Controlling Light Inside Disordered Materials: Matrix Model and Applications

S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A.C. Boccara, S. Gigan
Institut Langevin, ESPCI ParisTech, CNRS UMR 7587, ESPCI, 10 rue Vauquelin, 75005 Paris, France
sebastien.popoff@espci.fr

Abstract : We introduce a method to experimentally measure the monochromatic transmission matrix of a complex medium in optics. This method is based on a spatial phase modulator together with a full-field interferometric measurement on a camera. We determine the transmission matrix of a thick random scattering sample. We show that this matrix exhibits statistical properties in good agreement with random matrix theory and allows light focusing and imaging through the random medium.

Recently, a method has been proposed by I. Vellekoop et al. [1] to focus light through a multiple scattering material, using a spatial light modulator as a tool to shape the incoming beam to obtain a maximal interference on a speckle spot of the output speckle pattern. The result is a bright, diffraction limited, spot which can be several hundred time brighter than the rest of the speckle. By the same method, the same group also demonstrated the enhancement of the optical activity of a fluorescent object embedded in the material [2], and even shown strong evidence of the existence of open channels in a random medium [3].

However, there is a much more general approach to the problem of imaging and controlling light in a random medium. It consists of measuring the transmission matrix, i.e. the matrix linking the amplitude of the input to the output modes of the multiple scattering material. This approach not only gives several new possibilities for imaging, but also allows direct insight on the material itself, as has been demonstrated in acoustics [4] or electromagnetism [5] for instance.

We present here an original method [6] based on an interferometric measurement of the speckle on a camera, which has allowed us to measure the transmission matrix of an opaque slab of ZnO powder.

The experimental setup is presented in fig1. A laser is expanded and reflected off a phase-only spatial light modulator (SLM) and sent on the sample. The light on the other side of the sample is collected by a microscope objective and imaged on a CCD camera.

We choose as our input modes a 16x16 macropixels matrix of the SLM. The light that is shone on the sample but was reflected outside of this matrix is our reference and has been used as a reference to measure the amplitude of the output speckle on a 16x16 macropixels matrix on the CCD.

By choosing the Hadamart basis to encode our input vectors, and by extracting the amplitude and phase of the speckle produced by the input modes by a 4-phase full-field interferometric method, we have been able to extract the matrix K_{obs}, which is directly related to the transmission matrix K of the medium, but has a contribution due to the reference speckle that we can account for. This matrix is acquired in approximately 3 minutes, a time comparable to iterative methods.

As soon as we have measured the transmission matrix, it is in principle possible to perform a virtual phase conjugation to focus on any output E_{target} , by sending $E_{in}=K^{+} E_{target}$ (where $^{+}$ denotes the transpose conjugate). The result is a bright focus with the same SNR ratio as the one obtained by iterative methods. It is also possible to infer simply, by measuring the output speckle, the input image (this is the reciprocal problem of the focusing). Results are summarized on figure 2. All these results are obtained in one step.

To reconstruct a more complex image, one have to increase the number of degrees of information, either by averaging results obtained with different illuminations of the same amplitude object, or by increasing the number of segments recorded on the CCD camera. A typical result of the reconstruction of a complex pattern is shown in figure 3.

We also have been able to measure the singular value distribution of the transmission matrix, after filtering the effect of the reference on $K_{obs,}$, as well as the effect of residual correlations between neighboring pixels. We verified a well-known prediction of random matrix theory, i.e. that the normalized singular values follow the so-called quarter-circle law [8]. The result is shown on figure 4.

We believe that this method is very promising, both for imaging application, and for the study of wave propagation in complex materials.

References

[1] I. Vellekoop et al., Opt. Lett. **32** (2007) 2309.
[2] I. Vellekoop et al., Opt. Lett **1** (2007) 53.
[3] I. Vellekoop et al., Phys. Rev. Lett., **101** (2008) 120601.
[4] A. Derode et al., Phys. Rev. Lett., **90** (2003) 014301.
[5] G. Lerosey et al., Science, **315** (2007) 1120.

[6] S.M. Popoff et al., Phys. Rev. Lett., **104** (2010) 100601.
[7] A. Dubois et al., Appl. Opt, **41** (2002) 805.
[8] V. Marcenko and L. Pastur, Sbornik: Mathematics, **1** (1967) 457.

