The Controlling of Nanoparticles by the Polarization Methods

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Abstract **– We present the results of computer simulation of spatial distribution of the Poynting vector and illustrate motion of nano and microparticles in spatially inhomogeneously polarized fields. The influence of phase relations and the degree of mutual coherence of superposing waves in the arrangements of two-wave and four-wave superposition on the characteristics of microparicle's motion has been analyzed.**

Index Terms **– Poynting vector, spatial modulation of polarization, optical currents.**

I. INTRODUCTION

One of the most actual tasks, connected with the appearance of laser, is to control microparticles of different nature by the help of laser irradiation. The object of controlling may be a colloid particle, a molecule, an atom, a cell, including a bioobject, e.g. a DNA molecule, an organelle cell. It can be said, that the technology of particle manipulating is a powerful tool for the work with microobjects of different nature. The process of trapping and controlling the particles depends on the properties of the laser beam. One of the basic conditions of particle manipulation by the help of these laser beams is their full coherence.

Experimental study and computer simulation of behavior of small spherical conducting particles embedded in optical fields provides deeper understanding of the role of the Poynting vector for description of optical currents in various media [1]. Accounting the modulation of waves polarized at the incidence plane in forming desirable spatial distributions of the averaged Poynting vector is the step to creation of polarization micromanipulators and tweezers. On the other hand, it is the step to finding out of optimal experimental investigation of optical currents in vector fields [2-5]. Besides, the study of spatial and temporal peculiarities of motion of particles embedded into optical fields with various spatial configurations and with various scale distributions of the Poynting vector inherent in both completely coherent and partially coherent fields leads to new techniques for estimating temporal coherence of optical fields [6].

Computation of the spatial distribution of the averaged Poynting vectors determining the forces affecting on microparticles and moving them is performed in this paper following the algorithm proposed by M. Berry [1] who has shown that the force affecting a small particle in optical field is proportional to the Poynting vector. On the other hand, it is shown that the study of motion of microparticles in inhomogeneously polarized fields provides reconstruction of the spatial distribution of the averaged Poynting vectors (optical currents).

The dependence of the force value influencing the particles upon the degree of coherence of interacting waves is shown.

II. TWO-WAVE SUPERPOSITION FOR CHANGEABLE DEGREE OF COHERENCE OF ONE COMPONENT

Superposition of two plane waves of equal amplitudes polarized at the incidence plane (Fig. 1a) results into distribution of the averaged over the oscillation period Poynting vector shown in Fig. 1b. Such distribution arises when the interference angle equals to 90°, and the only periodical polarization modulation of a field (in absence of intensity modulation) takes place at the observation plane.

Analysis of the spatial distribution of the averaged Poynting vectors shown in Fig. 1b reveals periodicity of this distribution, where the absolute magnitudes of vectors are proportional to the lengths of lines shown in the figure. The lines corresponding to singularities of the Poynting vector are also shown in this figure by the set of points [7-9]. Comprehensive notion on the mechanisms of formation of such distribution follows from the consideration of them both in statistics and in dynamics with the corresponding comments, which we formulate below *in thesis*.

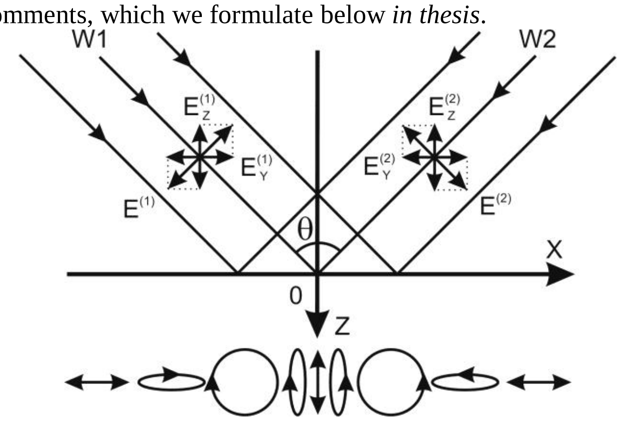

Fig. 1a. Superposition of plane waves of equal amplitudes linearly polarized at the incidence plane, with the interference angle 90°. Periodical spatial polarization modulation takes place at the incidence plane.

