PULSE TRANSMISSION AND DIFFUSIVE RADIATIVE TRANSFER THROUGH SCATTERING MEDIA

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INTRODUCTION

Radiative transfer through scattering media has attracted a great deal of interest recently, particularly for imaging applications through turbid media. Several techniques have been developed in order to determine the location of objects in strongly scattering biological tissues, using visible or near-infrared light[1]. Pulse transmission measurements on short time scales and optical coherence tomography give promising results[2]. Radiative transfer at short (time and length) scales is also a domain of growing interest with the rapid development of micro- and nano-technologies[3]. All these problems require a solution of the time-dependent radiative transfer equation (RTE) in a scattering medium.

In many applications, the diffusion approximation[4] is used to describe the non-ballistic part of the radiation intensity. Nevertheless, the domain of validity of this approximation at short scales has to be studied carefully. Moreover, although the diffusion approximation may be derived in different ways, the proper definition of the diffusion coefficient is still an open issue. In particular, its dependence on absorption was questioned recently[5].

In this work, we study the radiative transfer through strongly scattering slabs, in the presence of absorption. We solve the time-domain RTE using a discrete-ordinate scheme[6] in the frequency domain. We study the transmission and reflection of ultrashort pulses, and the transition towards the diffusive regime. Based on the modes decomposition of the discrete-ordinate method, we suggest a method to determine the diffusion coefficient which describes radiation transport in the asymptotic limit. We discuss the influence of both absorption and scattering anisotropy (phase function) on the diffusion constant.

PULSE TRANSMISSION

In order to study pulse transmission through strongly scattering slabs, we have developed a numerical scheme to solve the time-dependent RTE. The time-domain Fourier transform $I(\mathbf{r},\omega)$ of the specific intensity $I(\mathbf{r},t)$ obeys the time-independent RTE with an effective complex extinction coefficient. This equation is solved by a standard discrete-ordinate scheme. Both the ballistic beam and the diffuse intensity are accounted for. Once this problem is solved for a set of discrete frequencies, an inverse Fourier transform provides the transmitted or reflected specific intensity in a given direction. This method allows to deal with femtosecond light pulses, and to study its temporal spread over several orders of magnitude. Comparison with recent experiments is discussed. In particular, we study the long-time behavior of the transmitted and reflected pulses, and the transition towards the diffusive regime. We show that for thin

slabs (optical depth < 8), the diffusive regime is not reached, even for photons within the long-time tail of the pulse.

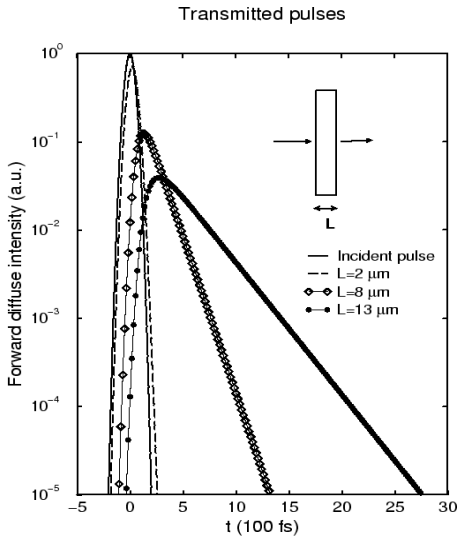

Figure 1. transmitted diffuse intensity through a slab containing TiO2 particles (radius 110 nm). Extinction coefficient β=1 μm^{-1}. Incident pulse : gaussian, with a width of 100 fs and a central wavelength λ=781 nm. The long-time exponential behavior of the pulse is clearly visible when the slab thickness L is larger than 8 μm. In this regime, the radiative transfer through the slab is diffusive.

PHOTON DIFFUSION COEFFICIENT

The diffusion approximation is very robust, in the sense that it can be derived from any transport theory as a limit when the spatial and temporal variations of the photon intensity are much larger than the mean free path and mean free time, respectively. However, all derivations do not necessarily lead to the same expression for the diffusion coefficient D. In particular, the dependence on absorption may change from one expression to the other. The correct prediction of this dependence is a crucial issue for imaging applications[5].

In the discrete-ordinate method, the specific intensity is written as a mode expansion. Each mode is caracterised by a decay length, and an amplitude describing its angular dependence. The decay lengths and amplitudes are eigenvalues and eigenvectors of an given operator[6]. In this approach, the diffusion approximation is obtained asymptotically, when only the mode with the larger decay length dominates[5]. We present a general method to define the diffusion constant, which is valid for any value of absorption and phase function. We show that $D=D_{P1}\ g_0$, where D_{P1} is the diffusion coefficient obtained from the P_1 approximation of the RTE and g_0 is a corretion factor. We compare this rigorously defined diffusion coefficient with coefficients obtained by other approaches, and show that it correctly accounts for the dependence on absorption and phase function.

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