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SOME TRENDS IN OPTICAL METROLOGY

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ЧЕРНІВЕЦЬКИЙ
НАЦІОНАЛЬНИЙ
УНІВЕРСИТЕТ
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INTRODUCTION

This paper offers some of the achievements of modern optical metrology. The basic approach of metrology from the nano to the pico level optical measurements is considered in this paper. Control of nano (micro) particle motion by an optical field and their using for testing complex optical fields is presented, as a general concepts of optical field metrology. Optical metrology, which is provided by three-dimensional polarization distributions of optical fields, where structured light plays a special role; by using femtosecond lasers, and much more, demonstrates the prospects of optical methods in modern measuring systems.

STRUCTURED FIELDS WITH 3D POLARIZATION DISTRIBUTION FOR SUPER RESOLUTION SYSTEMS

In the approximation of three-dimensional polarization structures it is possible to use all three components of the electromagnetic field, which allows us to generate a field that is structured not only in the transverse plane, but also along the longitudinal coordinate[1-2]. Recently, a method for reconstructing a full three-dimensional distributed information, contained in a focused light beam, was presented. This method uses an individual nanoparticle as a device that scans a field. The radiation field, scattered by nanoparticles, can interfere with the incident light beam, used in the study. Information about the local relative phase of the electrical components of the field is embedded in the interference components.

GENERAL APPROACHES TO FEMTO-LEVEL MEASUREMENTS

An example of femto-level measurements based on the real results of optical metrology is the use of optical forces of the femto-newton order to manipulate micro- and nano- objects with the study of the feedback effects of objects on optical fields[3-4].

Using of micro- and nanoparticles in metrology problems

Considering the methods of creating micro- and nano-manipulators, tweezers and motors, as well as using metrology elements[4], according to our work, based on classical optical principles, but supplemented with new, and possibly fundamentally new technical and technological solutions for auxiliary devices, new metrological problems for optical measurements of micro-, nano-, pico-, femtosecond ranges are solved.

Micro and nanoparticles as field probes

Our next paper[3] demonstrate the results obtained by separating the contribution of the orbital and spin angular momentum to the total picture of trapped particles' motion in the optical field. To identify the internal spin energy flows15, it was necessary to analyze the mechanical action of the spin momentum by testing, selecting size and property of the particles. The spin momentum manifests itself "in its pure form" with all the specific properties in the situation of a symmetric superposition of circularly polarized plane waves and thus the formation of a circularly polarized field having inhomogeneous energy[3]

