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Measuring large optical reflection matrices of turbid media

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ABSTRACT

We report the measurement of a large optical reflection matrix (RM) of a highly disordered medium. Incident optical fields onto a turbid sample are controlled by a spatial light modulator, and the corresponding fields reflected from the sample are measured using full-field Michelson interferometry. The number of modes in the measured RM is set to exceed the number of resolvable modes in the scattering media. We successfully study the subtle intrinsic correlations in the RM which agrees with the theoretical prediction by the random-matrix theory when the effect of the limited numerical aperture on the eigenvalue distribution of the RM is taken into account. The possibility of the enhanced delivery of incident energy into scattering media is also examined from the eigenvalue distribution which promises efficient light therapeutic applications.

1. Introduction

Wave propagation through disordered media is a fundamental physical phenomenon, where the input and the scattered wave field are linearly related via the scattering matrix (SM). A SM is formed by two transmission matrices (TM) and two reflection matrices (RM) taking into account the two sides of the medium which can act both as the input or output faces. Recently TMs of turbid medium have been optically measured [1–10], and various utilizations of TMs have been demonstrated including the reconstruction of an image from a speckle field that has transmitted through a turbid layer [1], optical manipulation [11], depth-enhanced wavefront shaping optical coherence tomography [12,13], the enhancement of energy delivery through scattering media [14–17], the subwavelength focusing and imaging using randomly distributed nanoparticles [18,19], and optical control of cell activities through biological tissue [20]. Furthermore, TMs can also provide important information for wavefront shaping techniques [21–27].

However, considering that these approaches have potentials for imaging or light delivery through biological tissues [9], the key breakthrough for practical applications may lie in the utilization of RMs of scattering media since optical instruments adequate for in vivo biomedical applications must function in reflection geometry. Recently, an acoustic RM of turbid media has been measured [28] and the measurement of the full scattering matrix including both the RM and TM to address the perfect transmission channel was demonstrated for elastic waves [29]. However, experimental investigations on the properties of optical RMs of turbid media have not been fully conducted. In optics, a RM has been first measured for weakly scattering media [30], which can be regarded as an aberration layer. More recently, a RM of complex media has been measured using the interferometric method, and the suppression of reflected light intensity has been demonstrated using the measured RM [31]. Measurements of the time-resolved RM was also demonstrated, providing information on the light field reflected from specific depths via low coherence interferometry. This enables enhanced light delivery at target depths inside the scattering media [32].

Here we present the measurement of a large optical RM of scattering media and address the statistical property of the measured RM. The input wave fields are modulated by a spatial light modulator (SLM) and the corresponding reflected fields from the sample are measured by a full-field Michelson interferometer. The optical modes are sampled finely so that the measured total mode number exceeds the total number of resolvable modes for the field-of-view (FoV) in the sample. After constructing the RM of the sample, we investigate the eigenvalue distribution of the acquired RM and made comparisons with the theoretical prediction by the random-matrix theory (RMT). Recent theoretical [33] and experimental studies [3] have shown that the acquirable information from SMs is limited by the numerical aperture (NA) of the optical imaging system. We study this limitation on the RM through a comparison between our simulation model and experimental results.

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2. Experimental setup

The experimental setup is depicted in Fig. 1. The setup comprises of a SLM and a Michelson interferometer to modulate and measure the respective optical light fields. A linearly-polarized collimated light beam from a HeNe laser (HNL020R, Thorlabs Inc.) is divided into a sample and a reference beam at a beam splitter. The beam impinged onto a scattering sample is phase-modulated by a SLM (LCOS-SLM X10468-02, Hamamatsu Photonics, Japan). A half-wave plate is used to rotate the polarization of the reference beam. The reflected beam from a scattering sample is projected onto a CCD camera (IMI Tech., IMC-30FC, Republic of Korea), and interferes with the reference beam to form an off-axis hologram, from which the amplitude and phase of the reflected field are retrieved via the Hilbert transform [34].

Since the field acquisition requires only a single-shot measurement of an off-axis hologram, the acquisition speed is limited by the recording speed of the detector and the modulation speed of input fields. In the current setup, the major limiting factor of the acquisition time is the refresh rate of the SLM which is 30 ms. To avoid cross-talk between successive measurements, the measurement time for a reflected field was set as 50 ms, resulting in the total measurement time of approximately 10 min for 12,288 incident modulated fields.

