The use of motion peculiarities of particles of the Rayleigh light scattering mechanism for defining the coherence properties of optical fields

Claudia ZENKOVA*, Iryna SOLTYS, Pavlo ANGELSKY

Chernivtsy National University, Kotsyubinsky, 2, Chernivtsy, Ukraine

*Corresponding author: zenkova@itf.cv.ua

The paper proposes an alternative possibility for using the motion dynamics of tested particles of the Rayleigh light-scattering mechanism for estimating the degree of coherence of mutually orthogonal fields. The velocity of nanoparticles motion in the inhomogeneous optical field is chosen as the measuring parameter for diagnostics. The direct connection between the velocity of nanoscale particle motion and the degree of coherence of interacting fields is analytically demonstrated.

Keywords: degree of coherence, nanoparticles, Poynting vector, light scattering.

1. Introduction

Reasoning from the modern tendencies for developing nanotechnologies, much attention is given to studying the behavior of micro- and nanoparticles and to controlling them. This process finds its realization in creating micromanipulators and micromachines. The trapping and transportation [1] of particles, molecules, atoms, biological objects, such as DNA molecules, organelle cells, also widen the potentialities of biomedicine for diagnosing the pathology of human organs [2, 3]. As a rule, beams of various nature, such as Gaussian beams [4], bottle beams [5], zero-order Bessel beams [6], self-focused laser beams [7] and even evanescent fields [8, 9], which reflect different forms of energy circulation, are used for given purposes. The variety of wave fronts with polarization and phase singularities [10–13] allows to extend significantly the possibilities to investigate and control nanoparticles of organic as well of inorganic origin.

The formation fields, where the redistribution and circulation of energy is observed, can take place in a simpler way as well. The given paper proposes a scheme of

interacting of two mutually orthogonal linearly polarized in the incidence plane waves, where the modulation of polarization occurs simultaneously with the modulation of the energy volume density in the observation plane [14].

In this case the modulation depth essentially depends on the degree of coherence of interacting waves. The mechanism of manipulating particles of the Rayleigh light scattering mechanism in the energy inhomogeneous optical field, taking into account the complex optical force affecting these particles, is proposed for investigation in this paper. The task of defining the degree of coherence of mutually orthogonal linearly--polarized plane waves by using the velocity of the particle motion in the created optical field is solved at the same time.

2. The statement of the problem

At present, optical traps and micromanipulators are created taking into consideration the basic properties of laser radiation when the components of the optical force compete with each other, *i.e.*, the components of radiation pressure, the scattering force and the gradient force [15]. The scattering force is proportional to the radiation intensity and acts in the direction of the incident laser beam. The gradient component acts in the direction of the gradient intensity. These components may create the stable point, which is localized near the focus. If one of the components is larger or smaller than the other one, the equilibrium point is missing and a directional particle motion is observed. Thus, the availability of field pressure, which is connected with the existence of the internal angular momentum of the field, results in the arising of the energy flux, because the momentum density and the density of the energy flux are proportional to each other [16]. The momentum of the field, which is passed on to a particle, causes the movement of that particle.

The calculation of the optical force, affecting particles of different light scattering mechanisms, depends on the sizes and properties of the tested particles as well as on the properties and characteristics of the optical field where the particles are localized.

We consider the particles, for which the Rayleigh light-scattering mechanism is applicable. There are particles, *i*) whose size (radius r) is much smaller than the light wavelength, or, according to the more accurate definition $r \ll \lambda/20$. In literature these particles are named Rayleigh particles [17]. The interaction of these particles with electromagnetic wave is described within the framework of the Rayleigh light scattering mechanism. In this case the approximation of the point dipole is introduced. *ii*) Particles whose size (radius) is defined as $\lambda/5$. The physical mechanism, setting the interaction of particles with the optical field, is explained in the context of the Rayleigh light scattering approximation, which agrees with the Mie theory.

A consideration of each component of the optical force and the calculation of the gradient, scattering and absorbing components is important for the given types of particles.

The instantaneous value of the Poynting vector sets is determined by the relation $\mathbf{S} = \mathbf{E} \times \mathbf{H}$. The density value of the energy current is

$$S \;=\; EH \;=\; w \frac{1}{\sqrt{\mu \varepsilon \mu_0 \varepsilon_0}}$$

where w is the energy of the electromagnetic field, $\varepsilon\,(\mu)$ are the values of the dielectric permittivity (magnetic permeability), $\varepsilon_0\,(\mu_0)$ are the values of the vacuum permittivity (vacuum permeability). As it is known, $w = 2w_E = 2w_H$, where the energy density of the electric field is $w_E = 0.5\varepsilon\varepsilon_0(\mathbf{E}, \mathbf{E})$ and the energy density of the magnetic field is $w_H = 0.5\mu\mu_0(\mathbf{H}, \mathbf{H})$.

The averaged value of the Poynting vector is the time-averaged distribution of the instantaneous value, taken over the whole period of time.