1. Light energy transfer is undulate in time and in space (Fig. 2). Here the vectors $\vec{E}$ and $\vec{H}$ are shown in blue and violet, correspondingly, and the Poynting vector is shown in black. The directions of oscillations of this vector are the direction of light energy transfer.

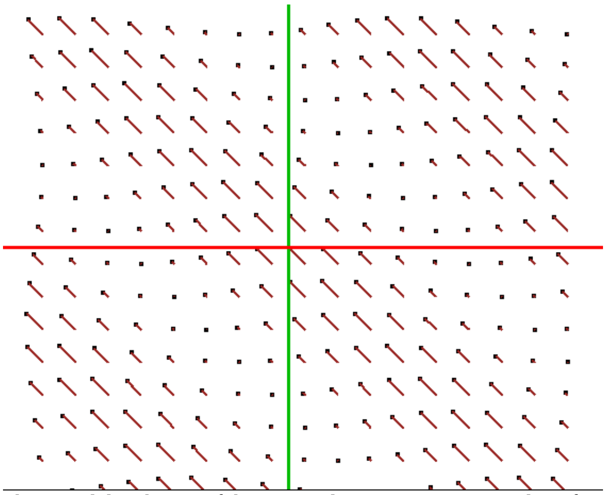

Fig. 1b. Spatial distribution of the averaged Poynting vectors resulting from superposition of two orthogonally linearly polarized waves with the interference angle 90°.

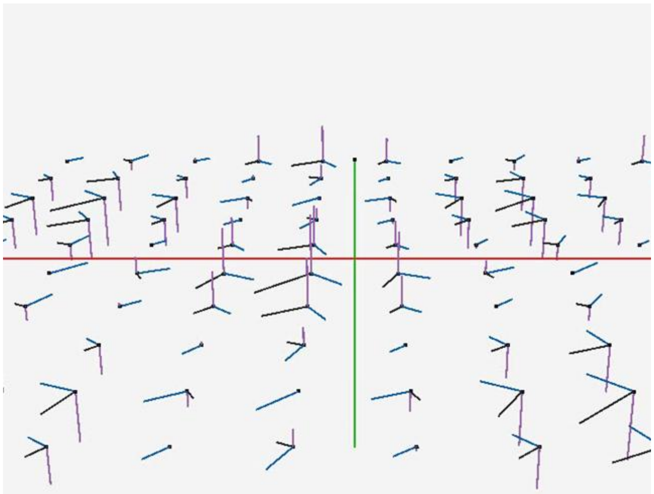

Fig. 2. It is illustrated wave-like light energy transfer in 2D field resulting from superposition of plane orthogonally polarized waves of equal amplitudes with the interference angle 90°. Energy transfer takes place along the bisectrix of the propagation directions of two waves at the incidence plane: the distribution of Poynting vector is presented in black color, of vector $\vec{E}$ in blue and $\vec{H}$ in violet.

2. Spatial distribution of the averaged over oscillation period Poynting vectors (Fig. 1b) is the map of the directions (trajectories) of energy transfer.

3. The points at the map of the averaged Poynting vectors (Fig. 1b) correspond to the areas through which energy transfer is absent:

- there are the points of singularities of the Poynting vector;

- there are the points forming the lines along which light energy is non-vanishing, but is conserved, no being transferred;

- there are the points where the vector $\vec{H}$ vanishes by interference, while in this arrangement (90°-superposition of plane waves) superposition of strictly coaxial vectors $\vec{H}$ of equal amplitudes associated with two superposing plane waves takes place.