In order to systematically and effectively modulate incident light fields, we employed the Hadamard patterns as the input basis. The amplitude of the modulated field is uniform, and the phase map, having the values of either 0 or π, is generated from the Hadamard patterns. The representative phase maps are shown in the inset of Fig. 1. The lateral magnification of the optical system is designed such that, when the phase patterns are projected onto a scattering sample, the minimum size of the phase patterns corresponds to the diffraction-limited spot size at the sample plane. In principle, these phase-modulated light fields span the same information that can be assessed by the light fields scanned in angular spectrum space, i.e. by tilting the illumination angle of the incident beam via a galvanometer mirror. Although deploying plane-waves with tilting illumination angles using a galvanometer-mirror may provide high-speed measurements as demonstrated in the measurements of TMs [1,14], the use of a SLM has the following advantages: (a) no mechanical parts eliminates mechanical noise; and (b) a SLM can also be used for applying any arbitrary shaped wavefront as well as measuring RMs of a turbid medium.

The scattering sample used for the experiments is a layer of ZnO nanoparticles (mean diameter = 200 nm) with a thickness of 160 ± 15 μm. Using an integrating sphere, the mean-free path of the sample was measured as 1.05 ± 0.11 μm. The FoV of the measurement was 27.3 μm × 20.5 μm. In 2-D slab waveguide geometry, the number of propagating modes is given as $N = p\pi A/\lambda^2$ [35], where A is the area of a waveguide and $p = 1$ or 2 with respect to the number of measured orthogonal polarization states. In our case, $p = 1$ since only one polarization state is modulated and measured. The total resolved number of modes inside the FoV is then calculated to be 4 381. For experiments, the number of input modes was set to be $M = 12{,}288$ to oversample all resolvable optical modes.

3. Measurement and calibration of RM

For calibration purposes, we first measure the RM of a mirror. When illuminated with a normal incident plane wave, the measured amplitude and phase maps of the light reflected from the mirror show uniform values (Fig. 2a, b). Here the amplitude is normalized so that both the total input and total reflected energy are equal to unity. Then we measure the RM of a scattering medium. Both the measured amplitude and phase maps of the beam reflected from the scattering sample, illuminated with a normal incident plane wave, exhibit highly disordered speckled patterns (Fig. 2c, d). The output intensity from the scattering sample is normalized to the reference data obtained from a mirror.

After acquiring the reflected fields for each input basis, the RM of the mirror is constructed as shown in Fig. 3a. The RM of the mirror plays the important role in the analysis since we presumably know that the RM is equal to an identity matrix multiplied by constant phase factor $e^{i\pi}$; the amplitude of the reflected field is the same with that of the input field and the phase is delayed by π according to the law of reflection. Then any deviation from this ideal value can be regarded to originate from measurement error. Since the input basis is the Hadamard basis and the output basis is represented in the spatial coordinate basis, the RM of the mirror is expressed in the following way,

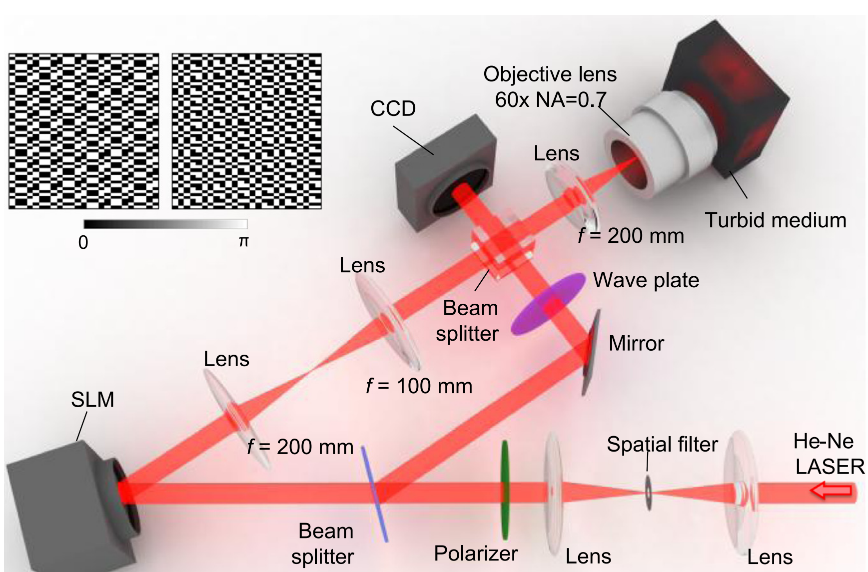

Fig. 1. Schematic of the experimental setup. The inset shows representative Hadamard patterns for phase modulation.