ENHANCED FEMTOSECOND LIDAR BACKSCATTERING BY A LIQUID PARTICLE CLOUD

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ABSTRACT

The paper presents the preliminary results of the numerical solution (the Monte-Carlo method) of the nonstationary radiation transfer equation in the optically dense disperse medium. As a model of the medium, the presence of a homogeneous water cloud is assumed. It is expected that an ultra short (about 50 fs) and ultra intense laser pulse stimulates the nonstationary transition process in the scattering particle volume resulting in time transformation of their optical characteristics and, primarily, the scattering phase function. To calculate the time dynamics of the scattering phase function of a laser pulse by a transparent spherical particle the nonstationary Mie theory was used, based on the Fourier representation of the original light pulse and the linear theory of radiation diffraction at a sphere. In our case, the scattering particle properties are characterized by the spectral response function representing the traditional Mie series written for all the frequencies from the spectrum of the original pulse. The scattered and internal fields are written in the form of an integral of contraction from the pulse spectrum and the function of the spectral particle response.

1. INTRODUCTION

Laser radiation is special for its broadbandness. The spectral pulse width $\Delta\omega_p$ is proportionate to the pulse duration t_p and can make $\Delta\omega_p \sim 10^{15}$-$10^{16}$ Hz at $t_p \approx 10^{-14}$-10^{-15}s. So wide a frequency range enables a simultaneous excitation in a particle of a large number of high quality electromagnetic vibrational eigenmodes (the whispering gallery modes, the WG), which were recorded experimentally and then proved theoretically [1]. When the frequency of an optical wave incident on a particle coincides with one of the particle eigenmodes, this results in resonant excitation of the internal optical field, whose spatiotemporal distribution is fully determined by the field of the excited mode. The lifetime τ_R of most high-quality resonances (WG modes) in micron-sized particles is as a rule of the nanosecond order. Therefore, if the original pulse duration is comparable to or less than the time τ_R , then its scattering at a particle can have a nonstationary character.

2. GOVERNING EQUATIONS

The considered problem of the femtosecond pulse scattering at a microsized particle belongs to the problems of diffraction of nonstationary and, generally, inhomogeneous optical field at a dielectric sphere. Its traditional solution is the use of the spectral Fourier method in combination with the linear Mie theory. The nonstationary problem of diffraction of a broadband radiation is thus reduced to the stationary problem of scattering of a set of monochromatic Fourier harmonics at a spherical particle. Here, the scattering properties of the particle are described by the so-called spectral response function $\mathbf{E}_\delta(\mathbf{r};\omega)$, which represents the traditional Mie series written for all the spectral wavelengths of the original pulse [2]. A thorough description of the method considered in this paper and some of its numerical realizations can be found in [3,4] And here we restrict our consideration to listing the governing expressions. In our numerical calculations, we used the following representation of the electric field intensity of the incident linearly polarized radiation:

$$\begin{aligned}\mathbf{E}^i(\mathbf{r};t) &= \tfrac{1}{2}\left[\mathbf{E}^i(\mathbf{r};t) + \left(\mathbf{E}^i(\mathbf{r};t)\right)^*\right] = \\ &= \tfrac{1}{2}E_0\mathbf{e}_y g(t)\cdot S(\mathbf{r}_\perp)e^{i\omega_0(t-(z+a_0)/c)} + c.c.\end{aligned}, \quad (1)$$

where $g(t)$, $S(\mathbf{r}_\perp)$ are the temporal and spatial pulse profiles, respectively; ω_0 is the carrier pulse frequency; E_0 is the effective field amplitude; $\mathbf{r} = \mathbf{r}_\perp + \mathbf{e}_z z$; $r_\perp = \mathbf{e}_x x + \mathbf{e}_y y$; $\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$ are the unit vectors along the x, y, and z axes, respectively; t stands for the time; c is the light speed in vacuum. We assumed that a dielectric spherical particle with the radius a_0 is placed at the point of origin, and the laser pulse diffracting at it propagates positively along the z axis. The temporal and spatial profiles of the laser beam are set by the Gaussian functions:

$$g(t) = \exp\left\{-\frac{\left(t-(z+a_0)/c-t_0\right)^2}{t_p^2}\right\}; \quad S(\mathbf{r}_\perp) = \exp\left\{-\frac{\left(x^2+y^2\right)}{w_0^2}\right\} \qquad (2)$$

where t_p, t_0 stand for the pulse duration and time delay; w_0 is the spatial beam half-width.