Figures

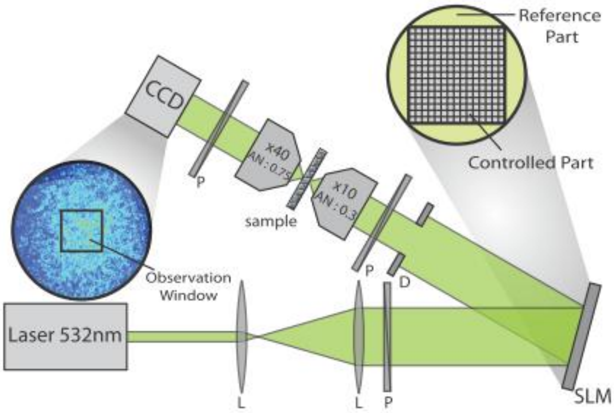

Figure 1 : Experimental setup

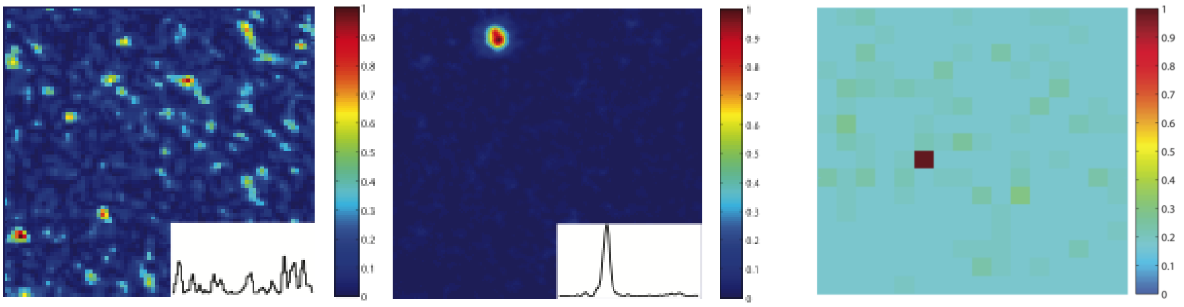

Figure 2 : Imaging by using the transmission matrix. (left) initial speckle at the output of the sample. (center) focusing on a single point. SNR of the focus over the background is 54, equal to approximately 40% of the ideal phase conjugation. (right) detection of a single ON pixel at the input by analysing the output speckle. Insets show profile along one direction.

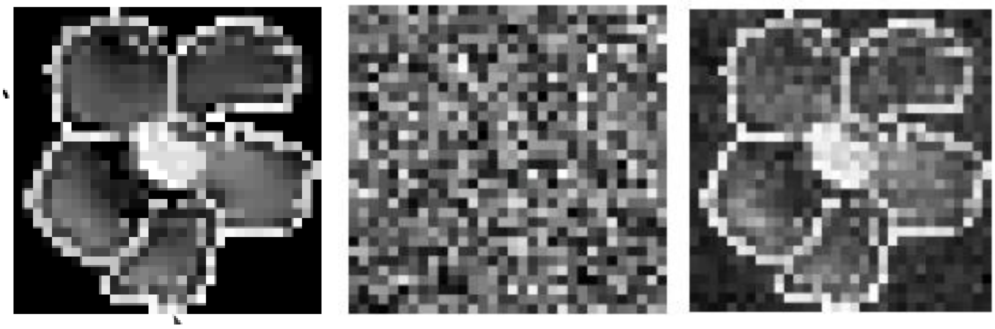

Figure 3 : A complex image reconstruction using the transmission matrix. (left) amplitude image displayed on the SLM. (center) the resulting output speckle. (right) the reconstruction using the transmission matrix.

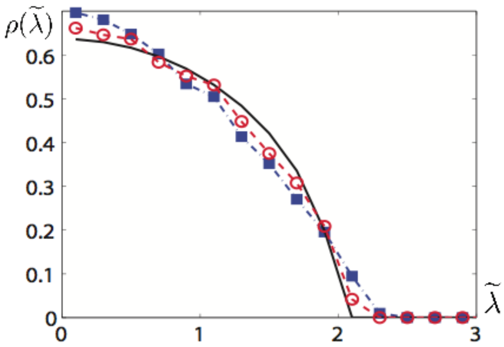

Figure 4 : Distribution of the normalized singular values. Solid line : quarter-circle law as predicted by random matrix theory. Squares : distribution for the transmission matrix. Circles : distribution for the measured transmission matrix when removing nearest neighbors to eliminate residual correlations.