4. Homogeneous intensity distribution and periodical spatial modulation of the Poynting vector simultaneously realized at the observation plane find out explanation within the framework of [10,11]. Spatial polarization modulation at the observation plane is caused by superposition of the E_x and E_z field components with changing from point to point phase difference (Fig. 1a). Photodetector registers only intensity $I = E_x^2 + E_z^2$. The sum of the squared amplitudes of the electrical fields is constant at the observation plane, though the state of polarization changes. The Poynting vector is defined by the vector product $\vec{S} = \frac{c}{4\pi}\left[\vec{E}\times\vec{H}\right]$. One can see the dependence of the result (*viz.* the vector magnitude and its direction) on the phase relation between vectors $\vec{E}$ and $\vec{H}$. This relation changes from point to point at the observation plane that manifests itself in polarization modulation. Obvious explanation follows from consideration of the product of the components of vector $\vec{E}$ (E_x and E_z components) with vector $\vec{H}$. Both the magnitudes of projections E_x and E_z and their phases change from point to point at the observation plane. As a consequence, the vector product as well as the Poynting vector also change.

The simulation of motion of conducting particles of diameter from 0.2 μm to 0.3 μm embedded in the field of the considered distribution of the Poynting vector has been carried out. It was concluded that in the case of the distribution resulting from superposition of completely mutually coherent waves, velocities of particle motion along the lines of maxima and zeroes of the Poynting vector are considerably different. Particle size is comparable with a half-period of the corresponding distribution, however the resultant force (Fig. 3) inducting particle motion along the lines close to the Poynting vector maxima exceeds the resultant force for the lines with vanishing and close to zero Poynting vector magnitudes.

If the degree of mutual coherence of superposed waves equals 0.2, the spatial distribution of the averaged Poynting vectors becomes more homogeneous Fig.4, the deep of modulation of such vector decreases considerably, and velocities of motion of microparticles become almost the same.

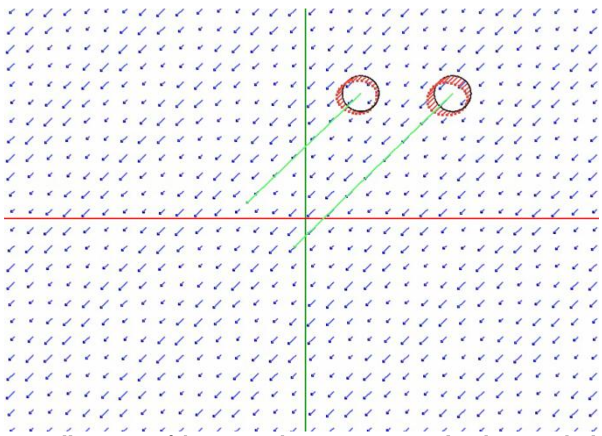

Fig.3. Illustration of the averaged Poynting vectors distribution, which forming in arrangement Fig. 1 for completely mutually coherent waves and the formation of the resulting force (green novertical line) inducting particle motion.

When the degree of mutual coherence equals 0.5, relative velocities of motion of microparticles along the same trajectories differ twice in comparison with velocities for completely mutual coherence of superposed waves. One can see the dependence of velocities of motion of microparticles of constant size and form in media with constant viscosity on coherent properties of superposed waves. These differences in velocities of motion of microparticles may be explained physically in the following manner. Increasing share of incoherent radiation in the resulting field distribution causes in decreasing of the modulation depth of the Poynting vectors spatial distribution (Fig. 5), as well as in decreasing of the resultant force magnitude along the lines of energy transfer which causes microparticle's motion [12, 13].

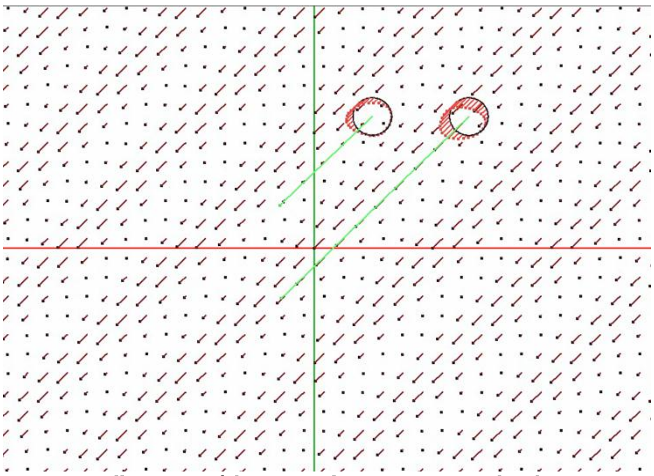

Fig. 4. Illustration of the averaged Poynting vectors distribution in arrangement Fig. 1 for the degree of mutual coherence of the components 0.2 and the formation of the resulting force (green novertical line) inducting particle motion.