Let us consider the superposition of two plane waves W1, W2 of equal amplitudes polarized in the plane of incidence (Fig. 1), determine the averaged value of the electric (magnetic) energy density and the direction of the resulting wave propagation [18]. Let $\mathbf{E}^{(1)}(\mathbf{r}_1, t)\,(\mathbf{H}^{(1)}(\mathbf{r}_1, t))$, $\mathbf{E}^{(2)}(\mathbf{r}_2, t)\,(\mathbf{H}^{(2)}(\mathbf{r}_2, t))$ be the vectors of the electric (magnetic) fields for the first and second interacting waves. In this case, the vector of the resulting electric (magnetic) field in the registration plane at the point $\mathbf{r}$ is defined as $\mathbf{E}(\mathbf{r}) = \mathbf{E}^{(1)}(\mathbf{r}) + \mathbf{E}^{(2)}(\mathbf{r})$ $(\mathbf{H}(\mathbf{r}) = \mathbf{H}^{(1)}(\mathbf{r}) + \mathbf{H}^{(2)}(\mathbf{r}))$. We shall find the direction of the Poynting vector of the resulting wave $\mathbf{S} = \mathbf{S}^{(1)} + \mathbf{S}^{(2)} + \mathbf{E}^{(1)} \times \mathbf{H}^{(2)} + \mathbf{E}^{(2)} \times \mathbf{H}^{(1)}$, where $\mathbf{S}^{(1)}\,(\mathbf{S}^{(2)})$ are the Poynting vectors of the superposing waves. Since in the offered interference scheme waves W1 and W2 are mutually orthogonal, the direction of the resulting vector $\mathbf{S}$ is determined by the direction of the vector, which is obtained when summing over the Poynting vectors $\mathbf{S}^{(1)}$ and $\mathbf{S}^{(2)}$ of the initial superposing waves.

To find the distribution of the volume energy density, we use the matrix approach and define the mutual coherence matrix, which describes the field correlation in
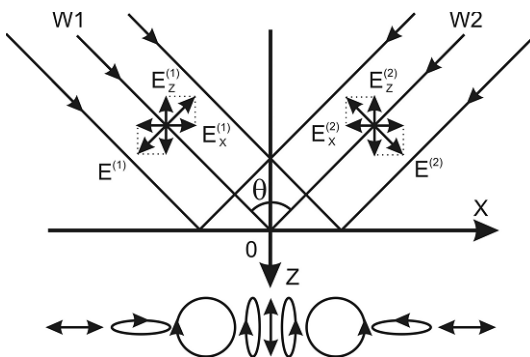

Fig. 1. The superposition of plane waves of equal amplitudes linearly polarized at the incidence plane, with an interference angle of 90°. Periodical spatial modulation of polarization [19–21] takes place in the plane of incidence.

two different spatial points $\mathbf{r}_1$ and $\mathbf{r}_2$ [22, 23]. It is defined as $W(\mathbf{r}_1, \mathbf{r}_2, t) = \langle E_i^{(1)}(\mathbf{r}_1, t) E_j^{(2)*}(\mathbf{r}_2, t) \rangle$, where $i, j = x, z$. In the given approximation, the components of the degree of mutual coherence of the field are determined as

$$\eta_{ij}(\mathbf{r}_1, \mathbf{r}_2, \tau) = \frac{W_{ij}(\mathbf{r}_1, \mathbf{r}_2, \tau)}{\sqrt{\text{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]}\sqrt{\text{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]}} =$$

$$= \frac{W_{ij}(\mathbf{r}_1, \mathbf{r}_2, \tau)}{\sqrt{\sum_{ij} W_{ii}(\mathbf{r}_1, \mathbf{r}_1, 0) W_{jj}(\mathbf{r}_2, \mathbf{r}_2, 0)}} \tag{1}$$

Let us assume that $\tau = 0$. This enables us to estimate the spatial coherence of the optical field. We define the time-averaged density of the energy current at the point of observation $\mathbf{r}$ [24]

$$S = \frac{\sqrt{\varepsilon\varepsilon_0}}{\sqrt{\mu\mu_0}} \sum_{i,j} \left\{ \varphi_{ij}^{(1)}(\mathbf{r}) + \varphi_{ij}^{(2)}(\mathbf{r}) + \right.$$

$$\left. + 2\sqrt{\text{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\text{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]} \left|\eta_{ij}^{(1, 2)}\right| \cos\left(\alpha_{ij}^{(1, 2)}\right) \cos(\delta_e) \right\} \tag{2}$$

where $\varphi_{ij}^{(m)}(\mathbf{r}) = \langle E_i^{(m)}(\mathbf{r}, t) E_j^{(m)*}(\mathbf{r}, t) \rangle$, $m = 1, 2$; $i, j = x, z$; $\alpha_{ij}^{(1, 2)}$ is an argument of $\eta_{ij}^{(1, 2)}$ and determines the phase difference between i- and j-components of the field; δ_e is the phase difference between the beams (in this case their electrical parts) at the registration plane.

The distribution of the time-averaged density of the energy current in space, according to (1), determines the current value at different points of the registration plane and is unambiguously determined by the degree of coherence of the superposing waves $\eta^{(1, 2)}$. The direction of the resulting energy current is set by the direction of the Poynting vectors of these waves.

When accounting the superposition of two mutually orthogonal linearly polarized fields, the modulation of the averaged Poynting vector value, *i.e.*, the spatial modulation of the energy density, is noticed in the observation plane. The optical force, expressed by the Poynting vector, forms the particle distribution in this plane. Moreover, the change in the degree of coherence leads to the change in the modulation depth of the energy volume density, which, in its turn, determines the optical force value and the peculiarities of particle motion.

In the general case, the forces exerted on the particles by a laser beam depend on the properties of both the beam and the particles.

We consider the behavior of the tested particles in the inhomogeneous optical field, which, according to the experiment proposed in [18], are particles of golden hydrosol of about 1 and 100 nm size and are located at room temperature. The length of the irradiation wave corresponds to the wavelength of a semiconductor laser RLTMRL-III-635 ($\lambda = 635$ nm).The mechanical action of spin flows [25, 26] on the motion of particles is not analyzed in this paper.

