Optimal Concentration of Light in Turbid Materials

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Compiled September 27, 2018

In turbid materials it is impossible to concentrate light into a focus with conventional optics. Recently it has been shown that the intensity on a dyed probe inside a turbid material can be enhanced by spatially shaping the wave front of light before it enters a turbid medium. Here we show that this enhancement is due to concentration of light energy to a spot much smaller than a wavelength. We focus light on a dyed probe sphere that is hidden under an opaque layer. The light is optimally concentrated to a focus which does not exceed the smallest focal area physically possible by more than 68%. A comparison between the intensity enhancements of both the emission and excitation light supports the conclusion of optimal light concentration.

In turbid materials such as white paint, biological tissue, and paper, spatial fluctuations in refractive index cause light to be scattered. Scattering is seen as a huge vexation in classical imaging techniques where it degrades the resolving power. [1] This decrease in resolution is caused by the fact that light carrying information about the fine spatial details of a structure has to travel further through the medium than the light carrying low spatial frequency information. [2] Due to the importance of imaging inside turbid materials, many researchers are trying to suppress turbidity. [3–8]

Although light scattering is detrimental to imaging, it is recently shown that scattering can be exploited to increase the amount of light energy deep inside turbid materials. [9] By spatially shaping the wave front of the incident light, the emission of a small dyed probe sphere hidden inside the turbid layer was strongly enhanced. Despite the fact that this enhancement proves an increase of excitation intensity at the probe position, it remains unclear what the spatial distribution of the excitation light is. From experiments with microwaves [10] and ultrasound [11] and recent far field experiments with light [12] it is known that scattering can be used to concentrate energy.

In this Letter we will experimentally show that we can also use scattering to focus light inside a turbid material to an optimal small spot, i.e, as small as it can physically be. The focus is created on a nano-sized dyed probe sphere hidden under a strongly scattering layer. A comparison between the intensity enhancements of the probe emission and the excitation light supports our conclusion of optimal light concentration.

Figure 1 shows the principle of our experiment. (a) Ordinarily a positive lens focusses an incident plane wave to a spot with a size that is limited by the numerical aperture (NA) of the lens. (b) A strongly turbid material behind the lens scatters the light so that no focus is formed. By matching the incident wave front to the scattering sample, we force constructive interference at

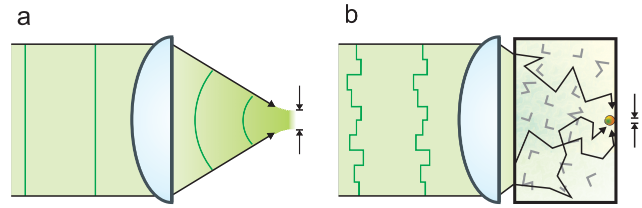

Fig. 1. Principle of the experiment. (a) A positive lens focusses a plane wave to a spot which is limited in size by the numerical aperture (NA) of the lens. (b) A strongly turbid material behind the lens scatters the light so that no focus is formed. By matching the incident wave front to the scattering sample, we force constructive interference at a target position inside the sample. The light now arrives from all directions at the target position, significantly increasing the NA of the system.

a target position inside the sample. At this position multiple scattered light arrives from all angles, significantly increasing the NA of the system. The focal size is no longer limited by the original lens, but can be minimized to the smallest spot size physically possible.

The possibility to focus light to a subwavelength spot inside scattering materials yields exciting opportunities. In biological imaging, for example, selective illumination of fluorescent areas with high resolution is highly desirable. The efficient light delivery to places inside scattering materials might also be used to study more fundamental properties of light transport in both ordered and disordered structures.

Our experiments are performed on opaque layers of strongly scattering zinc oxide (ZnO) pigment sprayed on top of a low concentration of dyed polystyrene spheres that will act as local intensity probes. We used probe spheres with a radius of R = 150 nm and R = 80 nm. ZnO is one of the most strongly scattering materials known and shows no fluorescence in the spectral region where the probes emit. The thicknesses of the scattering layers