The first step in solving this problem is translation from time coordinates to spectral frequencies using the Fourier representation of the original optical pulse $G(\omega)$:

$$\mathbf{E}^i_\omega(\mathbf{r},\omega) = \Im[\mathbf{E}^i(\mathbf{r},t)] = = \tfrac{1}{2}E_0\mathbf{e}_y S(\mathbf{r}_\perp)G(\omega-\omega_0)e^{-ik_0(z+a_0)}, \qquad (3)$$

where $\Im$ is the Fourier transform operator; $k_0 = \omega_0/c$.

Equation (3) multiplied by the exponent $e^{i\omega t}$ determines the spectral component in the original pulse as the monochromatic wave with the partial amplitude

$$\mathbf{A}(\omega) = E_0\mathbf{e}_y S(\mathbf{r}_\perp)G(\omega-\omega_0). \qquad (4)$$

Diffraction of this wave at a spherical particle is described within the stationary approximation of the Maxwell equations:

$$\mathrm{rot}\,\mathbf{E}_\omega(\mathbf{r};\omega) = -ik\mathbf{H}_\omega(\mathbf{r};\omega); \quad \mathrm{rot}\,\mathbf{H}_\omega(\mathbf{r};\omega) = i\varepsilon_a k\mathbf{E}_\omega(\mathbf{r};\omega), \qquad (5)$$

where $\mathbf{H}_\omega(\mathbf{r};\omega)$ is the vector of the magnetic field intensity; ε_a is the complex permittivity of particle matter; $k = \omega/c$. The boundary conditions on the spherical particle surface ($r = |\mathbf{r}| = a_0$) are set by the requirement of the cross-surface continuity of the tangential components of the internal field $\mathbf{E}_\omega, \mathbf{H}_\omega$:

$$\left[\mathbf{E}_\omega \times \mathbf{n}_r\right] = \left[\left(\mathbf{E}^i_\omega + \mathbf{E}^s_\omega\right)\times\mathbf{n}_r\right]; \quad \left[\mathbf{H}_\omega \times \mathbf{n}_r\right] = \left[\left(\mathbf{H}^i_\omega + \mathbf{H}^s_\omega\right)\times\mathbf{n}_r\right], \qquad (6)$$

where $\mathbf{n}_r$ is the vector of the outward normal with respect to the particle surface, and the subscript s refers to the scattered wave field.

Solution of Eq. (4) with account of Eqs. (4) and (6) and description of the spatial profile of the light beam by the Gaussian function (2) gives the following expression for scattering intensity of a short optical pulse at a spherical particle:

$$I_s(r,\theta,\varphi;\mathrm{t}) = I_0\sum_{n=1}^{\infty}\sum_{m=-n}^{n}\left\{\left|a_{nm}(m_a a_0;t)\tilde{\mathbf{M}}^{(3)}_{nm}(\theta,\varphi)\right|^2 + \left|b_{nm}(m_a a_0,t)\tilde{\mathbf{N}}^{(3)}_{nm}(\theta,\varphi)\right|^2\right\},$$

where $\tilde{\mathbf{M}}^{(3)}_{nm}, \tilde{\mathbf{N}}^{(3)}_{nm}$ is the angular part of the spherical harmonics, and the time-dependent expansion coefficients $a_{nm}(m_a a_0;\mathrm{t})$ and $b_{nm}(m_a a_0;\mathrm{t})$ are determined by the following expressions:

$$a_{nm}(m_a a_0;t) = = \Im^{-1}\left[G(\omega-\omega_0)\hat{\mathbf{M}}^{(3)}_{nm}(kr)a_{nm}(m_a k a_0)\right]; \quad b_{nm}(m_a a_0;t) = = \Im^{-1}\left[G(\omega-\omega_0)\hat{\mathbf{N}}^{(3)}_{nm}(kr)b_{nm}(m_a k a_0)\right].$$

Here, $\hat{\mathbf{M}}^{(3)}_{nm}, \hat{\mathbf{N}}^{(3)}_{nm}$ is the radial part of the spherical harmonics.

