this paper, we demonstrated both the recording of a transmission matrix of a disordered medium and the implementing of individual transmission eigenchannels of the medium by using the DMD as a wavefront shaping device. Specifically, we proposed a method that makes use of the individual binary control unit of the DMD. We measured the transmitted waves to a disordered medium for a number of random binary patterns written on the DMD. From this set of measurements, we constructed a transmission matrix of the medium, which relates the changes in the transmitted wave due to the control of each binary unit of the DMD. We then made use of the binary amplitude control of the DMD to shape a wave to the individual transmission eigenchannels identified by the transmission matrix. In doing so, we were able to achieve about two times more transmission than with the uncontrolled wave. This is the first use of a DMD for the implementation of transmission eigenchannels.

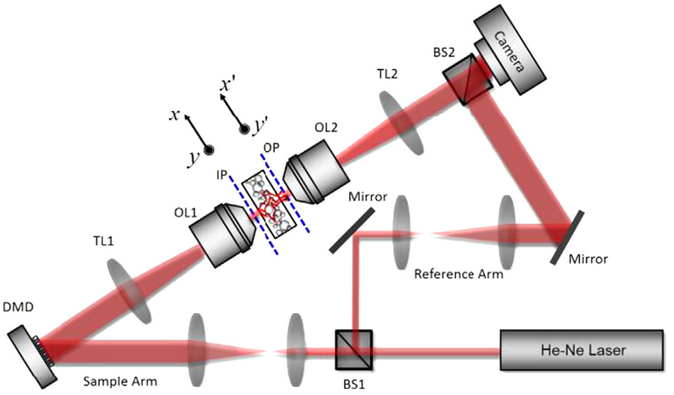

Fig. 1. Schematic experimental setup for recording a transmission matrix and implementing individual transmission eigenchannels. An off-axis interference microscope with a DMD installed in the sample beam path. The output beam from a He–Ne laser was divided into sample and reference beams using a beam splitter, BS1. Another beam splitter, BS2, recombined the two beams. OL1 and OL2: objective lenses; TL1 and TL2: tube lenses; IP and OP: the input and output plane of the disordered medium made of TiO_2 particles. The (x, y) and (x', y') are the spatial coordinates at the IP and OP, respectively. The magnification from DMD to IP was 1/133.33, and that from OP to camera is 111.

2. Measuring the transmission matrix

Direct access to the transmission eigenchannels of a disordered medium requires the recording of the medium's transmission matrix, $\boldsymbol{t}$, that relates output free modes to those of input. Then we can perform the singular value decomposition for $\boldsymbol{t}$ and factorize the matrix into

$$t = U\tau V^{+}, \tag{1}$$

where $\boldsymbol{t}$ is a rectangular diagonal matrix with non-negative real numbers on the diagonal called singular values and $\boldsymbol{V}^{+}$ denotes the conjugated transpose of matrix $\boldsymbol{V}$. The singular values are sorted in descending order of the column index of $\boldsymbol{t}$ with the column index defined as an eigenchannel index. The eigenvalue of $\boldsymbol{tt}^{+}$, which is the square of the singular value, is the expected transmittance of the corresponding eigenchannel. $\boldsymbol{V}$ and $\boldsymbol{U}$ are the unitary matrices, the columns of which are the transmission eigenchannels at the input and output planes, respectively. By shaping the incident wave in such a way as to implement the complex values in each column vector of $\boldsymbol{V}$, one can couple an incident wave to each transmission eigenchannel. In our approach, we used a DMD for both recording a transmission matrix and implementing individual transmission eigenchannels.

The schematic layout of the experimental setup is shown in Fig. 1. The backbone of the setup is an interferometric microscope with DMD (D4100, Texas Instrument, 1024 × 768 pixels, 13.68 × 13.68 μm^2 per pixel) installed in the sample beam path. The output beam from a He–Ne laser (wavelength: 633 nm) was divided into sample and reference beams using a beam splitter (BS1). The sample beam was expanded to illuminate the entire area of the DMD, and the wavefront of the reflected beam was shaped by selectively turning its micro-mirrors on and off. Then, the shaped pattern was delivered to the input plane (IP, x–y coordinate system) of a disordered medium by an objective lens (OL1, RMS40X, Olympus). We used $M = 5024$ macropixels, with each macropixel composed of 6×6 micromirrors of the DMD as a binary unit, and the diameter of the illumination area was 49 μm at the IP. In other words, a single macropixel corresponded to 610 × 610 nm^2 at the IP. The disordered medium used in the experiment was a TiO_2 nanoparticle (Sigma-Aldrich 204757) layer. The average transmittance of this medium is 0.7% at the collection angle corresponding to $NA = 0.65$. TiO_2 particles have a high refractive index (2.58) and are almost free from absorption at a wavelength of 633 nm. In order to prepare relatively uniform layers, we made a solution of TiO_2 in ethanol and spread the layer on the slide glass (or cover glass) using air spray. After going through a multiple-scattering process in the disordered medium, the transmitted wave at the output plane (OP, x–y' coordinate system) was delivered to the camera through an objective lens (OL2, RMS40X, Olympus) and then it was interfered with the reference beam. The interference image was recorded by a complementary metal-oxide semiconductor camera (Motionscope M3 (500 fps), IDT) and then processed to acquire the amplitude and phase maps of the sample beam at the OP. The view field of the camera at the OP was 54 × 54 μm^2. The complex field maps of the output speckles were used to construct a transmission matrix of the disordered medium.

The choice of input and output free modes for $\boldsymbol{t}$ is arbitrary, as long as they form orthogonal basis. In our configuration, we considered the spatial coordinates at the IP and OP to be input and output bases, respectively. Therefore, waves emanating from each macropixel serve as input basis and those impinging on each pixel of camera as output basis. The element of the transmission matrix, $\boldsymbol{t}_{ij}$, is determined as the complex field amplitude at the ith position in the OP when a macropixel corresponding to the jth position in the IP is turned on. A straightforward way to measure $\boldsymbol{t}$ is to turn on each macropixel and then record the complex field at the OP. However, this yields an extremely low signal to noise ratio (SNR) because only a tiny fraction of an incident wave is used for the illumination. In order to maximize the SNR, we measured the superposed response of the disordered medium for the randomly chosen $M/2$ macropixels in the input basis and then unfolded it to the response for each macropixel by means of matrix inversion. To be specific, we first prepared for the L binary sequences $\boldsymbol{S}_{jp}$, ($j = 1, 2, \cdots, M$; $p = 1, 2, \cdots, L$) whose M elements are either turned on or off with equal probability (Fig. 2(a)). These sequences represent the speckle basis. The speckle basis is not orthogonal, yet complete. By the use of pseudo-inversion process, we could effectively orthogonalize the basis. In the experiment, the number of speckle basis L is 6028 that is 1.2 times larger than of the binary unit M. This means that we oversampled the response of disordered medium for the binary unit, or the speckle basis is overcomplete. In this way, we could increase the signal to noise ratio for the measurement. Then, we measured optical responses $\boldsymbol{O}$, the complex field map at the OP for the series of speckle basis at the IP (Fig. 2(b)). Using the measured $\boldsymbol{O}$ and predetermined $\boldsymbol{S}$, we set the relation for the transmission matrix $\boldsymbol{t}_{ij}$:

$$O_{ip} = \sum_{j} \boldsymbol{t}_{ij}\boldsymbol{S}_{jp} \tag{2}$$