Let us discuss the formation of the optical force $\mathbf{F}_{opt}$ affecting the tested particles. The direction of the optical force gradient component is stipulated by the distribution gradient of the energy volume density. The direction of the scattering and absorbing components is set by the direction of the energy flow propagation. At the same time, the direction of the reflecting component is set by the orientation of the particle surface.

The gradient component of the optical force, when the polarizability of the molecule $\alpha = \alpha' + i\alpha''$ is taken into consideration, can be calculated as $\mathbf{F}_{grad} = -0.5n\alpha'\nabla E^2$. The polarizability of the molecule α can be derived from the Clausius–Mossotti equation as $\alpha = 3V(\varepsilon_p - \varepsilon_m)/(\varepsilon_p + \varepsilon_m)$, where ε_p (ε_m) is the value of the dielectric permittivity of a gold particle (a surrounded medium) correspondingly. Taking into consideration that for golden particles in water $n = 0.32 + 2.65i$ [27], the real and imaginary parts of the dielectric permittivity are calculated using the Kramers–Kronig relations.

As it is known $\mathbf{S} = \dfrac{c}{4\pi}\sqrt{\dfrac{\varepsilon}{\mu}}\,E^2\mathbf{s}$, where $\mathbf{s}$ is a unit vector in the direction of propagation [28]. Or $S = \dfrac{c}{4\pi}\sqrt{\dfrac{\varepsilon}{\mu}}\,E^2$. Then $E^2 = \dfrac{4\pi S}{c}\sqrt{\dfrac{\mu}{\varepsilon}}$ and

$$\mathbf{F}_{grad} = -\frac{1}{2}n\alpha'\nabla E^2 = -\frac{2\pi n\alpha'}{c}\sqrt{\frac{\mu}{\varepsilon}}\,\nabla S \tag{3}$$

Thus, one can find the gradient of the field in the general case. The gradient of the arbitrary function can be calculated at any point of the plane, including the observation plane. It is known that the modulus of the gradient of an arbitrary function is equal to the greatest rate of changing the function in the chosen point. Thus, it is possible to calculate the gradient distribution of the volume energy density.

$\nabla S = \mathbf{i}\dfrac{\partial S}{\partial x} + \mathbf{k}\dfrac{\partial S}{\partial z}$, assuming that the distribution of the energy density is to take place in the plane x, z.

May the coordinate of the point in the region of the minimum values of the volume energy density be x_{min}, z_{min}. In order to define the value of the gradient ∇S at the arbitrary point m with coordinates x_m, z_m in the observation plane, the remoteness of the given point relative to the nearest point is marked off in the minimum energy region.

Then for the *m*-point we can write down

$$|\nabla S|_m = \sqrt{\left(\frac{\partial S_m}{\partial x_m}\right)^2 + \left(\frac{\partial S_m}{\partial z_m}\right)^2} = \sqrt{\left(\frac{\Delta S_m}{\Delta x_m}\right)^2 + \left(\frac{\Delta S_m}{\Delta z_m}\right)^2} =$$

$$= \Delta S_m \sqrt{\left(\frac{1}{\Delta x_m}\right)^2 + \left(\frac{1}{\Delta z_m}\right)^2}$$

where $\Delta x_m = x_{\min} - x_m$, $\Delta z_m = z_{\min} - z_m$, and $\Delta S_m = S_{\min} - S_m$.

$$S_{\min} = \frac{\sqrt{\varepsilon \varepsilon_0}}{\sqrt{\mu \mu_0}} \sum_{i,j} \left\{ \varphi_{ij}^{(1)}(\mathbf{r}) + \varphi_{ij}^{(2)}(\mathbf{r}) + \right.$$

$$\left. - 2\sqrt{\text{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\text{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]} \, \eta_{ij}^{(1,\,2)} \right\}$$

$$S_m = \frac{\sqrt{\varepsilon \varepsilon_0}}{\sqrt{\mu \mu_0}} \sum_{i,j} \left\{ \varphi_{ij}^{(1)}(\mathbf{r}) + \varphi_{ij}^{(2)}(\mathbf{r}) + \right.$$

$$\left. + 2\sqrt{\text{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\text{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]} \, \eta_{ij}^{(1,\,2)} \cos\left[(\delta_e)_m\right] \right\}$$

then it is possible to calculate

$$S_m = -2\frac{\sqrt{\varepsilon \varepsilon_0}}{\sqrt{\mu \mu_0}} \sum_{ij} \sqrt{\text{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\text{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]} \, \eta_{ij}^{(1,\,2)} \left\{ 1 - \cos\left[(\delta_e)_m\right] \right\} =$$

$$= \frac{\sqrt{\varepsilon}}{\sqrt{\mu}} K_m \sum_{ij} \eta_{ij}^{(1,\,2)}$$

Here $K_m = -2\left(\sqrt{\varepsilon_0}/\sqrt{\mu_0}\right)\sqrt{\text{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\text{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]} \left\{ 1 - \cos\left[(\delta_e)_m\right] \right\}$ is

the parameter, which characterizers the energy density value for the chosen point *m* of the optical field, and depends on the phase difference between the initial waves at the corresponding point. Thus, it can be written as $\Delta S_m = \sqrt{\varepsilon/\mu} \, K_m \eta^{(1,\,2)}$.

