

LETTERS

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Microobject manipulation by laser beams with a nonzero orbital momentum

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***Abstract*. It is shown that the possibilities of manipulating microobjects can be considerably extended by using beams with preset intensity and orbital momentum distributions in the focusing plane. The results of experiments on the transfer of the orbital momentum of such beams to microparticles are presented.**

Keywords: *trapping, light beams with a nonzero orbital momentum, microobject manipulation.*

The methods of microobject manipulating with the help of laser beams, which are being developed extensively at present, are quite interesting for solving various problems in biology, medicine, and construction and control of micromechanisms. Polarised light has been used successfully for optical trapping of radiation and rotation of particles [1]. In the general case, the angular momentum of light beams consists of two components: the 'spin' moment caused by circular polarisation, and the orbital momentum determined by the amplitude – phase distribution of the light field. The idea of extending the possibilities of these methods seems to be quite tempting, but ways and means of forming beams with given intensity and orbital momentum distributions must be developed for this purpose.

The problem can be solved by placing special amplitude – phase masks outside as well as inside the laser cavity. The formation of beams with given spatial parameters by creating spiral beams [2 – 5] appears to be quite promising. These beams may have quite diverse structure of intensity distribution, which is preserved during their propagation and focusing. The vortex nature of propagation of light energy in beams is due to the presence of a nonzero orbital momentum in them. The Laguerre – Gauss modes are the simplest types of spiral beams. The rotation of absorbing particles with the help of such beams was demonstrated in Refs [6 – 8].

In this paper, we describe the experiments on trapping and rotation of microscopic particles by a beam with a nonzero orbital momentum created by using a diffraction optical element (DOE) in the form of a vortex axicon focusing the laser radiation to a ring.

The experimental setup for manipulating microobjects with the help of beams with a nonzero orbital momentum is shown schematically in Fig. 1. We used an argon laser (*1*) in our experiments. A beam with a nonzero orbital momentum was formed by means of a vortex axicon focusing the laser radiation to a ring of radius r_0 at a distance f_0 [5]. The phase characteristic of such an element in polar coordinates r and θ has the form

$$\varphi_0(r) = -\frac{kr^2}{2f_0} + \frac{krr_0}{f_0} + m\theta,$$

where k is the wave number; m is a nonzero integer determining the number of phase variations by 2π upon a variation of θ by 2π. For the beam formation, we used an axicon with $m = 2$, which provided the distribution of intensity and angular momentum density (Fig. 2) analogous to that for a Laguerre – Gauss beam with an angular momentum per unit energy of the beam $m/\omega = 2/\omega$ (ω is the circular frequency of radiation).

To form an optical trap, the laser beam was directed by a dielectric mirror (*10*) to a polarisation microscope MIN-8 with an immersion microobjective (*11*) ($90^{\times}$, NA = 1.25). The image plane was made coincident with the focal plane of the microobjective by using a converging lens (*7*) of focal length 0.1 m. This system allowed the formation of a laser

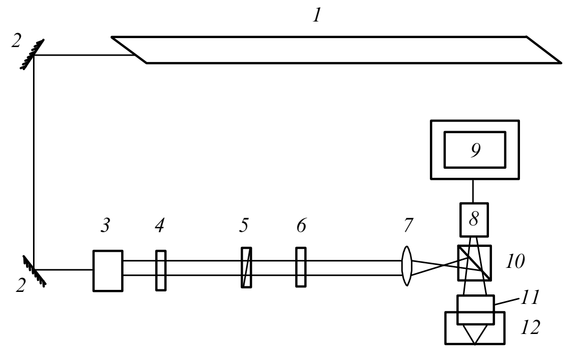

Figure 1. Schematic of the experimental setup: (*1*) argon laser; (*2*) mirrors; (*3*) beam expander; (*4*) diffraction optical element; (*5*) polariser; (*6*) quarter-wave plate; (*7*) auxiliary lens; (*8*) video camera; (*9*) monitor; (*10*) dielectric mirror; (*11*) microobjective; (*12*) cell with particles.

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Figure 2. Spatial distribution of (a) the intensity, (b) phase, and (c) angular momentum density in the cross section of a beam formed with the help of a vortex axicon. The phase variation from 0 to 2π corresponds to a variation from black to white.

beam with a waist of diameter ~ 1.5 μm. The maximum power of focused radiation incident on a particle was 50 mW. Particles of cetylpyridine bromide suspended in water were used as the absorbing medium. The cell (*12*) was filled with a suspension of such particles. The rotational frequency of particles trapped in the laser beam-focus region was measured for different polarisation directions and various powers of the incident beam.

The rotation of particles was not observed in a linearly polarised beam in the absence of a DOE, i.e., for a Gaussian beam, which indicates the absence of effective rotation due to the particle asymmetry. The introduction of a DOE led to a rotation of the particles. Turning the DOE by 180° in the horizontal plane reverses the sign of the orbital momentum of the beam, and the particles start rotating in the opposite direction. Thus, a particle of size 1.5×3 μm rotated in the counterclockwise direction with a frequency 0.28 Hz. Upon turning the mask by 180°, the direction of rotation was reversed and the frequency of clockwise rotation was 0.26 Hz. This is an additional evidence in favour of the fact that the particle rotation is caused by the absorption of orbital momentum of the beam.

We also performed experiments on particle rotation in the case of a nonlinear polarisation of the beam. As mentioned above, a circularly polarised radiation beam has a spin moment, which is transferred to the substance upon absorption of the beam. Upon summation of the polarisation and orbital momenta of the beam, the time required by a particle of size 2.5×4 μm to complete a revolution was 5 s, while it took the particle 15 s to complete a revolution upon subtraction of these momenta. These results correspond to the parameters of the optical element with $m = 2$ used in the experiment. Fig. 3 shows the photographs of a rotating particle. This particle completed a revolution in 2 min 46 s.

Thus, we have described the results of experiments on transfer of orbital momentum of a beam to absorbing particles of micrometer size. A DOE in the form of a vortex axicon was used for producing a beam with a nonzero orbital momentum.

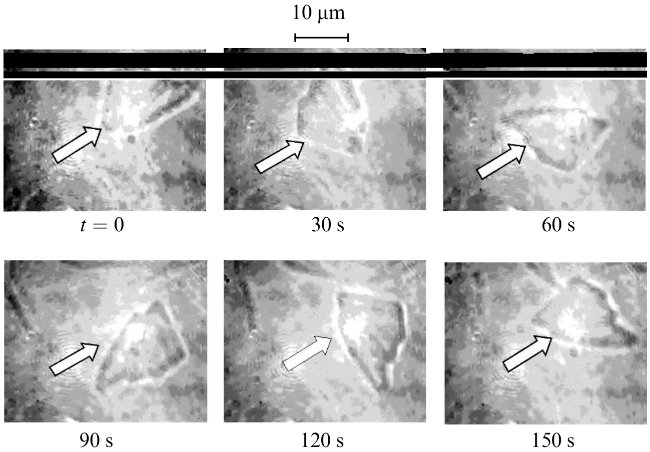

Figure 3. Rotation of a particle by a beam with a nonzero orbital momentum.

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