4. CHARACTERISTICS OF NONSTATIONARY ELASTIC SCATTERING

In the numerical modeling, the complex particle refraction coefficient m_a and the laser radiation wavelength λ_0 were assumed to be $m_a = 1.33 - i\cdot 10^{-8}$;

λ_0 = 0.8 μm, which corresponds to, for example, water molecules exposed to Ti:Sapphire laser pulses. The frequency dispersion of the particle refractive index in the chosen wavelength range was neglected, the same as neglected were nonlinear optical effects of multiphoton ionization and multiphoton absorption.

The normalized scattering phase function of a water droplet in the femtosecond pulse field $I_S(q)$ is shown in Fig. 1. In this figure, we can see four time samples of the scattering phase function that correspond to three conditional phases of the scattering process, namely, the moment of in-particle penetration of ~ 10% of the original pulse energy (1), scattering of a half of pulse energy (2), and the moment of a complete outgo of the pulse from the particle (3).

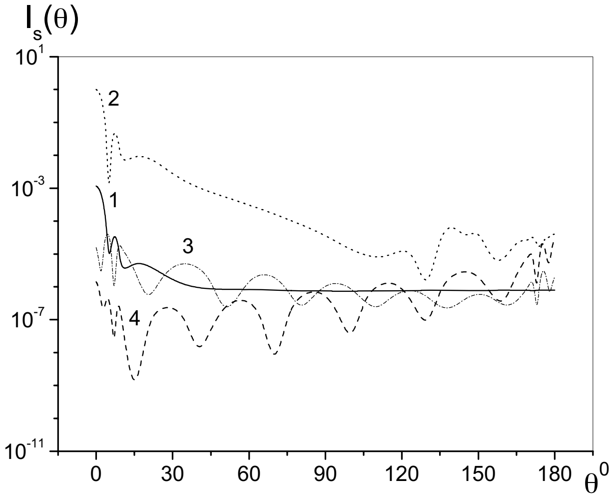

Fig. 1. The scattering phase function of a water droplet with a_0 = 5 μm irradiated by a 50 fs laser pulse at different time moments: $\bar{t} = t/t_p$ = 1 (*1*); 2 (*2*); 10 (*3*), and 20 (*4*).

We can see that the shape of the scattering phase function is different in each of the three phases. The first two phases give the most of a forward scattering, which is typical of a usual stationary optical scattering at an optically dense particle (the diffraction of a five-micron droplet at a 0.8 μm wavelength equals ~ 39). Note that the whole first phase (Curve 1) features no visible backscattering signal. It appears only at the end of the second phase (Curve 2). The third phase (Curves 3 and 4) has alternating forward and backward scattering peaks with a gradual decrease in their amplitude, which corresponds to pulsed lightning of the particle resonance modes, which have accumulated a part of pulse energy.

5. SOLUTION OF A TRANSFER EQUATION

The calculated characteristics of the nonstationary elastic scattering can be the basis for statement and solution of the problem of femtosecond radiation transfer in a finite volume of a liquid-droplet cloud medium. Formally, this implies solution of a nonstationary transfer equation with a time-dependent kernel. This is not a trivial problem. Our first numerical estimates [5] were based on the algorithm, where we combined the Monte-Carlo and the discrete ordinates methods. In the current calculations, the natural basis for discretization of the nonstationary transformation of the scattering phase function is the above phases of the electric field inside a particle. In our presentation, we report the statistical Monte-Carlo modeling that illustrates the optical field dynamics in a liquid-droplet medium exposed to an ultra short laser pulse and compare our results to a traditional solution. For the problem of laser sensing of clouds, of interest will be the expected variations of the time-resolved backscattering signal. Fig.2 (a, b) illustrates the calculated time dependence (in free photon path units) of the backscattering signal intensity $I(h, j_d)$ with respect to the receiving angle of a virtual lidar system. Case *a* reflects the situation when an a femtosecond (t_p = 50 fs) laser pulse is incident on a flat boundary of the scattering layer. Compare, case *b* corresponds to the standard stationary Mie scattering. The boundary conditions are approached to the real ones. A uniform 0.2 km thick scattering layer is positioned at a distance of 0.2. km. The scattering extinction coefficient corresponds to a liquid-droplet cloud with a narrow particle size spectrum, = 5 км$^{-1}$; absorption by particles is close to zero. The contribution of molecular scattering is ignored.