Then the value of the gradient component of the optical force in the scalar form is expressed as

$$(F_{\text{grad}})_m = -\frac{2\pi n \alpha'}{c} K_m \sqrt{\left(\frac{1}{\Delta x_m}\right)^2 + \left(\frac{1}{\Delta z_m}\right)^2} \, \eta^{(1,\,2)} \tag{4}$$

The effect of the gradient force is linked with the gradient of the energy volume density, and, correspondingly, with the value of the degree of coherence of interacting fields.

Accordingly to [17], using the Rayleigh approximation, it is possible to define the scattering and absorbing components of the optical force:

$$\mathbf{F}_{scat} = \frac{n}{c} C_{scat} \mathbf{S} \quad \text{where} \quad C_{scat} = \frac{k^4}{6\pi \varepsilon_0^2} |\alpha|^2, \quad k = \frac{2\pi}{\lambda}$$

$$\mathbf{F}_{abs} = \frac{n}{c} C_{abs} \mathbf{S} \quad \text{where} \quad C_{abs} = \frac{k}{\varepsilon_0} |\alpha''|^2$$

Thus

$$\mathbf{F}_{opt} = \mathbf{F}_{grad} + \mathbf{F}_{scat} + \mathbf{F}_{abs} \tag{5}$$

Depending on the relationship between the values of the gradient component of the optical force and the scattering or absorbing components, the particles are either trapped by the field or they move in the direction caused by the direction of the energy flow.

May the analyzed particles be situated in a viscous medium. Let us assume that the mixture consists of a viscous incompressible carrier phase and spherical particles, whose radius is r and whose mass is M.

When moving in the liquid, the particle experiences the friction force, which at the constant value of the velocity $\mathbf{v}$ is defined by the Stokes law as $\mathbf{F}_{st} = B\mathbf{v} = 6\pi \eta r \mathbf{v}$, where B is the particle friction coefficient, η is the dispersive medium viscosity, r is the particle radius. Then the equation of particle motion, under the effect of the optical force in the viscous medium, is put down as

$$M \frac{d\mathbf{v}}{dt} = \mathbf{F}_{opt} + \mathbf{F}_{st} \tag{6}$$

In the first approximation we ignore the Brownian motion of particles and believe that the particles were motionless before their bringing into the zone of the optical field effect.

We consider the particle m with the mass M and the radius r, which is situated at the point of the field with coordinates x_m, z_m, and write down the equation of motion for it in the scalar form

$$M \frac{dv_m}{dt} = -6\pi \eta r v - \frac{2\pi n}{c} \alpha' K_m \eta^{(1,\,2)} \sqrt{\left(\frac{1}{\Delta x_m}\right)^2 + \left(\frac{1}{\Delta z_m}\right)^2} +$$

$$+ (C_{abs} + C_{scat}) \frac{n}{c} S_m$$

When solving the obtained differential equation, we get

$$v_m(t) = \frac{1}{M}\left(e^{-\frac{6\pi\eta r}{M}t} + 1\right)\left\{\frac{2\pi n}{c}\alpha' K_m \eta^{(1,2)}\sqrt{\left(\frac{1}{\Delta x_m}\right)^2 + \left(\frac{1}{\Delta z_m}\right)^2} + \right.$$

$$- (C_{abs} + C_{scat})\frac{n}{c}\frac{\sqrt{\varepsilon\varepsilon_0}}{\sqrt{\mu\mu_0}}\sum_{i,j}\left\{\varphi_{ij}^{(1)}(\mathbf{r}) + \varphi_{ij}^{(2)}(\mathbf{r}) + \right.$$

$$\left.\left. + 2\sqrt{\mathrm{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\mathrm{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]}\,\eta_{ij}^{(1,2)}\cos\left[(\delta_e)_m\right]\right\}\right\}$$

As it is seen from this expression, the velocity value of each separate particle $v_m(t)$ depends on the position of the particle in the optical field.

We perform the averaging over the ensemble of particles localized in the optical field. Then the motion velocity of m particles averaged over the ensemble of the particles can be put down as

$$\bar{v}(t) = \frac{1}{M}\left(e^{-\frac{6\pi\eta r}{M}t} + 1\right)\left\{\frac{1}{m}\sum_m\frac{2\pi n}{c}\alpha' K_m \eta^{(1,2)}\sqrt{\left(\frac{1}{\Delta x_m}\right)^2 + \left(\frac{1}{\Delta z_m}\right)^2} + \right.$$

$$- \frac{1}{m}\sum_m\left[(C_{abs} + C_{scat})\frac{n}{c}\frac{\sqrt{\varepsilon\varepsilon_0}}{\sqrt{\mu\mu_0}}\sum_{i,j}\left\{\varphi_{ij}^{(1)}(\mathbf{r}) + \varphi_{ij}^{(2)}(\mathbf{r}) + \right.\right.$$

$$\left.\left.\left. + 2\sqrt{\mathrm{tr}\left[W(\mathbf{r}_1, \mathbf{r}_1, 0)\right]\mathrm{tr}\left[W(\mathbf{r}_2, \mathbf{r}_2, 0)\right]}\,\eta_{ij}^{(1,2)}\cos\left[(\delta_e)_m\right]\right\}\right]\right\} \qquad (7)$$

As can be seen from this equation, the influence of the degree of mutual coherence on the value of the averaged velocity of particle motion in the optical field is observed.

To obtain a direct connection between the averaged velocity of tested particles and the degree of coherence of superposing fields, we choose as an example such tested particles which are characterized by the following set of properties: the Rayleigh mechanism of light scattering is peculiar to them; the values of the scattering and absorbing components of the optical force affecting these particles are much smaller than the value of the gradient component of the optical force.