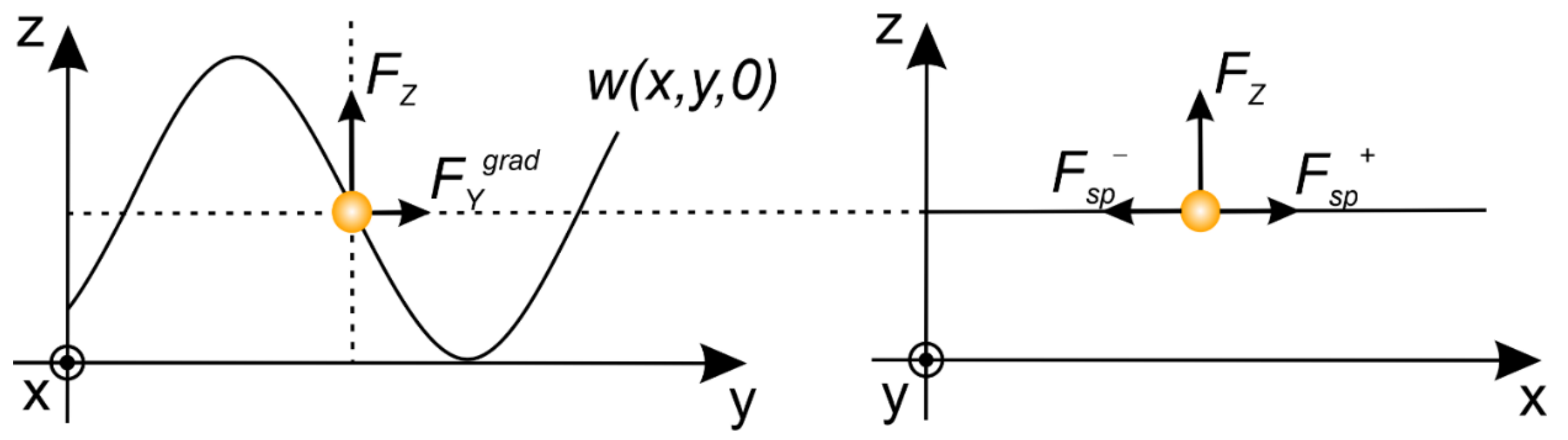

Fig. 1. The mechanical action of the incident field on test particles, when including the scattering components, was carried out through the calculation of the Cartesian components of the force (F_x, F_y, F_z) acting on particles that are placed in the optical field. The longitudinal component of the force (F_z) represents the traditional action of light pressure, which direct the particles forward; the transverse y-component (F_y) corresponds to the gradient force (F_y^{grad}) of an inhomogeneous optical field and traps particles or repels them from areas of high concentration of electromagnetic energy. The most interesting result is the analysis of the component $F_{sp}^{\pm}$ of the optical power along the transverse direction F_x - the only component of the force that is associated with the spin flow. This conclusion is confirmed by the fact that, in accordance with the behavior of the spin flow, the value of the force F_x changes its sign with a change of the helicity of the incident beam. In the case of linearly polarized light, this component of the force completely disappears[3].

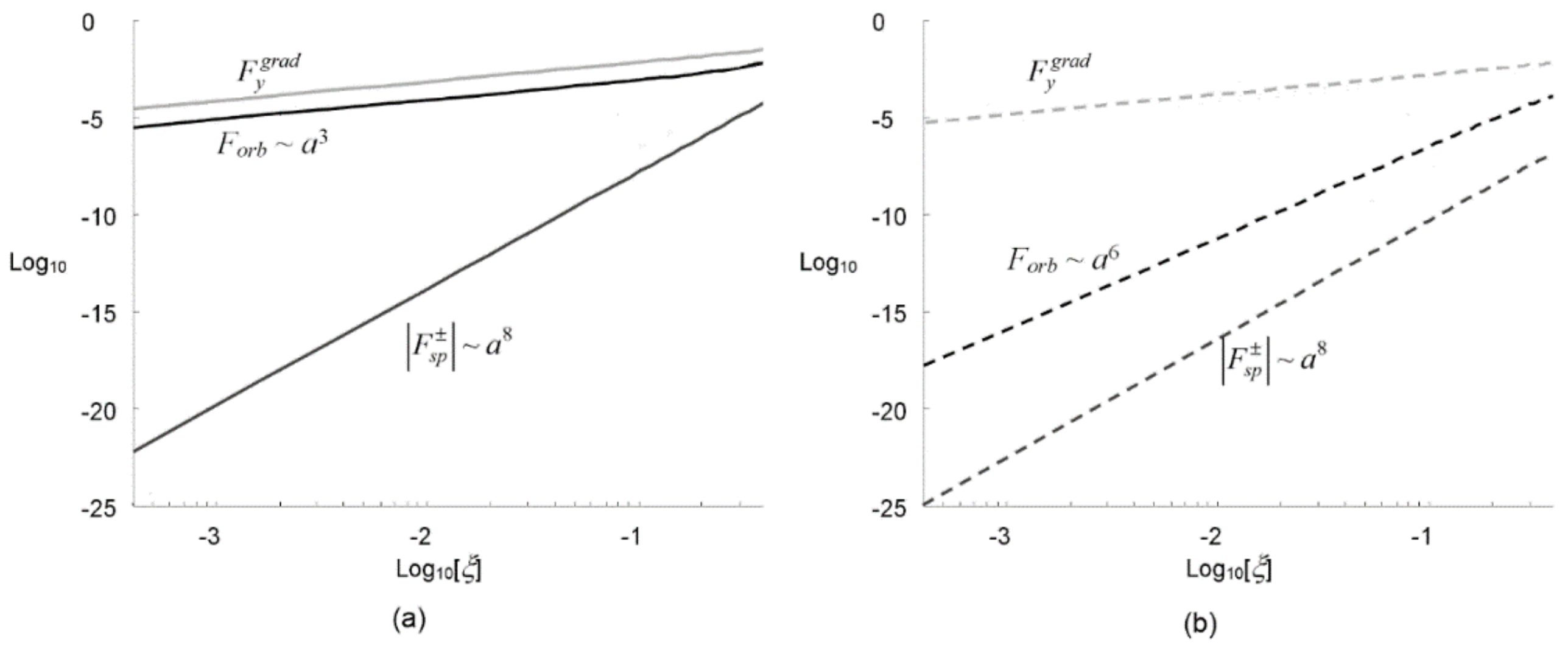

Fig. 2 . A comparative picture of the mechanical action of the optical forces associated with the spin and orbital internal energy flows is depicted in a double logarithmic scale. The curves are made for particles of small size. Solid lines: metal particles, dotted lines: dielectric particles. The order of optical force growth with a particle radius is indicated taking into account the normalization factor P_0. To compare the optical force, the gradient force F_y^{grad} is shown. Here $\xi = ka$ is a dimensionless particle size parameter (a – is the particle radius)[4].