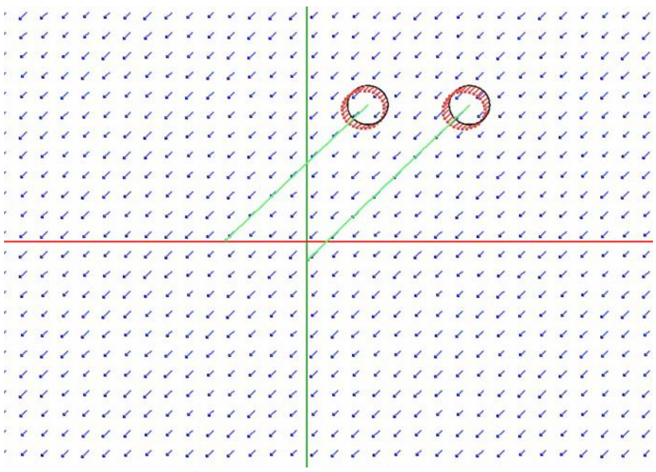

Fig.5. Illustration of the averaged Poynting vectors distribution in arrangement Fig. 1 for the degree of mutual coherence of the components 0.5 and the formation of the resulting force (green nonvertical line) inducting particle motion.

III. THE SUPERPOSITION OF FOUR WAVES FOR CHANGEABLE DEGREE OF COHERENCE OF ONE COMPONENT

In the case of superposition of four plane waves involving two sets of counterpropagating plane waves of equal intensities, linearly polarized at the incidence plane and oriented at the angle 90° to each other, the spatial distribution of the averaged Poynting vectors is formed, as it is shown in Fig. 6b.

One can see periodical 2D distribution of the Poynting vectors. As in the previous case, the lengths of the averaged Poynting vectors are proportional to their magnitudes. The points at this distribution correspond to zero magnitudes of the Poynting vector, i.e. singularities of the Poynting vector. In simulation, diameters of conducting particles are changed be comparable with a half-period of the corresponding spatial distribution of the Poynting vector.

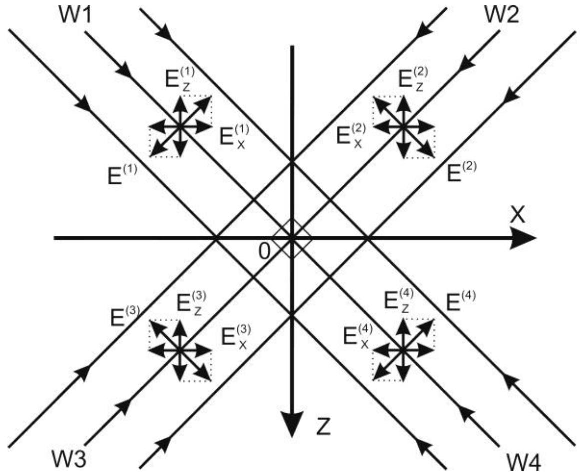

Fig.6a. Arrangement of the superposition of four plane waves

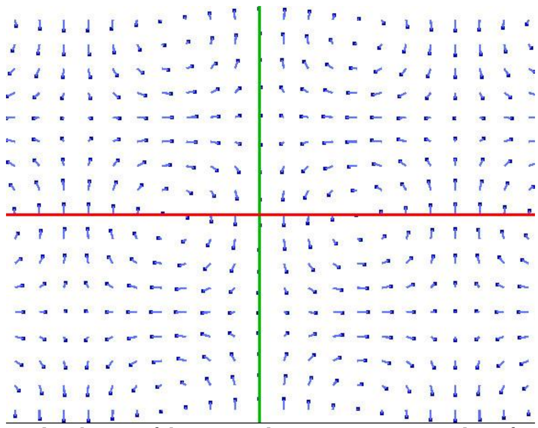

Fig. 6b. 2D distribution of the averaged Poynting vectors resulting from the superposition of four waves shown in Fig. 6a.