In this case, the value of the averaged motion velocity of nanoparticles in the optical field, or more precisely, the velocity of trapping the given particles by the field is

determined by the degree of mutual coherence of superposing fields and is written down as

$$\bar{v}(t) \;=\; \frac{1}{M}\left(e^{-\frac{6\pi\eta r}{M}t} + 1\right)\frac{2\pi n}{c}\,\alpha'\eta^{(1,\,2)}\frac{1}{m}\sum_{m}K_m\sqrt{\left(\frac{1}{\Delta x_m}\right)^2 + \left(\frac{1}{\Delta z_m}\right)^2} \qquad (8)$$

If to normalize the change of the averaged velocity with time to the maximum of the trapping velocity for each corresponding moment of time, obtained in the absolutely coherent field, we get

$$\bar{v}_{\text{rel}}(t) \;=\; \eta^{(1,\,2)} \qquad (9)$$

Thus, the relatively averaged motion velocity of nanometer range particles in the energy inhomogeneous optical field, created by the interaction of partially coherent optical fields converging at the angle of 90°, makes it really possible to estimate the degree of mutual coherence of these fields.

3. The results of simulation

Using the methods suggested in papers [14, 18, 22], we can demonstrate the motion of particles of various sizes in the optical field, formed by the superposition of coherent and partially coherent beams. To create a more complete picture of particle motion, it is necessary to take into consideration the set of forces acting on the side of the liquid, where the particles are maintained in suspension.

The optical field, in which the motion of different in nature particles can be observed, is the result of two plane waves with different degrees of coherence interacting in the proposed interference experiment. Though a homogeneous distribution of intensity is observed in the registration plane of the resulting field, the distribution of the Poynting vector can obtain an inhomogeneous character and essentially depend upon the degree of coherence of interacting beams.

Let us reproduce the full picture of particle motion in the optical field. The essential polarizability of golden particles and the availability of absorption determine the picture of particle motion: *i*) the redistribution of particles between the maximum and minimum regions in the energy inhomogeneous optical field, caused by the action of the optical field and *ii*) the further behavior of the particles in accordance with the size of particles and the relation between the components of the optical force. The initial conditions determine the distribution of particles by velocity at the beginning of the motion, *i.e.*, at the initial moments of time. Correspondingly, the resulting optical force and the full force, determining the particle motion, are due to the place of particle localization. The calculation of the resulting optical force is performed using Eq. (5). In this case, in the first approximation, the particles are considered motionless at the initial moment.

The analysis of the particle behavior we will begin with simulating the motion of tested particles whose size is about 100 nm.

In the case of incoherent interaction of plane waves in our interference experiment [18, 24] there is no spatial modulation of polarization in the observation plane. As suggested by these papers, the modulation of the Poynting vector is absent as well. The gradient component of the optical force, caused by the gradient of the Poynting vector value (the gradient of the volume energy density), does not change the direction of the particle motion. The particle motion of the offered simulated situation is explained by the presence of the resulting force, caused by the scattering and absorbing components of the optical force, which is closely linked with the radiation pressure and the viscous friction on the liquid side.

As an example, Fig. 2 demonstrates the distribution of the resulting optical force at the initial moment of time, affecting the particles of about 100 nm, localized in the energy inhomogeneous optical field. This field is formed by the superposition of waves whose degree of coherence is one. The length of the arrows set the averaged value of the Poynting vectors. The arrows connected with the particles show the direction of the effect of the optical force. The motion of particles takes place along the lines marked by these arrows.

The value of the resulting optical force affecting the tested particles is presented in Fig. 3. The graphical representations of the optical force (Fig. 3) are obtained by normalizing the force value at a certain moment of time to the force value obtained if absolutely coherent fields interact at the same moment of time.

In the given situation the particles move in the direction of the energy current propagation in the observation plane. The particle motion velocity depends on the relationship between the field momentum value and the viscous friction force.

The account of essential light absorption by golden particles determines the direction of the resulting optical force. The absorption component becomes important for
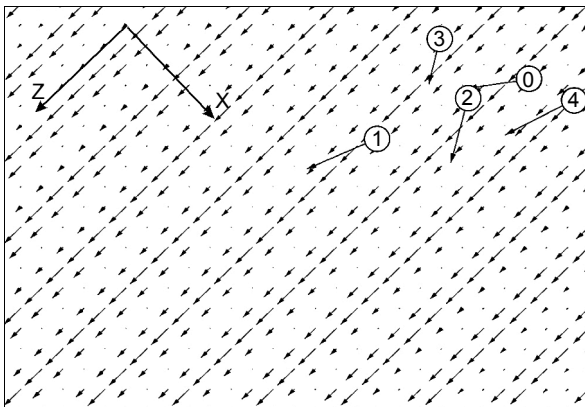

Fig. 2. The distribution of the resulting optical force in the energy inhomogeneous optical field, affecting the particles of about 100 nm.
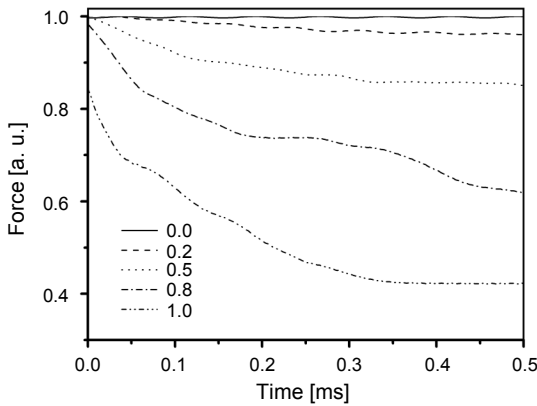
Fig. 3. Changes in resulting optical force affecting the Rayleigh particles observed with time and changing degree of coherence $\eta^{(1, 2)}$ of the interacting waves: the legend shows degrees of coherence that correspond to different curves.

the particles of the chosen size, and with the increase in the particle size, the actuality of the given component increases.

