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INFLUENCE OF ABSORPTION ON THE TIME OF FLIGHT OF THE LIGHT GOING THROUGH A COMPLEX MEDIUM

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ABSTRACT. The aim of this work is to evaluate the influence of absorption processes on the time of flight of light going through an absorbing and scattering thick medium (clouds, paints, gas cell, etc). In order to study statistical scattering and absorbing processes, we use a Monte-Carlo simulation code with temporal phase function and Debye modes. The main result is that absorption inside particles induces a decrease of the global time delay.

1. Introduction

The understanding of interaction between light and scattering dense media such as clouds, paints, biological tissues or gas cell is a major issue as far as optical diagnosis is concerned [1, 2, 3, 4]. In order to carry out such an investigation, model systems made up of spherical particles in suspension in a host medium have been widely studied [5, 6]. An important goal is to evaluate the time of flight (TOF) of light crossing such a medium for different reasons. First, TOF is a key criterion to isolate ballistic and scattered light (ballistic imaging [7, 8], optical density measurement of very thick media [9, 10]). Then, temporal scattering can be used to get information about the sample itself, either in the forward [11] or backward [12, 13] direction. Time of flight determination in absorbent media is not straightforward, and absorption tends to be strong when water based media in the IR, or more complex systems including absorbent organic molecules need to be studied.

The aim of this work is to evaluate the influence of absorption on the TOF of light going through an absorbent and scattering thick medium. The influence of absorption on temporal phase function will be presented.

2. Temporal phase function

The first step consists in determining the temporal phase function, *i.e.*, the probability for a photon to be scattered out of the particle with a given angle, and a given delay. Ultra short laser pulses (less than 100 *fs*) impinging on spherical particles are usually

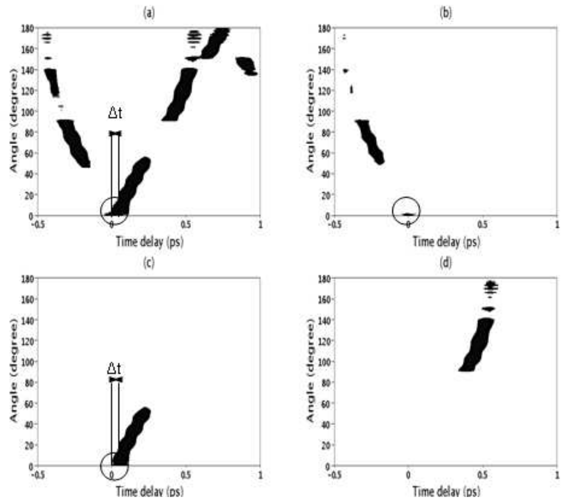

Figure 1. Normalized temporal phase functions ((a) total, (b) for mode 0, (c) for mode 1 and (d) for mode 2) of particle (n_{pa}=1.5) of 50 μm in water (n_{li}=1.33) obtained with a 100 *fs* pulse at λ=400 *nm*. The *x* axis denotes the time delay in *ps*. We report the angle on *y* axis. More than 80% of energy is contained in the 3 circles, *i.e.* in the forward direction. The mode 1 is delayed of Δt compared with the mode 0.

Table 1. Weight of the different Debye modes for spherical particle ((n_{pa}=1.5) of 9 μm in water at λ=800 *nm* for different cases ((a): k_{li}=k_{pa}=0, (b): k_{li}=0 and k_{pa}=0.005, (c): k_{li}=0.05 and k_{pa}=0)

	No absorption (a)	Absorbent particle (b)	Absorbent host medium (c)
Mode 0	50.06	99.98	0.37
Mode 1	48.06	0.02	99.22
Mode 2	1.52	0.00	0.41
Mode 3	0.37	0.00	0.00

considered[14]. For all studied wavelengths, the regular phase function is calculated, and the temporal phase function is obtained by Fourier Transformation (Fig. 1 (a)).

To understand the behaviour of the scattering process [18], we introduce Debye modes [15, 16, 17]. Different modes can be observed for different angles and time delays (Fig. 1 (b), (c), and (d)). Only the first two modes are representative of the scattering process. The mode 0, mainly directed in the forward direction, is a surface mode propagating along the interface host medium/particle. The mode 1 corresponds to the transmission of energy through the bulk of the particle. The latter mode is approximately delayed of $\Delta t = (n_{pa} - n_{li}) * \frac{D}{c}$, compared to the mode 0. *D* is the diameter of the particle, *c* the speed of light in vacuum, n_{pa} and n_{li} denote the refractive index of the particle and the host medium respectively.

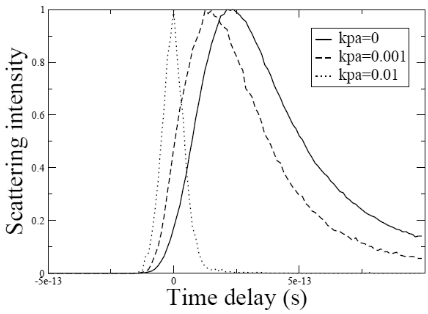

Figure 2. Global time delay for spherical particles ((n_{pa}=1.5) of 9 μm in water obtained with a 100 *fs* pulse at λ=800 *nm*, for different values of k_{pa} and for an optical thickness of 21.

3. Influence of absorption on time of flight

We have carried calculation of temporal phase functions for a significant and arbitrary absorption coefficient (imaginary part of the refractive index) either in the particle, k_{pa}, or in the host medium, k_{li}. The relative time delay of the Debye mode is not affected, contrary to the angular distribution. In order to evaluate the impact of absorption on the relative weight of different modes, we have calculated their energy with and without absorption in the particle and in the host medium (Table 1).

We note that the main part of the energy goes into modes 0 and 1 without absorption. Half of the photons are delayed (mode 1) relatively to the others (mode 0). The mode 1 becomes predominant for absorbent host medium, whereas mode 0 dominates for absorbent particles. Moreover, the angular distribution of the scattered light is broader for mode 1 compared to mode 0. Then, the trajectory of light, through the medium, will be less straight. As a result, the time of flight is even more increased when there is absorption in the host medium. On the other hand, if the medium is made of absorbent particles, the mode 0 is predominant, and the global TOF should be shorter.

In order to demonstrate the decrease of the global TOF when particles are absorbent, we use a Monte-Carlo simulation scheme. This complex process is simulated by a succession of elementary events (absorption in the particle, scattering). We report on Fig. 2 the normalized scattering intensity (without ballistic contribution) as a function of the global time delay for increasing values of k_{pa}.

We observed a strong decrease of the global time delay when k_{pa} increases. For strong k_{pa} (=0.01), the scattered light temporally overlaps ballistic light (the ballistic light temporal distribution, not represented here, is centred on zero-delay and has 100 fs linewidth (FWHM)) which is a major issue for isolation of ballistic imaging on strong optical density measurement.

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