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Subwavelength, standing-wave optical trap based on photonic jets

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Abstract. **We propose a new modification of a subwavelength, standing-wave optical trap based on photonic jets formed in the 'reflection' regime. The results of the numerical calculations of the electromagnetic field intensity of the generated photonic jet modulated by antinodes of the standing wave are presented. In contrast to known schemes, in the subwavelength optical trap in question, the minimum size of the focusing spot is determined by the width of the generated photonic jet rather than by the focusing lens parameters. A decrease in the diameter of the photonic jet waist compared with the size of the waist in the focus of the lens leads to an increase in the energy density in the focal region.**

Keywords: *optical trap, mesoscale, dielectric particle, photonic jet, standing wave.*

As one of the rapidly developing fields of photonics, laser manipulation of microscopic and nanoscale objects is of great interest for biology, medicine and micromechanical technologies.

The method of optical trapping (or optical tweezers) is based on the fact that the focal spot of tightly focused light can serve as a potential trap for dielectric particles. In a classical scheme of an optical trap [1] – the scheme of a classical microscope (i.e. radiation is directed downward) – a substantial force acting in a direction opposite to that of propagating radiation is required to focus the beam as tightly as possible. In this case, the axial force is always several times less than the transverse force, and thus the particle is easily released from the trap because surface forces are always greater than optical ones [2]. In addition, the use of classical lenses and objectives do not permit generating a focused beam with a waist size (in the direction transverse to that of radiation propagation) that is less than the diffraction limit. It is significant that in the case of classical lenses the tighter the beam is focused, the faster it diverges beyond the focus. This means that the force trapping a particle decreases very rapidly with increasing distance from the trap region, and at a distance of several tens of micrometres the force is insufficient to re-capture a particle. Therefore, a single-beam trap is really useful only for capturing a single particle and only in the focal spot region, the size of which, due to fundamental limitations, is greater than the diffraction limit.

In a standing-wave optical trap [3], a surface with a high reflection coefficient is placed behind a sample; therefore, near this surface a standing wave is produced by the interference of incoming and reflected beams [4–6], and microparticles will be localised in the trap antinodes separated by half the laser wavelength from each other along the optical axis of the trap. Thus, a flat reflecting screen produces an additional gradient force that immobilises a microparticle, which results in particle trapping and localisation near the maxima of the electric field of the standing wave. The trapping effect has a significant impact on the potential of the optical trap, which leads to a significant increase in trap stiffness along the optical axis due to a large gradient of the electromagnetic field of the generated standing wave [7]. In fact, this version of the optical trap represents a modification of an alternating-beam light trap [8]. The principle of design of a standing-wave optical trap is sufficiently effective not only in optical, but also in the ultrasonic spectral range [9, 10].

In optical localisation the diffraction limit can be exceeded by using optical control methods based on the application of the electromagnetic near field [11]. One of the methods of light focusing in the near field is the phenomenon of a photonic jet [12], where the light is localised in subwavelength space. In this paper we propose a modification of the well-known principles of construction of a standing-wave optical trap, which consists in the fact that the (unfocused) light is incident on a dielectric particle with special properties that allow a photonic jet to be generated in the 'reflection' regime [12–15].

The photonic jet in the reflection regime was simulated using the numerical solution of Maxwell's equations, which describe the incidence of a plane wave front of radiation with a wavelength of 671 nm on a dielectric (SiO_2) with a refractive

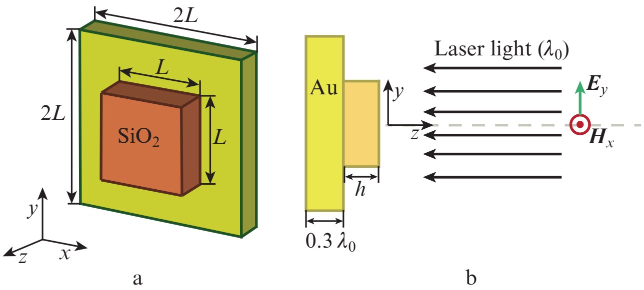

Figure 1. (a) Target for optical trapping based on a photonic jet and (b) scheme of its irradiation.

