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Few-cycle pulse propagation in multiple scattering media

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Abstract

The propagation of an ultrashort pulse (pulsewidth ~8 fs), comprised of few optical cycles, through a strongly scattering random medium is studied using Monte-Carlo simulations. The disordered medium is made up of passive high-index sub-wavelength sized alumina microspheres. The transmitted pulse decays non-exponentially, exhibiting a significant departure from typical diffusive profiles. This effect originates from the frequency response of the multiple scattering medium. A strong spectral shift in the transmitted pulse profile with time is observed, suggesting a positive chirp-like phenomenon in random media. The chirp depends upon scatterer size and degree of disorder, and not on the dispersive properties of the scatterer. The relevance of these investigations on biological imaging through turbid media is discussed, including the possibility of a novel gating technique to extract images from turbid media using few-cycle pulses.

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1. Introduction

The study of wave propagation through random media is of fundamental relevance to various fields, such as biomedical imaging, astronomy, atmospheric optics, and acoustics [1]. The application of light transport within random media to biomedical optics has attracted great attention in the last few years [2]. In a typical random medium, light is transported via multiple scattering off various scattering centers. When the scattering is sufficiently strong, interference effects become important and inhibit light transport leading to interesting phenomena such as enhanced backscattering or Anderson localization. In typical scattering systems, however, interference effects do not dominate. In such cases, wave transport is essentially treated within the diffusion approximation,

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where the light energy density is considered to obey the diffusion equation with a characteristic diffusion coefficient D [1]

$$\frac{\partial I(\mathbf{r},t)}{\partial t} = D\nabla^2 I(\mathbf{r},t) - \frac{v}{l_i} I(\mathbf{r},t) + S(\mathbf{r},t). \quad (1)$$

The second term on the right hand side describes absorption, where l_i is the absorption length and v is the transport velocity of light in the medium, and $S(\mathbf{r},t)$ is the source term. The sensitivity of the diffusion equation to the wavelength is evident from the fact that D, v and l_i are wavelength-dependent. Since the diffusion model has been successful in explaining a wide variety of phenomena observed in light scattering, the diffusion coefficient of light inside a material is studied as a key parameter of light propagation. Typically, time-resolved short-pulse propagation techniques have been utilised for performing various fundamental studies of light diffusion [3–5]. In these techniques, a short pulse is propagated into the random medium and the transmitted light is recorded (for example, on a streak camera) as a function of time. The temporal profile of the exiting light, or the temporal point spread function (PSF) is predicted by the diffusion theory as [6]

$$I_{tr}(t) = \frac{D}{\pi L^2} \sum_{n=1}^{\infty} n \left(\frac{\pi L}{L_{eff}}\right)^2 \sin\left(\frac{n\pi L}{L_{eff}}\right) \times \exp\left[-Dt\left(\frac{n\pi}{L_{eff}}\right)^2\right] \exp\left(\frac{-vt}{l_i}\right), \quad (2)$$

where $L_{eff} = L + 2z_0$. The parameter z_0 is the extrapolation length given by $0.71l^*$, l^* being the transport mean free path. In the long time limit, the transmitted intensity decays exponentially with a time constant $\tau = (L + 2z_0)^2/D\pi^2$ in the absence of absorption. Such a diffusive decay, a typical temporal PSF of a random medium, is one of the most fundamental properties of a multiply scattering medium.

To measure the temporal point spread function of any system, it needs to be ideally irradiated by a $\delta(t)$ function. An ultrashort pulse, comprised of a few optical cycles, is the closest available approximation to a $\delta(t)$ function. Due to rapid technological advancements, it has now become feasible to either create or compress pulses to durations comparable to very few oscillations of the carrier frequency [7,8]. The propagation of such pulses through various optical systems such as, for instance, vacuum, linear, non-linear and dispersive media has become a field of intense activity [9]. Perhaps the most significant property of few-cycle pulses is their super-broad bandwidth. Several interesting phenomena have been observed in a homogeneous medium that originate from its spectral response to the bandwidth [9]. However, in the context of inhomogeneous media, no such studies have been performed so far. Since the physics of scattering is strongly frequency dependent, an ultra-broad bandwidth is expected to introduce a vital parameter in the study of scattering. By virtue of the bandwidth, few-cycle pulses offer the possibility of studying the behaviour of random media when multiple frequency modes are simultaneously excited. This is expected to have significant consequences in various interesting phenomena observed in random media. Hence, the study of few-cycle pulses in random media merits attention.

A vast majority of theoretical studies on light transport through multiply scattering media have been done either analytically using the diffusion equation, or numerically through Monte-Carlo (MC) simulations based on photon transport [10–13]. For application of these techniques to few-cycle pulse propagation through scattering media, the large bandwidth of the pulse must be accounted for. A convenient method to involve the ultra-broad bandwidth is offered by the MC simulation technique. The MC technique involves a probabilistic calculation of photon migration from one scattering site to another, keeping track of various physical quantities [10]. Thus, multiple scattering is treated as a sequence of repetitive single scattering events, providing an accurate description of single photon trajectories. The collective behaviour of a large number of such single photon trajectories can accurately model diffusive propagation both in reflectance and transmittance [11].

In this paper, we investigate the transport of a few-cycle pulse (pulsewidth ~8 fs) in a random medium using MC simulations. This is, to our knowledge, the first study of the interaction of