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Range of Imaging and Focusing through Scattering Media

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Abstract: Control of interference enables new methods of focusing and imaging through scattering media. We explore basic physical processes that enable such methods and ultimately limit their range. Exciting opportunities for applications exist, especially in tissue.
OCIS codes: (290.7050) Turbid media, (030.6140) Speckle

Random scattering of light by micro-and nanoscale structures is an impediment to optical imaging and focusing in turbid materials such as intact biological tissues and through media such as fog and snow. The manipulation of the coherence properties of laser speckle has led to a new class of methods based on shaping of the incident wavefront [1]. By shaping the incident wavefront, light can be focused tightly through a turbid medium [2] or inside it on a guide star such as a fluorescent or nonlinear nanoparticle. Phase conjugation methods can be used to focus light on a moving object, or motion can provide a basis for imaging [3], and ultrasound can facilitate a focus [4,5]. While incoherent light can be used in these imaging methods [6], this approach relies on coherence being preserved in the medium

For phase coherent methods to be able to function, it is important that any coherent operation is performed within the correlation time of the medium, i.e., the time in which all correlations in the transmitted light are lost [7]. This correlation time typically decreases with the thickness of the medium. Hence, to image or focus deeply inside a scattering medium one needs fast detection and generation of complex light fields. In present implementations the time scale is limited mostly by electronic and software processing, even for the fastest implementations [8]. Given several years of development, phase conjugation equipment that couples quantum-limited detectors may push the speed of phase conjugation to the physical limit. In that limit, the range inside a medium to which phase conjugation and related methods will work is mostly determined by the necessary integration time to count signal photons, and in some cases even by the round trip time of the light.

Here we present a general framework for assessing the depth to which coherent optical methods may be useful and compare them to other methods of imaging in turbid media. We find that excellent opportunities for phase coherent imaging may be found in tissue optics, while the advantage over other methods in terms of range is more limited in dilute media such as fog and clouds, mostly due to the large size of such media relative to the wavelength and the motion speed of the scatterers.

References

[1] A. P. Mosk, A. Lagendijk, G. Lerosey, and M. Fink, “Controlling waves in space and time for imaging and focusing in complex media,” Nature Photon. **6**, 283-292 (2012).
[2] I.M. Vellekoop and A.P. Mosk, “Focusing coherent light through opaque strongly scattering media,” Opt. Lett. **32** 2309-2311 (2007).
[3] J. A. Newman, Q. Luo, and K. J. Webb, “Imaging hidden objects with spatial speckle intensity correlations over object position,” Phys. Rev. Lett. **116**, 073902 (2016).
[4] X. Xu, H. Liu, and L. Wang, “Time-reversed ultrasonically encoded optical focusing into scattering media,” Nature Photon. **5**, 154 (2011).
[5] Y. Wang, B. Judkewitz, C. DiMarzio and C. Yang, “Deep-tissue focal fluorescence imaging with digitally time-reversed ultrasound-encoded light,” Nature Comm. **3**, 928 (2012).
[6] O. Katz, E. Small and Y. Silberberg, “Looking around corners and through thin turbid layers in real time with scattered incoherent light,” Nature Photon. **6**, 549-553 (2012).
[7] G. Maret and P. Wolf, "Multiple light scattering from disordered media. The effect of Brownian motion of scatterers," Zeitschrift für Phys. B Condens. Mat. **413**, 409–413 (1987).
[8] D. Wang, E.H. Zhou, J. Brake, H. Ruan, M. Jang and C. Yang, “Focusing through Dynamic Tissue with Millisecond Digital Optical Phase Conjugation,” Optica **2**, 728 (2015)