The change in the degree of coherence of the interacting waves leads to the change in the depth of the energy inhomogeneity of the optical field. The modulation of polarization and the modulation of the energy volume density are observed in the observation plane and lead to the arising of the gradient component of the optical force.

As a result, the increase in the degree of coherence produces the decrease in the resulting optical force (Fig. 3) acting on the type of particles under discussion.

Since the gradient force value is rather small in comparison with the other two components of the optical force, the value of this component is not enough to capture the particles. As a result, the particles, according to the main laws of thermodynamics, move to the region of the potential energy minimum. These zones are localized in the region of the Poynting vector energy minimum value (Fig. 2).

The particles continue to move there with the velocity, which is determined by the force whose components are the scattering and absorbing components of the optical force and the viscous friction force. The results of simulation fully justify the results of the experiment suggested in [14]. At the same time, the information of the gradient force value, which is due to the gradient volume density and the degree of coherence of superposing fields, is lost in the general picture of particle motion.

According to our mathematical model (Eq. (9)), to make a quantitative estimation of the degree of coherence of the optical field, we choose such particles, in which the gradient component of the optical force will be the defining the component of the motion. Let us analyze the behavior of about 1 nm sized particles. It is precisely these particles that are considered point ones and can be called Rayleigh particles. As the simulation results showed, with taking into account all components of the resulting optical force, the gradient force value gets much bigger than the values of other
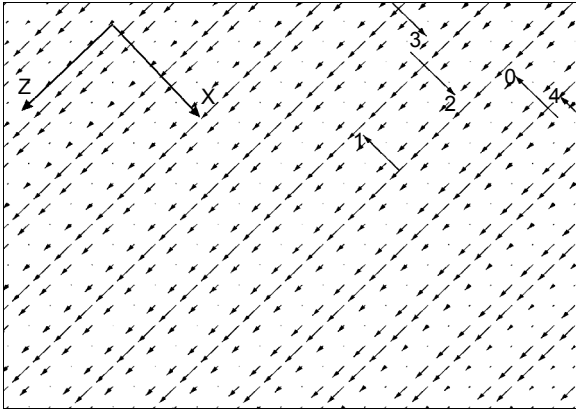
Fig. 4. The distribution of the resulting optical force in the energy inhomogeneous optical field, affecting the particles of about 1 nm.
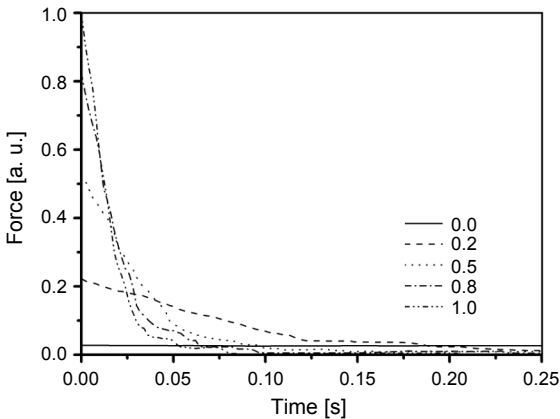

Fig. 5. The change in the optical force affecting Rayleigh particles with time and with the change in the degree of coherence of interacting waves $\eta^{(1, 2)}$: the legend shows degrees of coherence that correspond to different curves.

components. That is why the field gradient is able to move the particles into the maximum region, where the trapping takes place (Fig. 4). The disposition of particles is marked by numerals.

When the homogeneous optical field results from the incoherent interaction of two superposing fields (the distribution gradient of the energy value is absent), the optical field does not influence the particles (Fig. 5).

A greater modulation depth of the energy volume density corresponds to a greater value of the degree of coherence, and, consequently, the degree of the energy inhomogeneity of the optical field increases. Correspondingly, the influence of the gradient component of the optical force increases (Fig. 5).

The value of the optical force transverse component is sufficient to trap the nano-particles and keep them in the "capture" zone. In this case, depending on the initial position of the corresponding nanoparticles, the velocity with which the particles are trapped by the field will be different. The velocity value is also influenced by the gradient value of the energy volume density.

The motion velocity of nanoparticles depends on the distribution of the energy volume density in the observation plane, and, accordingly, on the degree of coherence of superposing waves. The change in the degree of coherence causes the change in the normalized value of the averaged velocity of particle redistribution in the optical field under the effect of optical forces and is trapped by this optical field (Fig. 6). The velocity graph presented in this figure is derived of Eq. (9). It describes the nor-malized value of the averaged particle motion velocity with time.

The maximum value of this velocity and, respectively, the maximum value of the resulting force are unequivocally related to the degree of coherence of the initial superposing beams, which form the optical field under investigation. For instance, the maximum normalized value of the averaged particle motion velocity is 0.8 (Fig. 6), the degree of coherence value is 0.8. Any changes in the degree of coherence of the superposing waves cause the change in both the normalized value of the averaged motion velocity and the maximum value of this velocity of particle "trapping" into the maximum energy region in the analyzed field. Thus, to the degree of coherence 0.5 corresponds the maximum normalized value of the averaged velocity of particle "trapping", which is equal to 0.5, *etc*.