In the statistical modeling scheme, we use the method of local flux estmation. The shape transformation of the scattering phase function (Fig.1) is simulated by the tabular of inverse functions method at each step of the Markovian chain. Formal aspects of the Monte-Carlo calculation algorithm are considered by Yu. Geints *et al.* [4]. The main inference we have deduced from these results consists in the following: the nonstationary resonance scattering induced by an ultra short pulse at a spherical droplet, whose size is comparable to pulse duration, causes noticeable changes in the spatial configuration of the brightness field around the laser beam. Due to reduction in anisotropy of the resulting phase function there occurs a sharp increase in scattering in the location angles, which will certainly affect the quantitative interpreting of the lidar sensing data.

In conclusion, note that according to further estimates, in the real cloudiness conditions the enhanced lidar backscattering effect will not be so much expressed because of the leveling contribution of fine water droplet fraction, which falls outside the region of optical resonance. Besides, there are quite recent results [6] pointing out the possibility to considerably increase the imaginary part of the water refractive index in the region where the femtosecond pulse propagates. We find it wise to take this into consideration.

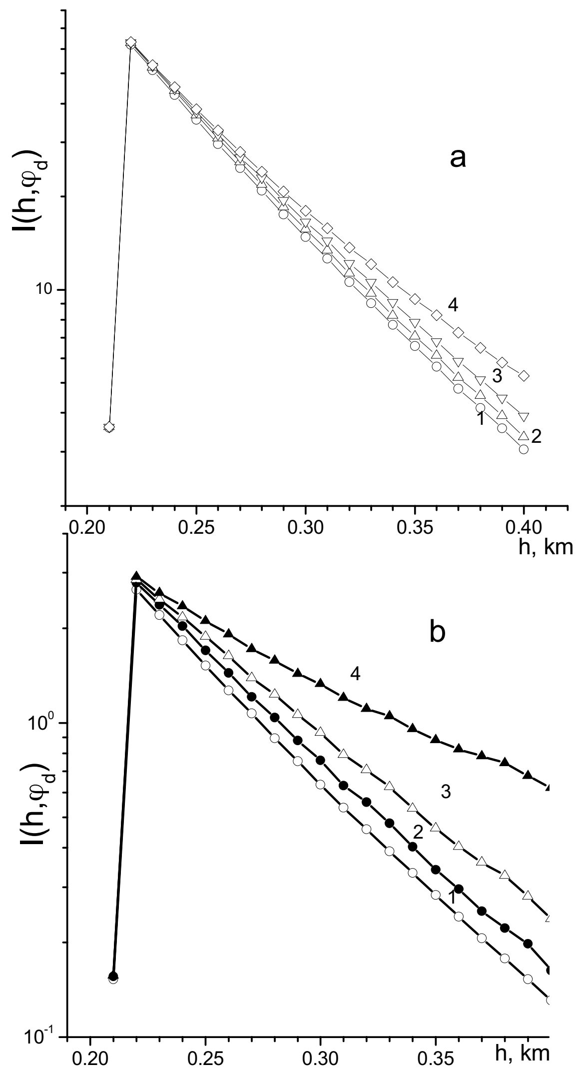

Fig. 2. Backscattering signal intensity depending on the receiving angle. 1- 4- $1/2j_d$= 0.5;10;17.5;175 *mrad*

7. REFERENCES

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