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Light lens response in nanofluid

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Abstract. The light lens response in transparent nanosuspension with electrostrictive nonlinearity was analyzed. The theoretical analysis of the light-induced heat and mass transfer in the nanosuspension was carried out for the Gaussian beam radiation, when the concentration change gives rise to the thermal response due to the Dufour effect. The results are relevant to the study of the radiation self-action in the nanosuspension and optical diagnostics of such materials.

1. Introduction

Nonlinear optical methods are used successfully for the diagnostic of the nanomaterials [1-3]. The noncontact methods for determining the kinetic coefficients of such media are useful in the critical conditions (for example, near the phase transitions) and so they are very interesting instruments for investigators [3-5]. The light-induced thermal lens in a homogeneous fluid is formed as a result of thermal expansion of a medium. The optical nonlinear response of the nanosuspensions includes the parameters of the nanoparticles. The thermodiffusion effect (Soret effect) in the binary mixtures was experimentally investigated by the optical nonlinear methods in many works [6]. 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 [7]. This optical nonlinearity was studied experimentally in nanosuspensions and microemulsions [8-10].

The purpose of this work is the theoretical analysis of the contribution of the Dufour effect to the light induced lens response in the transparent nanosuspension with the electrostrictive nonlinearity.

2. Electrostrictive mechanisms of the cubic nonlinearity in nanosuspension

The coefficient of cubic nonlinearity for the electrostrictive mechanism is determined by the concentration nonlinearity:

$$n_2^{eff} = (dn/dC)(dC/dI) \quad (1)$$

Where n is the refraction index of the medium, I is the radiation intensity, C is the concentration of nanoparticles, $n_2^{eff} = (dn/dI)$ is the coefficient of effective cubic nonlinearity.

In nanosuspension the particle radius is much smaller than the radiation wavelength λ , therefore the refractive index of the medium is proportional to the concentration of particles [4]:

$$n = n_1(1 + f\varepsilon), \quad (2)$$



where $\varepsilon = (n_2 - n_1)/n_1$; n_1 and n_2 are the refractive indices of the liquid and the dispersed phase, respectively; $f = v_0 C$ is the volume fraction of the dispersed phase, a_0 is the radius of the nanoparticle, $v_0 = (4/3)\pi a_0^3$ is the volume of the nanoparticle.

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

$$\frac{\partial C}{\partial t} = D\Delta C - \text{div}(\gamma C \nabla), \quad (3)$$

where D is the diffusion coefficient, $\gamma = 4\pi\beta D(\bar{c}nk_B T)^{-1}$, β is the particle polarizability, k_B is the Boltzman constant, \bar{c} is the velocity of light in vacuum, $I(r)$ is the intensity of radiation.

The transparent nanosuspension is under the influence of laser radiation with Gaussian intensity profile [2]:

$$I = I_0 e^{-r^2/r_0^2}, \quad (4)$$

where I_0 is the radiation intensity on the beam axis, r is the radial distance from the beam axis, r_0 is the beam radius.

This equation can be linearized in the case of low concentrations ($C \ll 1$):

$$(C(r,t) = C_0(1 + C'(r,t)), C'(r,t) \ll 1). \quad (5)$$

The exact solution of the equation (7) for this case can be written as [8]:

$$C(r,t) = C_0 \left\{ 1 + \delta \frac{r_0^2}{4D} \left(\exp\left[-\frac{r^2}{r_0^2}\right] - \frac{r_0^2}{r_0^2 + 4Dt} \exp\left[-\frac{r^2}{r_0^2 + 4Dt}\right] \right) \right\}, \quad (6)$$

where C_0 is initial mass concentration of dispersed particles, $\delta = 4\tilde{I}_0\gamma r_0^{-2}$, $\tau_D = r_0^2/4D$ is the diffusion time.

3. Dufour effect in the Gaussian light field

Dufour effect describes a heat flow when there is a stream of one component of a binary system [5]. Induced radiation modification of particle concentration leads to heat flow. This kind of phenomena in linear non-equilibrium thermodynamics is called cross-effects and is described by the balanced equations [11]:

$$c_p \rho \frac{\partial T}{\partial t} = \lambda \nabla^2 T + \rho_1 T \mu_{11}^c S_T \left(\frac{\partial C}{\partial t} \right), \quad (7)$$

where T is the fluid temperature, c_p, λ are thermal constants, ρ is the density of the material, $\mu_{11}^c = \frac{\partial \mu_1}{\partial C}$, μ_1 is the chemical potential of dispersed phase, S_T is Soret coefficient, D is the diffusion coefficient.

The second term in equation (7) is related to that part of the heat flow, which occurs as a result of the particles flow in the system (Dufour effect).

Using equation (6) the heat problem is:

$$\frac{\partial T}{\partial t} = a \nabla_r^2 T + b C_0 \frac{\delta r_0^4}{(r_0^2 + 4Dt)^2} \left(1 - \frac{r^2}{r_0^2 + 4Dt} \right) \exp \left[-\frac{r^2}{r_0^2 + 4Dt} \right], \tag{8}$$

$$T(r,0) = T_0, \quad \frac{\partial T}{\partial r} \Big|_{r=0} = 0. \tag{9}$$

where $a = \lambda(c_p \rho)^{-1}$ is the thermal conductivity, $b = \rho_1 T \mu_{11}^c S_T C_0 (c_p \rho)^{-1}$.