As it is shown by the results of the computer simulation, the particles are practically immediately "trapped" into the region of the maximum gradient value of the Poynting vector. As a result, the maximum normalized value of the averaged motion velocity is realized in the initial moments of time. At the same time, nanoparticles, possessing
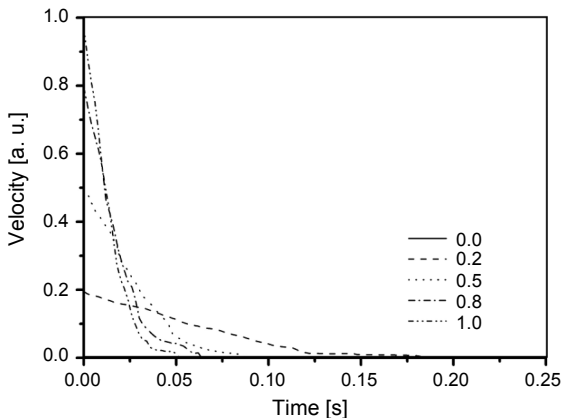

Fig. 6. The change in the normalized value of the averaged motion velocity of Rayleigh particles with time and with the change in the degree of coherence of interacting waves $\eta^{(1,2)}$: the legend shows degrees of coherence that correspond to different curves.
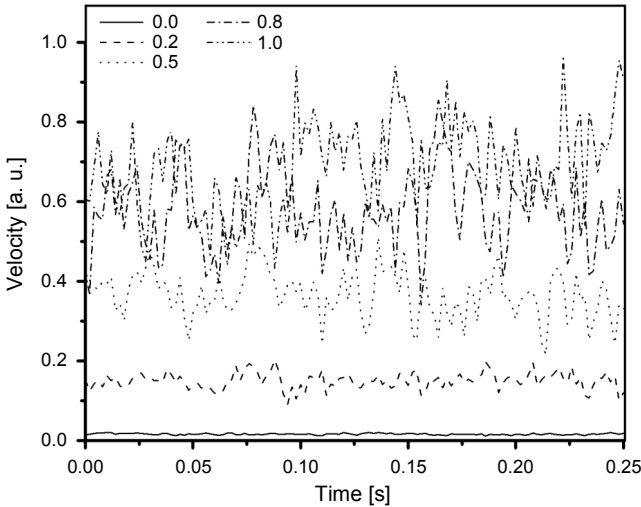
Fig. 7. The change in the normalized value of the averaged motion velocity of Rayleigh particles with time and with the change in the degree of coherence of interacting waves $\eta^{(1,\,2)}$, when Brownian motion of particles is taken into consideration: the legend shows degrees of coherence that correspond to different curves.

a certain mass, are characterized by some, say, insignificant inertia. Because of this, a certain period of time is necessary after "trapping", a period of "relaxation", for the particles to take a stable position. It is explained, firstly, by the progressive decrease of the velocity after "trapping", and, secondly, by the fact that the maximum motion velocity is chosen as the estimating criterion of the gradient of the field inhomogeneity and, consequently, of the degree of coherence.

The optical force, which causes the trapping of particles by the field, and the normalized value of the averaged velocity particle motion are connected directly with the degree of coherence of interacting fields. In this case, the particle motion velocity is a rather easy quantity for measuring and can be chosen as an estimating parameter of the degree of coherence of interacting fields.

At the same time, when random fluctuations of particle motion, caused by Brownian force action, are taken into consideration, the uniqueness of the particle motion velocity and the degree of coherence of the optical field are lost (Fig. 7). The Brownian motion masks the information about the coherence and polarization properties preset in the optical field under investigation.

4. Conclusions

A direct connection between the degree of coherence of mutually orthogonal linearly polarized fields and the normalized value of the averaged motion velocity of tested particles in the energy and polarization inhomogeneous optical field is obtained. It is shown that the motion of nanoparticles of the Rayleigh light scattering mechanism can

be used as an auxiliary instrument for defining the field coherence properties, where the classical methods cannot be applied.

References

[1] LI-GANG WANG, CHENG-LIANG ZHAO, LI-QIN WANG, XUAN-HUI LU, SHI-YAO ZHU, *Effect of spatial coherence on radiation forces acting on a Rayleigh dielectric sphere*, Optics Letters **32**(11), 2007, pp. 1393–1395.

[2] ANGEL'SKII O.V., USHENKO A.G., ARKHELYUK A.D., ERMOLENKO S.B., BURKOVETS D.N., USHENKO YU.A., *Laser polarimetry of pathological changes in biotissues*, Optics and Spectroscopy **89**(6), 2000, pp. 973–978.

[3] ANGEL'SKII O.V., USHENKO A.G., ARKHELYUK A.D., ERMOLENKO S.B., BURKOVETS D.N., *Scattering of laser radiation by multifractal biological structures*, Optika i Spektroskopiya **88**(3), 2000, pp. 495–498.

[4] ASHKIN A., DZIEDZIC J.M., BJORKHOLM J.E., CHU S., *Observation of a single-beam gradient force optical trap for dielectric particles*, Optics Letters **11**(5), 1986, pp. 288–290.

[5] CHING-HSU CHEN, PO-TSE TAI, WEN-FENG HSIEH, HSIEH W.F., *Bottle beam from a bare laser for single-beam trapping*, Applied Optics **43**(32), 2004, pp. 6001–6006.

[6] GARCÉS-CHÁVEZ V., ROSKEY D., SUMMERS M.D., MELVILLE H., MCGLOIN D., WRIGHT E.M., DHOLAKIA K., *Optical levitation in a Bessel light beam*, Applied Physics Letters **85**(18), 2004, pp. 4001–4003.