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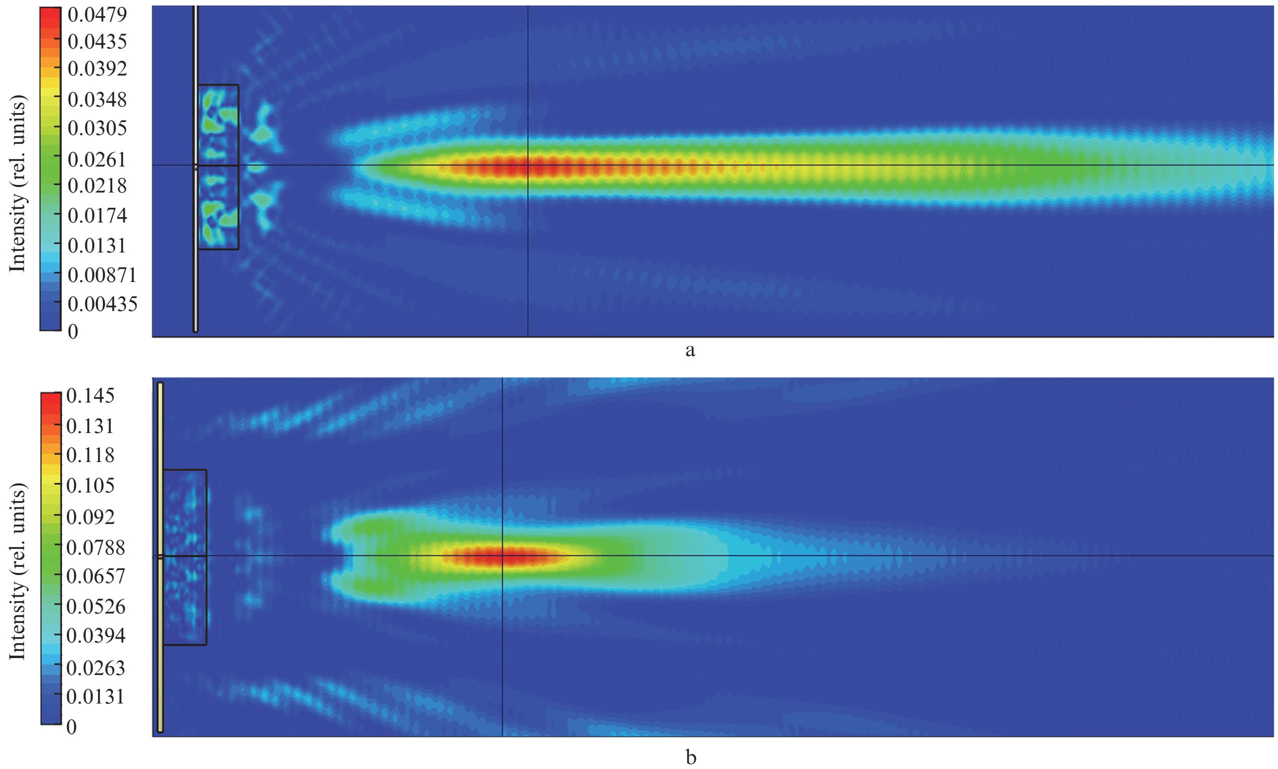

Figure 2. (Colour online) Formation of a photonic jet modulated by the antinodes of a standing wave in the 'reflection' regime (a) in the air and (b) in water.

index of 1.46. The thickness h of the dielectric plate placed on a metal (gold) screen was 1 μm and the side of the square was $L = 3.17$ μm (Fig. 1).

Figure 2 shows the photonic jet formed during reflection of a plane (unfocused) wave from a flat screen with a square dielectric plate in the air (the photonic jet length in this example at the level of half the power is 15 wavelengths of the incident light) and in water (refractive index is 1.3337). Figure 3 demonstrates the field intensity distribution along the axis of the photonic jet. Figures 2 and 3 clearly show the field intensity oscillations along the direction of propagation of the light beam, the peaks of which correspond to the antinodes of the standing wave produced by the interference of the incident and reflected light waves. The microparticle will be localised in the antinodes of such a trap. An increase in the refractive index (a decrease in optical contrast) leads to a decrease in the length of the produced photonic jet with increasing maximum field intensity in the jet (in this case, almost by three times) and to a decrease in the spatial period of the field intensity oscillations along the jet.

Unlike the well-known schemes, in the subwavelength optical trap in question, the minimum size of the focal spot is determined by the width of the produced photonic jet rather than the parameters of the lens (and the laser beam). Reducing the waist size of the photonic jet, compared to the waist size of the laser beam focused by the lens, leads to an increase in the energy density in the focal spot region. At the same time, by turning the reflecting screen and/or by changing the direction of the light incidence, one can move the particle in space. Since the functionality of optical tweezers is largely determined by the spatial structure of optical traps and the degree of light beam focusing, the optical control methods based on the use of photonic jets allow one to exceed the optical diffraction limit in the case of optical localisation and open up new opportunities in the optical sorting of particles. The proposed approach to the construction of a subwavelength optical trap makes it possible to stabilise the position of a mic-

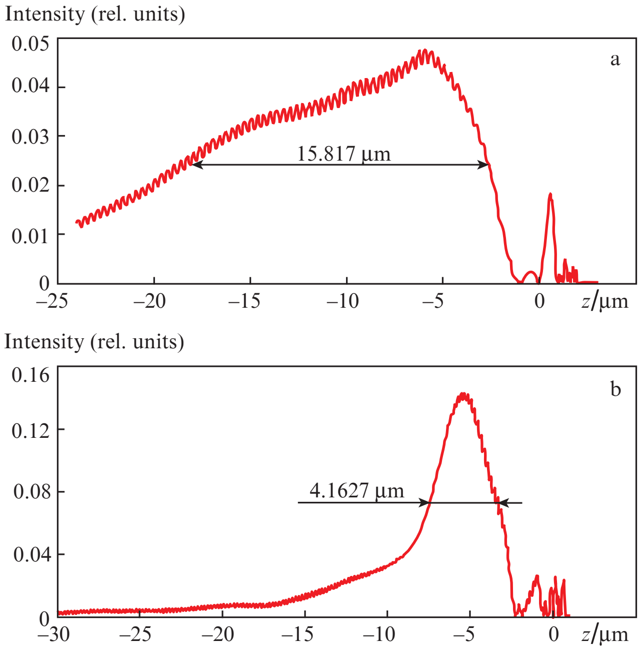

Figure 3. Distribution of the field intensity along the axis of the photonic jet (a) in the air and (b) in water. The metal screen is on the right (at $z = 0$), and the light (flat front) is incident on the left.

roparticle at a certain distance from the surface and to significantly improve the accuracy of its localisation.

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