The resulting expression describes the temperature dynamics of optically transparent nanofluid influenced by Gaussian beam:

$$T(r,t) = T_0 + C_0 \frac{b \delta r_0^4}{a} \left\{ \frac{1}{r_0^2 + 4Dt} \exp \left[-\frac{r^2}{r_0^2 + 4Dt} \right] - \frac{1}{r_0^2 + 4at} \exp \left[-\frac{r^2}{r_0^2 + 4at} \right] \right\}. \tag{10}$$

where $\tau_{th} = r_0^2 / 4a$ is the thermal relaxation time.

It is easy to see that $T(r,t)$ as a function of time has a maximum. The appropriate time value t_m in beam center ($r = 0$) is:

$$t_m = r_0^2 / \sqrt{aD}. \tag{11}$$

4. Light lens response

Let's take a two beam thermal lens scheme (see Figure 1). The reference (Gaussian) beam generates the thermal field in the optical cell with nanosuspension. The second (Gaussian) beam tests the light lens.

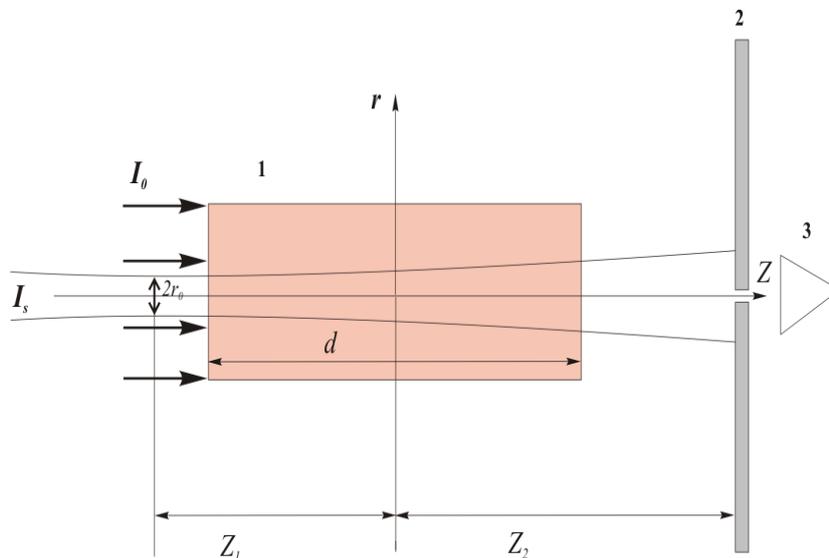


Figure 1. A light lens scheme (1 - the optical cell, 2- the screen with a pinhole, 3- the photodetector). The light lens signal shows the change of the beam intensity $I(t)$ on the optical axis behind the screen:

$$g(t) = \frac{I(t) - I(0)}{I(0)} \quad (12)$$

where $I(0)$ is the beam intensity on the optical axis behind the screen at the starting point. The term for the lens transparency of the cell is used to calculate the light lens signal [5]:

$$g_{st} = -\frac{2(z_1/l_0)\Phi_{nl}(0)}{(1+z_1^2/l_0^2)(1+3z_1^2/l_0^2)} \quad (13)$$

Where z_1, z_2 are the distances from the cell centre to the Gaussian beam waist and to screen, respectively (fig. 1), $l_0 = \pi r_0^2 / \lambda$ is the confocal parameter, r_0 is the radius of the Gaussian beam waist, $\Phi_{nl}(0)$ is the nonlinear phases in optical cell on the beam axis.

Nonlinear phase consists of two deposits: the first appears due to thermal expansion of the liquid phase and the second is associated with a change in the concentration of dispersed particles:

$$\Phi_{nl}(0) = \Phi_T(0) + \Phi_C(0) \quad (14)$$

$$\Phi_T(0) = k \int_0^d \left(\frac{\partial n}{\partial T} \right) \Delta T(z, r=0) dz \quad (15)$$

$$\Phi_C(0) = k \int_0^d \left(\frac{\partial n}{\partial C} \right) \Delta C(z, r=0) dz \quad (16)$$

Where $k = 2\pi/\lambda$ is the wave vector of the probing beam, d is the thickness of a layer of the fluid.

The obtained results (6,10) allow us to calculate the summarized light induced lens response (for nonlinear phases):

$$\Phi_{nl} = n_1 d \delta \left\{ f_0 D^{-1} [1 - (1 + 4Dt / r_0^2)^{-1}] + (\partial n / \partial T) C_0 b a_0^{-1} (1 + 4Dt / r_0^2)^{-1} \right\} \quad (17)$$

where $(\partial n / \partial T)$ is the fluid parameter.

The last expression is received for the time $t \gg \tau_{th}$. The second term is characterized by the negative sign and reduces the whole lens response. But this contribution disappears in the stationary state.

Thus, the expression was achieved for the light induced lens response in the nanosuspension.

5. Conclusions

The two-dimensional diffusion in the nanosuspension with electrostrictive nonlinearity in a Gaussian beam of radiation was analyzed taking into account the Dufour effect. The Dufour effect leads to the existence of the thermal contribution to the lens response in the transparent nanosuspension which disappears in the stationary state.

The expression was received for light induced lens response in nanosuspension. The results are relevant to nonlinear optics of nanosuspension [9-11], including the optical diagnostics of such nano-materials [12-15].

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