Looking inside a 3D scattering medium to observe the 3D spatially-resolved optical energy density that is enhanced by wavefront shaping

Peilong Hong, Oluwafemi S. Ojambati, Ad Lagendijk, Allard P. Mosk*, and Willem L. Vos

Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

Present address: Nanophotonics, Debye Institute, Utrecht University, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands

It is well known that a thick scattering medium (e.g. a slab of paint) is opaque since incident waves are thoroughly scrambled [1,2]. In the diffusive transport regime, the scattered light has an (ensemble-averaged) energy density that linearly increases with depth from the front surface to about one mean free path ℓ, and then decreases linearly with depth to the back surface. Two main questions arise: (A) Can one increase (or decrease) the energy density? (B) What is the new position-dependence? Answers to these questions are crucial for light-matter interactions with applications to white LEDs, random lasers, solar cells, and biomedical optics.

Due to the inherent opaqueness, it seems hopeless to probe the internal 3D energy density by optical means. Recently, however, it was demonstrated that spontaneous emission of embedded fluorescent nanoparticles do report the energy density at the excitation wavelength; moreover, it was shown that the *overall* energy density increases by wavefront shaping [3]. Unfortunately, however, Ref. 3 lacks 3D position sensitivity. Moreover, studies on low-dimensional systems [4] (2D slabs or 1D waveguides) indicate that the energy density has a maximum near the centre of the slab. However, to unambiguously investigate how the 3D optical energy density is controlled by wavefront shaping, a 3D position-resolved measurement is outstanding.

Therefore, we report here on a wavefront shaping experiment on ZnO samples (ℓ=580 nm [2]). Dilute single fluorescent nanospheres probe the local energy density. The depth z of each single sphere is obtained by modelling the observed intensity pattern with diffusion theory for a point source. The wavefront is shaped to yield a bright spot at the back surface, which closely corresponds to the excitation of a so-called open transmission channel [5]. The resulting energy density enhancement is obtained from the ratio of the emitted fluorescence power measured with shaped incident wavefronts to that measured with reference wavefronts. Fig. 1 shows that results on a 3D sample with thickness $L/l = 28$ provide affirmative answers to both questions above: (A) the internal energy density is strongly redistributed by wavefront shaping. (B) The redistribution is strongly depth dependent. The energy density is enhanced compared to the diffusive case, and increases when approaching the back surface, contrary to 1D theory. In contrast, our newly developed 3D theory successfully models the data without adjustable parameters.

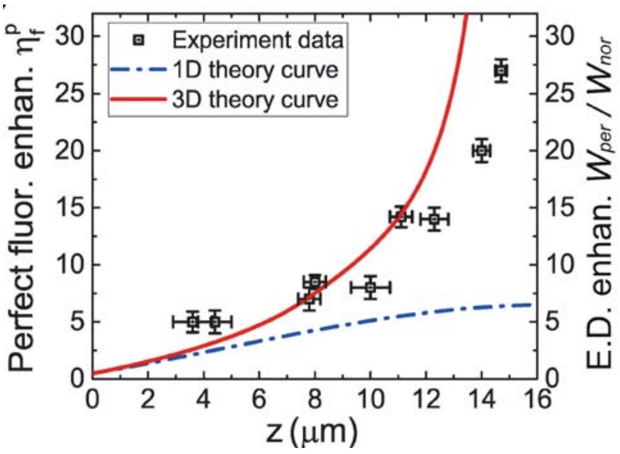

Fig. 1. Perfect fluorescence enhancement η_f^p versus depth z for a sample with thickness L = 16 μm. Black squares are measurements with error bars. The blue dash-dot curve is the energy density enhancement predicted by 1D diffusion theory. The red curve is the energy density enhancement predicted by our new parameter-free 3D theory.

References

[1] F. Sgrignuoli, *et al*., “Necklace state hallmark in disordered 2D photonic systems”, ACS Photonics, **2** 1636 (2015)

[2] A. Mohammadi, M. Agio, “Light scattering under nanofocusing: Towards coherent nanoscopies,” Opt. Commun. **285**, 3383 (2012).

[3] O.S. Ojambati, H. Yılmaz, A. Lagendijk, A.P. Mosk & W. L. Vos, “Coupling of energy into the fundamental diffusion mode of a complex nanophotonic medium," New J. Phys. **18**, 043032 (2016).

[4] W. Choi, A.P. Mosk, Q. Park & W. Choi, "Transmission eigenchannels in disordered media," Phys. Rev. B **83** 134207 (2011); M. Davy, Z. Shi, J. Park, C. Tian & A.Z. Genack, "Universal structure of transmission eigenchannels in opaque media,” Nat. Commun. **6** 6893 (2015); R. Sarma, A.G. Yamilov, S. Petrenko, Y. Bromberg & H. Cao, "Control of energy density in disordered media by coupling to open or closed channels," Phys. Rev. Lett. **117** 086803 (2016).

[5] I.M. Vellekoop & A.P. Mosk, "Universal optimal transmission of light through disordered media," Phys. Rev. Lett. **101** 120601 (2008).

978-1-5090-6736-7/17/$31.00 ©2017 European Union