[7] JING YONG YE, GUOQING CHANG, NORRIS T.B., TSE C., ZOHDY M.J., HOLLMAN K.W., O'DONNELL M., BAKER J.R., *Trapping cavitation bubbles with a self-focused laser beam*, Optics Letters **29**(18), 2004, pp. 2136–2138

[8] OKAMOTO K., KAWATA S., *Radiation force exerted on subwavelength particles near a nanoaperture*, Physical Review Letters **83**(22), 1999, pp. 4534–4537.

[9] VOLPE G., QUIDANT R., BADENES G., PETROV D., *Surface plasmon radiation forces*, Physical Review Letters **96**(23), 2006, article 238101.

[10] ANGELSKY O., MOKHUN A., MOKHUN I., SOSKIN M., *The relationship between topological characteristics of component vortices and polarization singularities*, Optics Communications **207**(1–6), 2002, pp. 57–65.

[11] ANGELSKY O.V., BURKOVETS D.N., MAKSIMYAK P.P., HANSON S.G., *Applicability of the singular-optics concept for diagnostics of random and fractal rough surfaces*, Applied Optics **42**(22), 2003, pp. 4529–4540.

[12] ANGELSKY O.V., MAKSIMYAK P.P., RYUKHTIN V.V., HANSON S.G., *New feasibilities for characterizing rough surfaces by optical-correlation techniques*, Applied Optics **40**(31), 2001, pp. 5693–5707.

[13] ANGELSKY O.V., POLYANSKII P.V., HANSON S.G., *Singular-optical coloring of regularly scattered white light*, Optics Express **14**(17), 2006, pp. 7579–7586.

[14] ANGELSKY O.V., GORSKY M.P., MAKSIMYAK P.P., MAKSIMYAK A.P., HANSON S.G., ZENKOVA C.YU., *Investigation of optical currents in coherent and partially coherent vector fields*, Optics Express **19**(2), 2011, pp. 660–672.

[15] ASHKIN A., *Optical Trapping and Manipulation of Neutral Particles Using Lasers*, Singapore, Hackensack; NJ, World Scientific, 2006.

[16] BEKSHAEV A.YA, ANGELSKY O.V., SVIRIDOVA S.V., ZENKOVA C.YU., *Mechanical action of inhomogeneously polarized optical fields and detection of the internal energy flows*, Advances in Optical Technologies, Vol. 2011, 2011, article 723901.

[17] DIENEROWITZ M., MAZILU M., REECE P.J., KRAUSS T.F., DHOLAKIA K., *Optical vortex trap for resonant confinement of metal nanoparticles*, Optics Express **16**(7), 2008, pp. 4991–4999.

[18] ZENKOVA C.YU., GORSKY M.P, SOLTYS I.V., ANGELSKY P.O., *Possibilities of using inhomogeneity in light energy distribution for estimating the degree of coherence of superposing waves*, Applied

Optics **51**(10), 2012, pp. C38–C43.

[19] ANGELSKY O.V., YERMOLENKO S.B., ZENKOVA C.YU., ANGELSKAYA A.O., *Polarization manifestations of correlation (intrinsic coherence) of optical fields*, Applied Optics **47**(29), 2008, pp. 5492–5499.

[20] ANGELSKY O.V., ZENKOVA C.YU., GORSKY M.P., GORODYNS'KA N.V., *Feasibility of estimating the degree of coherence of waves at the near field*, Applied Optics **48**(15), 2009, pp. 2784–2788.

[21] ANGELSKY O.V., HANSON S.G., ZENKOVA C.YU., GORSKY M.P., GORODYNS'KA N.V., *On polarization metrology (estimation) of the degree of coherence of optical waves*, Optics Express **17**(18), 2009, pp. 15623–15634.

[22] ELLIS J., DOGARIU A., PONOMARENKO S., WOLF E., *Degree of polarization of statistically stationary electromagnetic fields*, Optics Communications **248**(4–6), 2005, pp. 333–337.

[23] MUJAT M., DOGARIU A., WOLF E., *A law of interference of electromagnetic beams of any state of coherence and polarization and the Fresnel–Arago interference laws*, Journal of the Optical Society of America A **21**(12), 2004, pp. 2414–2417.

[24] ZENKOVA C.YU., GORSKY M.P., MAKSIMYAK P.P., MAKSIMYAK A.P., *Optical currents in vector fields*, Applied Optics **50**(8), 2011, pp. 1105–1112.

[25] ANGELSKY O.V., BEKSHAEV A.YA., MAKSIMYAK P.P., MAKSIMYAK A.P., HANSON S.G., ZENKOVA C.YU., *Orbital rotation without orbital angular momentum: mechanical action of the spin part of the internal energy flow in light beams*, Optics Express **20**(4), 2012, pp. 3563–3571.

[26] ANGELSKY O.V., BEKSHAEV A.YA., MAKSIMYAK P.P., MAKSIMYAK A.P., MOKHUN I.I., HANSON S.G., ZENKOVA C.YU., TYURIN A.V., *Circular motion of particles suspended in a Gaussian beam with circular polarization validates the spin part of the internal energy flow*, Optics Express **20**(10), 2012, pp. 11351–11356.

[27] PALIK E.D., *Handbook of Optical Constants of Solids*, Academic, San Diego, 1985.

[28] BORN M., WOLF E., *Principles of Optics*, Pergamon, Oxford, 1980.