# Limits of light focusing through turbid media

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Wave emission and propagation in random media has been a matter of intense research during the last decades. Effects induced by coherent multiple scattering of waves explain to a large extent phenomena such as enhanced coherent backscattering, universal conductance fluctuations, strong Anderson localization of waves and random lasing, to cite a few. [1]

Contrary to what intuition may suggest, the introduction of scattering sources in a system can enhance the focusing ability of an optical system. A simple heuristic argument shows that scattering can efficiently open new propagating channels which are closed otherwise. As has been demonstrated in the microwave regime [2], the inclusion of scatters in the near field of a selected focusing point can even enable subwavelength focusing.

By using wavefront shaping techniques, it has been recently shown [3] in the optical range that, despite experimental limitations, it is possible to achieve the best theoretical focus as predicted by Cittert-Zernike theorem. Using a different approach, it has been shown that the full transmission matrix of a thick turbid medium can be measured both in amplitude and phase [4]. Hence, using an appropriate inversion algorithm, any intensity pattern can be transfered through the sample.

In this work, we theoretically analyze the focusing capabilities of a system with varying amounts of disorder. In particular we shall deal with scalar wave models in confined (guided) geometries.

In this kind of systems, several transport regimes appear depending on the ratio of the system length to the scattering mean free path and the propagating number of channels. For lengths small compared with the mean free path, transport is quasi-ballistic. Diffusive transport is dominant for lengths ranging from about a mean free path up to the so-called localization length. For larger lengths, the system undergoes a crossover to the deep localized regime where transport is exponentially inhibited.

It has been shown [5] that the averaged conductance of the system can account for many transport statistical properties in a universal manner, all the way from quasi-ballistic to deep localization regimes. On the other hand, conductance can be properly defined not only in electronic systems but on optical ones [6]. Being hence conductance a key parameter describing the optical transport properties of a disordered system.

By generating random scattering matrices corresponding to previously defined number of propagating channels, scattering mean free path and system length [7]. We are able to determine all the relevant optical transport parameter of the system. Also, through the use of different inversion algorithms, we can determine the set of appropriate incoming amplitudes for each channel in order to focus light at the other side of the system. In figure 1 we show an example of diffraction-limited focusing by using a Montecarlo algorithm through a system of one mean free path thickness.

It can be shown that, if incoming amplitudes can present an arbitrary dynamic range while keeping a sufficiently small signal-to-noise ratio, focusing is diffraction limited for any transport regime including localization. Nevertheless, The amount of transmitted power in strongly reduced as the scattering increases. It is worth stressing that the transmittance in the focusing mode is much smaller than the channel-averaged transmittance of the sample. Hence, one of the limitations we find is that the transmitted power can be negligible even prior to the onset of localization. As can be seen in figure 2.

On the other hand, if we consider a finite signal-to noise ratio for the incoming amplitudes, focusing ability deteriorates as scattering increases.

In conclusion, we show that, although some amounts of disorder provide an effective coupling to new propagating channels, hence increasing the effective numerical aperture of the optical system. Focusing capabilities of the system and the effective power transmission are severely reduced if disorder is further increased.

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## References

*[1] P. Sheng, Introduction to Wave Scattering, Localisation, and Mesoscopic Phenomena (Academic Press, New York, 1995).*

*[2] G. Lerosey, A. Tourin, and M. Fink, Science* ***315****, (2007) 1120.*
*[3] I. M. Vellekoop, A. Lagendijk, and A. P. Mosk, Nature Photonics* ***4****, (2010) 320.*
*[4]S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A. C. Boccara, and S. Gigan ,Phys. Rev. Lett.* ***104****, (2010)100601*
.
[5]L. S. Froufe-Pérez, P. García-Mochales, P. A. Serena, P. A. Mello, and J. J. Saenz , Phys. Rev. Lett. **89**, (2002) 246403.
[6]S. Albaladejo, M. Lester, L.S. Froufe-Pérez, A. Garcia Martín y J.J. Sáenz, App. Phys. Lett. **91**, (2007) 061107.
[7]*L. S. Froufe-Pérez, M. Yépez, P. A. Mello y J. J. Sáenz,Phys. Rev. E* ***75****, (2007) 031113.*

## Figures

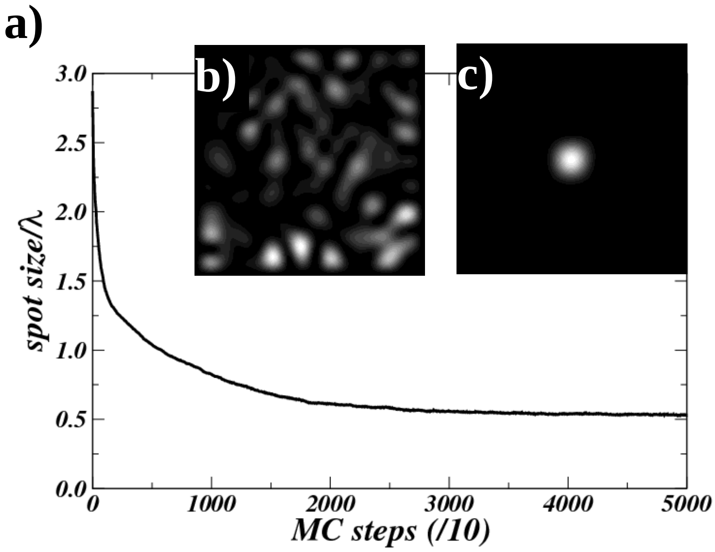

*Figure 1. Focusing through a disordered system of 1 mean free path thickness. a) Spot size as a function of the Montecarlo step. b) intensity map in the focusing plane for a random pattern of incoming field amplitudes. c) intensity map in the focusing plane after incoming amplitudes have been adapted for focusing through a Montecarlo procedure.*

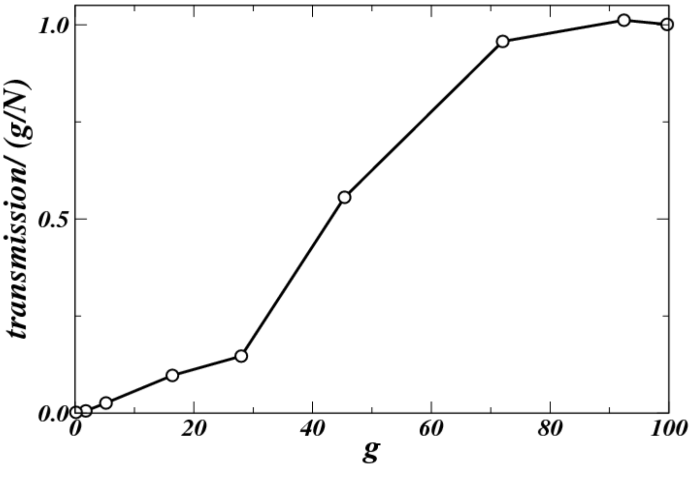

*Figure 2. Power transmission of the focused beam normalized to the average one-channel transmittance (conductance divided by the number of channels) as a function of the waveguide conductance.*