Maximal energy transport through disordered media

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Transmission through a disordered medium can be increased by a factor of four using a new experimental technique that optimizes constructive interference of scattered light.

Disordered media, such as fog and fine powders, scatter light in random directions, so that only a small fraction of incident light is transmitted. The randomness would seem to prevent any control over light propagation through the medium. However, a disordered medium is still a linear system, regardless of the degree of disorder. When two incident waves propagate simultaneously through the medium, the total transmitted wave is just the sum of the two transmitted waves. Therefore, the input-output response of a disordered medium can be described by a so-called transmission matrix, which relates free modes at the input to those at the output.

Random matrix theory developed in the 1980s suggests that a particular incident wave with a specific pattern can propagate through a disordered medium without undergoing any loss.\(^1\) Mathematically, this special wave is the eigenvector of the transmission matrix with maximum eigenvalue and is often called the open eigenchannel. The high transmittance of the open eigenchannel is due to strong constructive interference of scattered waves at the opposite side of the medium.

In spite of recent technical advances in wavefront sensing and recording, the injection of waves into single eigenchannels has not been realized experimentally. Coupling waves into unique eigenchannels is difficult because of two stringent requirements. First, the transmission matrix of the disordered medium must be recorded in a relatively short time. Second, the eigenchannels of highly complicated wavefronts derived from the measured matrix should be precisely realized in the experiment. We have overcome these difficulties in our experimental study.\(^2\)

For the measurement of a transmission matrix, we generated a set of plane waves that spanned all possible incident angles, which we characterized by two angles \((\theta_x, \theta_y)\) that corresponded to two orthogonal directions \((\xi, \eta)\) in the input plane. For each incident angle, we measured the complex field as a function of the spatial coordinates \(\xi\) and \(\eta\), see Figure 1(a). We then introduced a disordered medium and recorded the transmission as a function of a second set of spatial coordinates, \(x\) and \(y\), defined on the output plane. Figure 1(b) shows a few representative phase maps of the transmitted waves for different incident angles. From the two sets of complex field maps, we constructed a transmission matrix \(T\). The amplitude and phase of the transmission matrix are shown in Figure 1(c) and 1(d), respectively. If there were no disordered medium, the matrix would be diagonal. In a disordered medium, however, multiple scattering processes cause the incident beam to spread, thereby generating non-zero off-diagonal elements. In order to acquire

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the transmission eigenchannels and their corresponding transmission eigenvalues, we performed singular value decomposition for the constructed transmission matrix. Specifically, we factorized the transmission matrix into $T = U \Sigma V^*$, where $\Sigma$ is a rectangular diagonal matrix with nonnegative real numbers on the diagonal called singular values, while $V$ and $U$ are unitary matrices whose columns are the transmission eigenchannels at input and output plane, respectively. The $V^*$ denotes the conjugate transpose of the matrix $V$.

Although we acquired the eigenchannels from the measured transmission matrix, it is important to implement each eigenchannel in the experiment to verify whether it truly exhibits enhanced (or reduced) transmission, in accordance with its eigenvalue. By using a spatial light modulator (SLM), we could experimentally generate an optical wave corresponding to a given eigenchannel. The SLM in our experiment operated in a phase-only mode, so in order to implement spatial variations in the wave amplitude, we applied a method in which multiple SLM pixels are combined into a single pixel at the target plane.3

We sent SLM-generated eigenchannels into the disordered medium and then captured the complex field map at the output plane. Figure 2(b) shows the transmission image from the first eigenchannel (the one with the largest eigenvalue), which can be compared to the output from an uncontrolled wave (plane wave) in Figure 2(a). The enhancement factor, which is defined as the ratio of the transmittance of the first eigenchannel to that of the uncontrolled wave, was 2.8 for this particular disordered medium sample. We repeated the same experiment for more than 20 different samples and observed that the transmission enhancement was highly reproducible in each case. The enhancement factor varies somewhat from sample to sample, typically in the range of 2 to 4.

In summary, we demonstrated that we can control the wave interference between scattered waves in a highly disordered medium by means of coupling light into individual transmission eigenchannels. In particular, we could selectively generate an eigenchannel of maximum transmittance and achieve significant transmission enhancement of as much as a factor of 4. Our method could potentially be useful in facilitating laser radiation therapy and biomedical imaging by enhancing light energy delivery deep into biological tissues.

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References