Scattering matrix measurements and applications

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Technology Overview

Light propagation through disordered media is often treated as a statistical process in which photons diffuse in a random fashion. The wave nature of the light is clearly manifested, however, if it stays coherent during propagation and the structural variations of the medium are negligible over the transit time. It is then possible to deterministically control the light propagation through disordered media, which even enables us to use the media as useful optical elements. Recording a scattering matrix, either in forward direction or in backward direction, of a disordered medium relates the complex amplitudes of output free modes to those of input modes, and thus, provides us with a lot of useful information. With the transmission matrix - a part of scattering matrix in forward direction, the input wave for a desired output can be determined and vice versa. It permits not only controlling the wave at the far side of the medium [1] but also transmitting extended object information [2-4] and enhanced energy delivery through the disordered media [5].

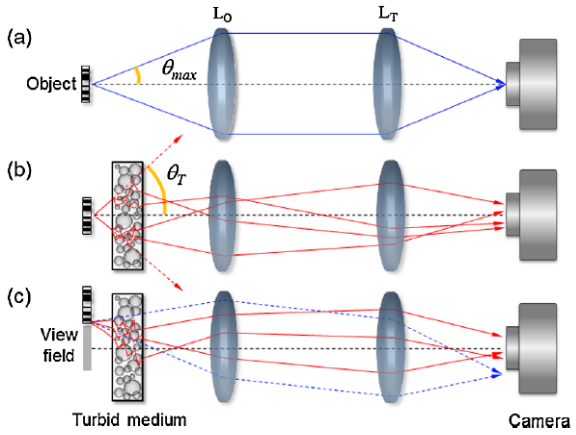
Since most biological applications require signal acquisition in reflection mode, technical advance is also needed to assess and control light scattering for reflection geometries. LBRC researchers have recently developed a unique approach to experimentally measure the time-resolved reflection matrix (TRRM) of a scattering medium in the near-IR regime. Unlike the transmission matrix, the TRRM describes the input-output response of a scattering medium at the same port generated by a laser source with low temporal coherence. Our approach allows us to extract the response of the medium for a particular arrival time (at the detector) with respect to each input. This information is further processed to find the combination of input channels that maximizes the backscattered wavefield with a specific arrival time. We note that this approach is distinct from previous studies where feedback optimization has been used [6-8]. By experimentally implementing this unique input wave, LBRC researchers have been able to demonstrate enhanced light energy delivery within a scattering medium.

Biomedical Application Potential

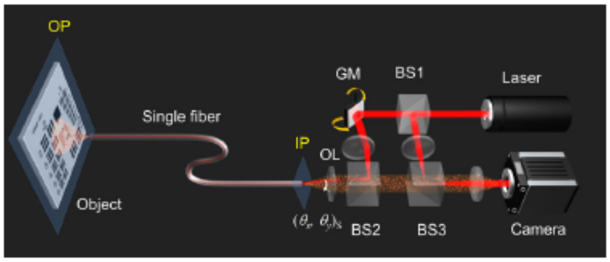
This approach, when combined with other imaging modalities such as multi-photon or fluorescence microscopy, has the potential to improve imaging contrast as well as the measurement sensitivity since more light energy can be effectively delivered to a specific depth within turbid tissue samples. In addition, the efficiency of photodynamic therapy may also be maximized by appropriately controlling the intensity distribution besides enhanced optical energy delivery.

Ongoing Projects

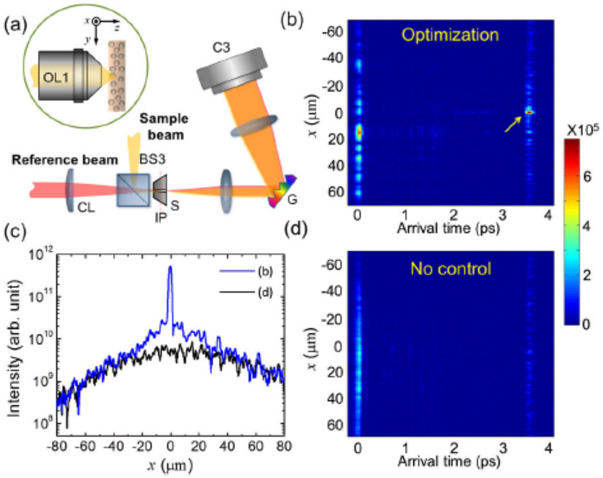
a. Improved TRRM measurement for enhanced energy delivery
b. Application of TRRM to improve image contrast in optical coherence tomography