For the sake of qualitative comparison of temporal and spatial parameters of motion of micoparticles, we have analyzed the maps of the averaged Poynting vector in the arrangement of four plane waves superposition over a large area. The dependence of microparticles motion velocities on the phase difference of the superposing beams has been proved. So, in the case of pair-by-pair four opposite-in-phase superposed beams, particles become motionless. Here, oppositeness-in-phase presumes the situation when two sets of mutually orthogonal in space standing waves are characterized by the fact, that their nodes strictly coincide.

It follows form the presence of the minimum of the modulation depth at the spatial distribution of the Poynting vector. Gradual decreasing of the degree of coherence of one of the superposed beams causes revival of particle motion with increased velocity as the degree of coherence of one of beams decreases.

If the phase relations of four superposed beams is such that the modulation depth of the spatial distribution of the Poynting vector is maximal, velocities of moving of microparticles also depend on the degree of mutual coherence of superposed beams. This situation is realized when two orthogonal systems of standing waves are such as their maxima coincide. This case we refer to as co-phasing of waves. The change of the degree of coherence of interacting waves causes the change of the modulation depth of the averaged Poynting vector and, correspondingly, the change of the movement velocity of particles.

There is exists two points, which can explain the superposition of four waves. At the first, the dependence of the depth of modulation at the distribution of the averaged Poynting vectors on the phase relation of superposing waves. It is assumed that changing the phase relation of superposed waves causes transition (at the observed pattern) from the situation when the maxima of two systems of mutually orthogonal standing waves coincide - to the case when the nodes of two such systems coincide. Thus, the velocities of particles in such fields are dependent on the depth of modulation of the distribution of the averaged Poynting vector. Secondly, the superposition of four waves linearly polarized at the incidence plane results in forming so-called "cellular" structure in the resulting field distribution, which can be used for transfer (transporting) *as a whole* of the set of periodically positioned microparticles to the desirable zone, see Fig. 7.

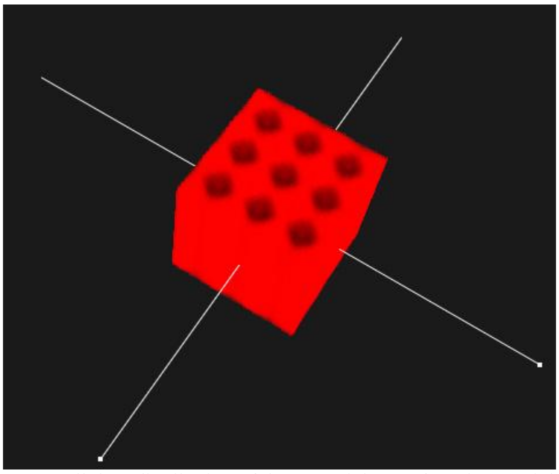

Fig. 7. "Cellular" distribution of the potential traps for microparticles in the case of the superposition of four waves

We consider as prospective the deeper investigation of peculiarities of motion of microparticles at the considered here fields to reveal the regularities of dynamics of their motion as a function of the coherent characteristics of the waves constituting certain spatial polarization distributions. Such investigations put in evident the prospectives of experimental investigations of light coherence.

IV. CONCLUSIONS

Motion of microparticles at the field in absence of intensity modulation, only due to polarization modulation causing the spatial modulation of the Poynting vector makes obvious the feasibilities for creating on this base pure polarization micromanipulators and tweezers. Temporal and space peculiarities of particle's motion in optical fields with spatial modulation of the averaged Poynting vector (depending on the degree of mutual coherence of superpose waves) show some new feasibilities of the use of such field characteristics and the parameters of microparticles motion for estimating the temporal coherence of the tested field. Initial experimental results prove these conclusions.

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