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Delivering Broadband Light Deep into Diffusive Media

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Waves propagate diffusively through disordered media, such as biological tissue, clouds, and paint, due to random scattering. Recent advances in optical wavefront shaping techniques have enabled controlling coherent light propagation in multiple-scattering samples. We overcome wave diffusion to deliver optical energy into a target region of arbitrary size and shape anywhere inside a strong-scattering system. This is particularly important for applications such as photoacoustic microscopy and optogenetics, where light needs to be deposited deep into biological tissue. For monochromatic light, we previously introduced the deposition matrix (DM) Z(ω), which maps its input wavefront to the field distribution in the target region [1]. The eigenchannel with the largest eigenvalue provides the wavefront for maximal energy delivery. Since the enhancement is achieved via constructive interference of scattered waves, the optimal wavefront will vary with input wavelength.

In this work, we show it is possible to find a common wavefront to enhance energy delivery over a broad spectrum. We introduce the broadband deposition matrix (BDM), $A = \int d\omega\, I(\omega)\, \mathcal{Z}(\omega)^{\dagger} \mathcal{Z}(\omega)$, where I(ω) is the input spectrum [2]. The eigenvector of the BDM with the largest eigenvalue gives the input wavefront for maximal energy delivery to the target by a broadband light.

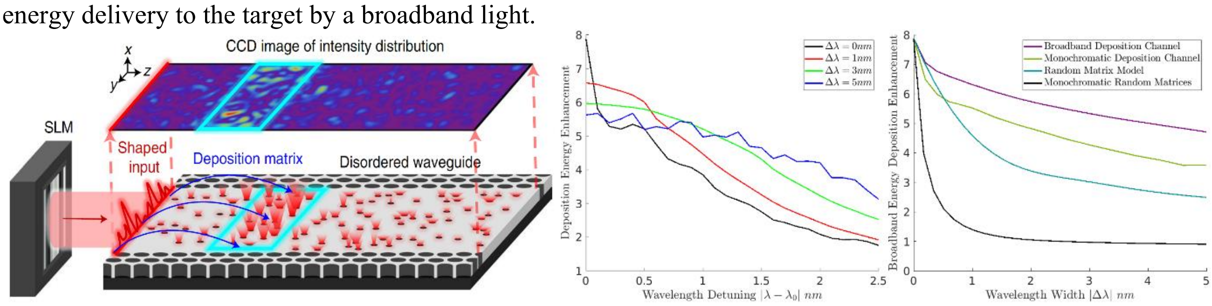

Fig. 1 (a) Schematic of our experimental setup. Incident light is wavefront shaped by a spatial light modulator (SLM) and then injected into a 2D diffusive waveguide of length L. The spatial distribution of light inside the waveguide is imaged from the top by a CCD camera. (b) Enhancement of energy deposited at depth z = 0.6L as a function of wavelength detuning for eigenvectors of broadband deposition matrix with different bandwidths Δλ. (c) Enhancement of broadband energy deposition obtained with the eigenvector of broadband deposition matrix, compared to that of monochromatic deposition matrix. Further comparison is made with an uncorrelated random matrix model.

Experimentally we measure the frequency-resolved DM Z(ω) for an extended target at varying depth inside a two-dimensional diffusive waveguide (Fig. 1a). From it we reconstruct the BDM for a range of bandwidths Δλ, where the largest eigenvalue gives the maximal energy that can be delivered to the target region. The corresponding eigenvector gives the input wavefront that enhances the energy over a broad wavelength range. With increasing bandwidth Δλ, the energy enhancement (compared to random inputs) is lower at the center wavelength but persists over a broader range. Integrating the energy over Δλ gives the total energy enhancement, which is plotted versus Δλ in Fig. 1c. It decreases much slower with increasing Δλ than the maximum eigenchannel of a monochromatic DM. We further compare with an uncorrelated random matrix model, illustrating the importance of long-range frequency correlations in achieving broadband control. We perform numerical simulation and theoretical analysis to support the experimental data.

In summary, we believe this work will pave the way for numerous applications including deep-tissue imaging, optogenetic control of cells, photothermal therapy, and probing and manipulating photoelectrochemical processes deep inside nominally opaque media.

Example References

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