Fiber optics method for nanomaterials diagnostics

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Abstract. This paper analyzed the light induced lens response at the fiber optics scheme in transparent nanosuspension with electrostrictive nonlinearity. The theoretical analysis of the light-induced mass transfer in the nanosuspension was carried out for large intensities of the Gaussian beam radiation, when the concentration change is comparable to the primary. The nonlinear lens in this mode is the exponential function of the incident light intensity. The results are relevant to the study of the radiation self-action in the nanosuspension and optical diagnostics of such materials.

1. Introduction

Thermal lens technique is widely used for the optical diagnostics of materials [1-3]. The light-induced thermal lens in a homogeneous fluid is formed as a result of thermal expansion of a medium. In two-component fluid the heat flow also can cause concentration stream arising from occurrence of thermodiffusion (Soret effect [2]). Another mechanism of optical nonlinearity of the medium is due to the forces operating on the particles of the dispersed phase in gradient light field. Gradient electrostrictive forces may cause concentration streams in nanosuspension [4]. Depending on the sign of polarizability nanoparticles drift from areas with higher intensity of the electromagnetic wave (if their refractive index is more than one for liquid) [5]. This optical nonlinearity was studied experimentally and theoretically in nanosuspensions [5] and microemulsions [6] (artificial Kerr media). The nonlinear response corresponds to cubic nonlinearity for small intensities of radiation, because changing of the particle concentration (and effective refractive index) is proportional to radiation intensity [7].

The aim of this work is to analyze the light induced lens response at the fiber optics scheme in transparent nanosuspension at high intensities of radiation.

2. Light induced lens response

Let us take a single beam light lens fiber scheme [8]. In our scheme, two co-axis fibers are inserted to the optical cell with nanosuspension. The first fiber generates the Gaussian beam and the second one is connected with the photodiode to detect the passed beam power.

For a Gaussian beam we have the next distribution in a plane perpendicular to the optical axis $z$:

$$I = I_0 [1 + (z/l_0)^2]^{-1} \exp \{-r^2(z)/r_1^2(z)\},$$

(1)

$$r_1(z) = r_0 [1 + (z/l_0)^2]^{0.5},$$

(2)
where $I_0$ is the intensity of radiation on the axis in the plane of the beam waist, $\lambda$ is radiation wavelength, $r$ is the distance from the axis of the beam, $r_0$ is the radius of the beam waist, $r(z)$ is the radius of the beam at a distance $z$ from the beam waist, $I_0 = (\pi r_0^2 / \lambda)$ is the confocal parameter.

Thermal lens signal $\Theta(t)$ shows the change of the beam intensity $I(t)$ on the optical axis behind the nonlinear layer [7]:

$$\Theta(t) = \frac{I(t) - I(0)}{I(0)}.$$  (3)

The light lens signal is defined by the lens transparency of the cell [9]:

$$\Theta(t) = \frac{2(z_1 / I_0)F_{nl}(0,t)}{(1 + z_1^2 / I_0^2)(1 + 3z_1^2 / I_0^2)},$$  (4)

where the distance between the two fiber ends is $2z_1$, $F_{nl}(0,t)$ is nonlinear phase of the optical path on the beam axis.

3. Light induced mass transport task

We will consider the transparent nanosuspension under the influence of laser radiation with Gaussian intensity profile [9].

Balanced equation describing the dynamics of concentration of nanoparticles considering diffusion and electrostrictive flows can be written as [4]:

$$\frac{\partial C}{\partial t} = DC - \text{div}(\gamma CV),$$  (5)

where $C(r,t)$ is mass concentration of dispersed nanoparticles, $D$ is the diffusion coefficient, $\gamma = 4\pi\beta D(\bar{\varepsilon}nk_BT)^{-1}$, $\beta$ is the particle polarizability, $k_B$ is the Boltzmann constant, $n$ is effective refractive index, $\bar{\varepsilon}$ is the speed of light in vacuum, $I(r)$ is the intensity of radiation.