We can note the level of optical force up to 10^{-15}-10^{-25} degree for the spin-induced component of the optical force in accordance with the particle size. The use of dielectric test particles of the Rayleigh light scattering mechanism made it possible to evaluate experimentally the action of spin and orbital flows.

The value of the force is estimated at the level of pico-, femto-Newton, and in accordance with our experiments[4] (Fig.3) the obtained results can be considered as a proof of the mechanical action of the spin energy flow of the light beam on test particles of the chosen shape and properties. The experimental observation of the polarization-dependent orbital motion of test particles in a transversely inhomogeneous beam with circular polarization, where the rotational action of the orbital momentum density is absent or insignificant, is demonstrated. Moreover, this demonstration of motion required an ultra-precise experiment, when the peculiarities of the femto- level evaluation of optical force action on nanoparticles is taken into consideration.

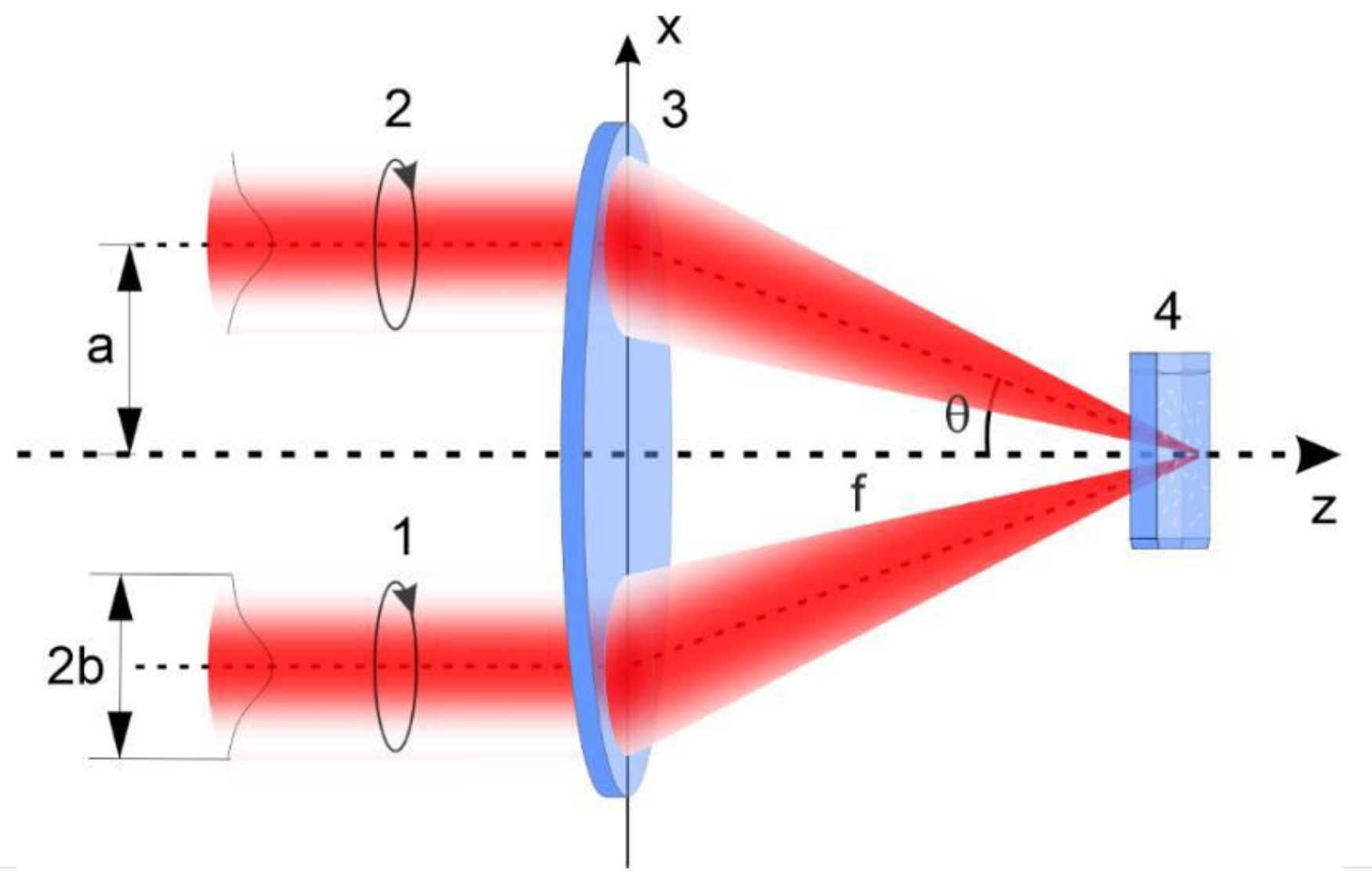

Fig. 3. Scheme of the experimental setup for demonstration of the mechanical action of spin energy flow: (1), (2) - input beams; (3) objective lenses; (4) cuvette with test particles suspended in water