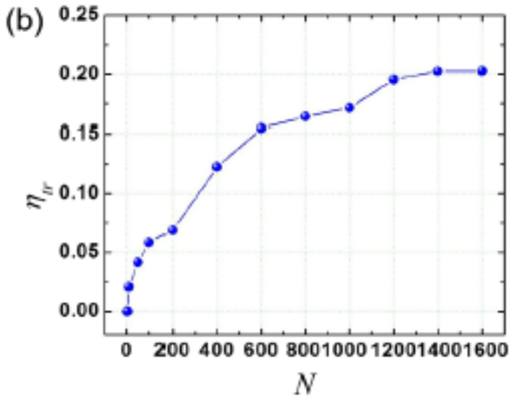
A scattering lens can be used for improving the performance of optical imaging as long as it is deterministically characterized by measuring its transmission matrix. (a) Conventional imaging. (b) A scattering lens can capture the waves with larger angles than the NA of the imaging optics. (c) A scattering lens can capture the information outside of conventional imaging field of view.



Lensless microendoscopy using a single fiber. A single multimode optical fiber can be used as an endoscope working in a reflection configuration after deterministically characterizing its transmission property. BSs: beam splitters; OL: objective lens; IP: input plane; OP: object plane; GM: scanning mirror.



Spatiotemporal focusing of backscattered light from a scattering medium. (a) Schematic of 1D line-field detection setup. (b) A spatiotemporal distribution of backscattered wave from a scattering medium after the control of incident wavefront. (c) Intensity profiles along the target arrival time. (d) The same as (b), but without the control.



Relative enhancement of energy delivery to a target depth inside a scattering medium as a function of the number of measured TRRM elements.

Background Publications

1. S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A. C. Boccara, and S. Gigan, Measuring the transmission matrix in optics: an approach to the study and control of light propagation in disordered media. *Phys. Rev. Lett.* **104**, 100601 (2010).
2. S. M. Popoff, G. Lerosey, M. Fink, A. C. Boccara, and S. Gigan, Image transmission through an opaque material. *Nature Communications* **1**, 81 (2010).
3. Y. Choi, T. D. Yang, C. Fang-Yen, P. Kang, K. J. Lee, R. R. Dasari, M. S. Feld, and W. Choi, Overcoming the diffraction limit using multiple light scattering in a highly disordered medium. *Phys. Rev. Lett.* **107**, 023902 (2011).
4. Y. Choi, C. Yoon, M. Kim, T. D. Yang, C. Fang-Yen, R. R. Dasari, K. J. Lee, and W. Choi, Scanner-fee wide-field endoscopic imaging by using a single multimode optical fiber. *Phys. Rev. Lett.* **109**, 203901 (2012).
5. M. Kim, Y. Choi, C. Yoon, W. Choi, J. Kim, Q. H. Park, and W. Choi, Maximal energy transport through disordered media with the implementation of transmission eigenchannels. *Nature Photonics* **6**, 581 (2012).
6. I. M. Vellekoop, A. Lagendijk, and A. P. Mosk, Exploiting disorder for perfect focusing. *Nature Photonics* **4**, 320 (2010).
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8. E. G. van Putten, D. Akbulut, J. Bertolotti, W. L. Vos, A. Lagendijk, and A. P. Mosk, Scattering lens resolves sub-100 nm structures with visible light. *Phys. Rev. Lett.* **106**, 193905 (2011).

Center Publications

1. Y. Choi, T. D. Yang, C. Fang-Yen, P. Kang, K. J. Lee, R. R. Dasari, M. S. Feld, and W. Choi, Overcoming the diffraction limit using multiple light scattering in a highly disordered medium. *Phys. Rev. Lett.* **107**, 023902 (2011).
2. Y. Choi, C. Yoon, M. Kim, T. D. Yang, C. Fang-Yen, R. R. Dasari, K. J. Lee, and W. Choi, Scanner-fee wide-field endoscopic imaging by using a single multimode optical fiber. *Phys. Rev. Lett.* **109**, 203901 (2012).
3. Y. Choi, T. R. Hillman, W. Choi, N. Lue, R. R. Dasari, P. T. C. So, W. Choi, and Z. Yaqoob, Measurement of the time-resolved reflection matrix for enhancing light energy delivery into a scattering medium. *Phys. Rev. Lett*. **111**, 243901 (2013).

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