The source in (4) is due to the gradient force $F_V$ by the electric field of the light wave [5]:

$$F_V = 4\pi\beta\nabla I / \bar{\varepsilon}n.$$  (6)

In the stationary mode equation (5) takes the next form:

$$0 = DC - \text{div}(\gamma CV).$$  (7)

The general solution to the equation (6) is looking for in the form of:

$$C = B \exp\{I / I_s\},$$  (8)

where $I_s = \gamma D^{-1}$ is the “saturation” intensity, $B$ is the normalization constant.

Let us introduce dimensionless parameter of light intensity $\alpha = I_0I_s^{-1}$. For small intensities of radiation the change of the particle concentration is proportional to the radiation intensity ($\alpha \ll 1$).

The constant of normalization $B(\alpha)$ is given from conservation of particle number:
\[ \int_0^R C2\pi rdr = \pi R^2 C_0, \quad (9) \]

where \( R \) is the radius of the cylindrical cell, \( C_0 \) is the initial concentration of dispersed particles.

The concentration dependence versus the distance from the axis of the beam \( \rho = (r/r_0) \) was calculated for \( R/r_0 = 5 \).

Figure 1 shows that the concentration of the nanoparticles \( C_{st} = C/C_0 \) on the axis of the optical beam depends exponentially versus the beam intensity (as opposed to the usual cubic nonlinearity).

\[ \frac{C}{C_0} \text{ vs } \rho \]

**Figure 1.** The concentration of nanoparticles \( C_{st} = C/C_0 \) (a.u.) versus distance \( \rho \) (a.u.) from the axis of the beam for different values of the intensity of the light: \( \alpha_1 = 0.5 \); \( \alpha_2 = 1 \); \( \alpha_3 = 2 \).

The nonlinear phase \( F_{nl}(0) \) is proportional to the change of the concentration \( \Delta C_{st} \) on the axis of the beam (for the stationary regime):

\[ F_{nl} = 2d(\partial n/\partial C)C_0\Delta C_{st}, \quad (10) \]

\[ \Delta C_{st} = B(\exp \alpha - 1). \quad (11) \]

where \( \Delta C_{st} = (C_{st} - 1) \).

Figure 2 plots the change of the concentration \( \Delta C_{st} \) on the axis of the beam versus normalized intensity \( \alpha \).
Figure 2. The change of the concentration $\Delta C_{st}$ on the axis of the beam versus normalized intensity $\alpha$ (—). The linear dependence $\Delta C_{st} = \alpha$ is shown for comparison (—). 

In nanosuspension the particle radius is much smaller than the radiation wavelength $\lambda$, therefore the refractive index of the medium is proportional to the concentration of particles [8]:

$$n = n_1(1 + f\delta),$$

where $\delta = (n_2 - n_1)/n_1$; $n_1$ and $n_2$ are the refractive indices of the substance and the dispersion medium of the dispersed phase, respectively; $f = v_0C$ is the volume fraction of the dispersed phase, $r$ is the radius of the nanoparticle, $v_0 = (4/3)\pi r^3$ is the volume of the one nanoparticle, $C$ is the concentration of nanoparticles.

$$F_{nt}(0) = 2dn_1v_0\delta C_0\Delta C_{st},$$

Thus, the expression for stationary response was achieved for the light induced lens response in nanosuspension. As the lens grows exponentially, it is fair to call it "super lens".

4. Conclusions

The light induced lens response is analyzed in the fiber optics scheme. We have analyzed the two-dimensional diffusion in the nanosuspension with electrostrictive nonlinearity in a Gaussian beam radiation field. As a result the exact expressions were achieved for the light induced lens response in nanosuspension.

The analysis gives you the ability to determine not only concentration of nanoparticles, but also the transport coefficients of nanoparticles [10-12]. The results are relevant to optical diagnostics of dispersed liquid nanomaterials, including the thermal lens spectroscopy [13-15].

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