By changing the circulation of the electric field vector, the captured particle carries out orbital motion being it clockwise or counterclockwise rotational motion with respect to its own axis. Both the orbital and rotational motions stop when the polarization of the incident beam is linear. The possibility of particle transfer by the force induced by the influence of spin energy flows opens up new prospects for the creation of controlled optical micromachines, micromanipulators in which the regulation and switching are performed through polarization control without changing the beam intensity or its spatial profile. Such methods can be useful in many systems requiring high switching speed.

Metrology of optical parameters for low-absorbing microparticles

The next step is to demonstrate one of the metrological solutions for determining the absorption coefficient of low-absorbing microparticles by estimating the rotation speed of such objects in the field of a circularly polarized beam. The uniqueness of the proposed experimental approach is that the accuracy in determining the optical parameter is of the order of femto units. It is a confirmation of the breakthrough in optical metrology and relies on the fact that modern experimental equipment and corresponding experimental approaches and measurements have lifted the microrange up to a new, more delicate level.

The criterion of optical fields action on micro- and nano-particles is the rotational motion of the particle under the influence of a torque, which is inherent in an optical field of circular polarization with a spin angular momentum was introduced. The spinning motion of the particle is due to the field spin angular momentum absorbed by the particle, and its angular velocity Ω is related to the radiation torque by the equation:

$$\Omega = \frac{T}{8\pi\eta r^3}$$

The absorption index κ of the particle suspended in water and trapped in the center of a focused Gaussian beam waist with radius w_0 = 2 µm can be directly derived from the observed spinning velocity Ω exhibited by the particle in the beam with power P = 100 mW, $\kappa = q\Omega P$, where q is the transition coefficient. At the same time, the particle must have low absorption, so that there is no local heating of the medium surrounding the particle. Effective particle capture requires that the particle size be several times smaller than the size of the focused spot, but in such a way as to prevent diffraction by the captured object.

We have used weakly absorbing ($\kappa \le 10^{-3}$) dielectric particles with diameter 0.5 to 2 µm. As a result of the optical field action, the particle acquires a rotational motion, and the angular velocity of the particle corresponds to the part of the torque that is absorbed. As absorption increases, an acceleration of the rotational motion is observed. The measured value of the spinning velocity obtained in the experiment, e.g. for a gamboge particle of about $\Omega_e = 25.8\ \mathrm{sec}^{-1}$, differs from the theoretically obtained spinning velocity and amounts to about 20%. Such an error can be explained by the longitudinal displacements of the particle with respect to the beam waist, heating of the cell with particles, changes in the properties of water inside the cell, and other reasons. The introduction of the normalization coefficient, obtained by comparing the theoretical and experimental results, made it possible to determine the value of the particle absorption coefficient, here for this type of particle, giving $12.4 \cdot 10^{-4}$.

Of course, the question arises about the accuracy of the proposed method for measuring the absorption index. The flexibility of this method is determined by the refractive properties of the particle, the density of the medium where the particles are dispersed, the characteristics of the irradiating beam, and the cross-section of the focused beam. Restrictions for the determination of the particle rotation speed of about $0.1\ \mathrm{sec}^{-1}$ are formed. Then, with the introduction of transition coefficient (q), the error in estimating the absorption coefficient δ can be obtained in the range $10^{-8} \le \delta \le 4 \cdot 10^{-7}$. Obtaining reliable results of measuring the absorption coefficient of particles is possible for absorption less than 10^{-2}.

CONCLUSIONS

The results presented in this paper provide some metrological approaches and provided results are obtained in ultra-sensitive precision measurements. Such methods are based in the existing interconnection between the correlation and polarization parameters of optical fields and properly the polarization and coherence properties of optical field. According to the latest new results on the use of structured light in the problems of creating systems with super-resolution within the framework of three-dimensional polarization distribution approaches with increased importance of the longitudinal component allows the users to overcome the classical transverse resolution barrier and reach the limit of tens of nanometers.

The femto level of optical forces, which occurs in complex optical fields with a rich morphology of the distribution of internal optical energy flows, interacts with micro- and nano-objects of various shapes and properties, but also control their spatial motion in optical traps, the nature of which can differ significantly in accordance with the trap formation mechanism. The optical forces of this physical nature and the values are used to determine the optical parameters of trapped particles, where the accuracy of the determination is controlled at the nanoscale level.

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