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Optical Manipulation of Micro- and Nanoobjects Based on Structured Mesoscale Particles: a Brief Review

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Abstract—Spatial resolution of conventional optics, which is necessary for nondestructive trapping of micro-objects, is limited by diffraction to a value equal to half of the radiation wavelength. Despite this limitation, use of optical methods is one of the main directions in biological and biomedical researches because only these methods have a minimal impact on living organisms. The rapid advance in this area is largely owing to the development of new optical technologies and the considerable advance in mesoscale photonics, which has allowed researchers to develop techniques for controlling structured beams for optical traps. In this work, we consider some recent trends in the field of optical manipulation based on mesoscale dielectric particles.

Keywords: mesoscale element, dielectric particle, optical power, photonic nanojet, photonic hook, optical manipulation

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INTRODUCTION

The conjecture about the existence of light pressure was made for the first time by J. Kepler in the 17th century; P.N. Lebedev discovered it experimentally in 1899 [1]. The possibility of trapping and nondestructive transferring individual objects with micron and submicron sizes under the action of the light force has bright prospects in different branches of science and technology [2–4]. The Nobel Prize for Physics in 2018 was awarded for the invention of the optical tweezers and their application in biophysics. In recent times, problems of developing new techniques for optical control for nano- and microparticles, as well as spatial localization and amplification of the electromagnetic field on subwavelength scales, are especially topical. However, it is well known that the spatial resolution of conventional optics is determined only by the radiation wavelength (in the medium) and numerical aperture of the optical lens; it does not exceed a value on the order of half the wavelength due to fundamental diffraction limitations [5].

In recent years, various types of structured optical beams [6–8] for the mechanical impact on nanoparticles in the subwavelength scale [9–11] were obtained and used. Below, we briefly consider electromagnetic field localization methods based on using the principles of mesoscale dielectric photonics.

Mesoscale dielectric photonics presupposes the interaction between the radiation and dielectric objects of the intermediate scale (the dimensional Mie parameter $q = 2\pi r/\lambda \sim (2–20)\pi$ [12–15], where λ is the radiation wavelength and r is the characteristic particle radius) which are too large to be characterized as simple dipoles and too small to be described within the limits of geometrical optics.

Subwavelength control for electromagnetic energy is usually related to resonance phenomena [16, 17]. In what follows, we briefly consider the class of nonresonant diffraction elements (mesoscale dielectric particles) for manipulations of nano- and microparticles.

1. NANOSTRUCTURED DIELECTRIC PARTICLES

Possibilities for manipulation of light based on mesoscale dielectric structures is attracting the attention of an increasingly large number of researchers. A wide range of ways of subwavelength localization of light has been proposed. Photon crystal (PC) lenses [17–19], elements of three-dimensional diffractive optics [20, 21], and planar plasmonic lenses based on

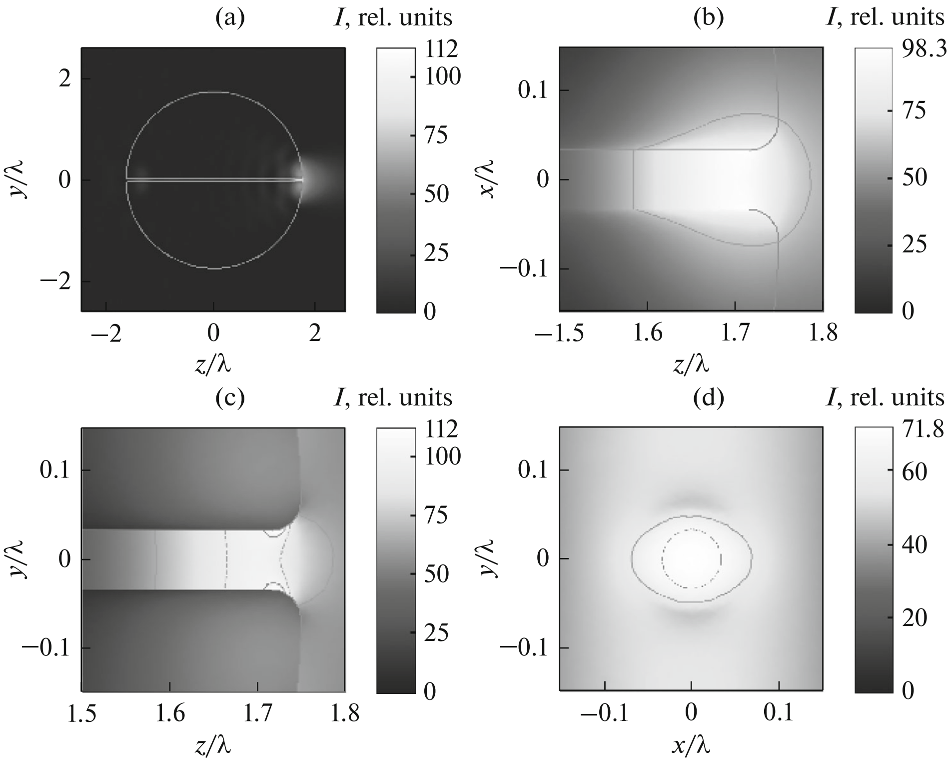

Fig. 1. Intensity distribution in the neighborhood of a dielectric microsphere (diameter $D_s = 3.5\lambda$, refractive index $n = 1.5$) with a through hole (diameter $\lambda/15$): (a) general view, (b, c) magnified image of the outlet section of the hole; and (d) intensity in the transverse plane xy at a distance $\lambda/1000$ from the hole section. The optical radiation is incident from left to right. The figure is taken from [22].

nanolayers [22–24] for focusing light beyond the diffraction limit have been studied. In 2017, a conical two-dimensional plate lens based on a nanolayer with a plasmonic zone for far-field focusing with superresolution [25] by excitation of surface plasmonic waves and their coupling with propagating radiating modes was proposed. Gradient-index PC-lenses with air holes of different size were studied in [26, 27]. It was reported that, using such a lens, one can obtain a localized light beam with a full-width at half maximum (FWHM) as fine as $\sim\lambda/75$ [27].

Photonic nanojets (PNJs) [12–15, 28] seem to be more attractive due to simplicity of implementation and compact size of the focusing particle. However, the minimum width of a PNJ beam is usually $\sim\lambda/3$ [12–15]; therefore, it is necessary to seek new ways for a further decrease in the size of the localization region of the PNJ electromagnetic field.

For deep subwavelength focusing of light far beyond the diffraction limit $\lambda/2n$, a nanostructured dielectric microsphere was proposed in [27]. Amplification of the field in such a nanostructured sphere is caused by the contrast between dielectric permittivity of the material of the nanorods and material of dielectric microparticles. The proposed nanostructured mesoscale sphere has a number of unique properties. For example, it can produce high electric field strength in the region of the hole (with a low refractive index, e.g., in air) at levels that cannot be reached using usual PNJs [12–15] produced by spherical particles with the same diameter but without nanostructuring. Numerical simulation demonstrates [27] that the light field is localized inside the nanohole even when the diameter of this hole is subwavelength (at least $\lambda/40$). The transverse size of the focal spot near the shadow surface of the particle is comparable with the size of the nanohole.

An example of field localization in a nanostructured mesoscale sphere is presented in Fig. 1. It shows the distribution of the relative intensity of the optical field in different longitudinal cross sections (along the propagation of the optical radiation) of a dielectric microsphere having a nanometer through hole and illuminated by a plane electromagnetic wave. In Fig. 1d, a transverse intensity profile is constructed in the xy plane spaced from the hole section by a distance of $\lambda/1000$. It is seen that a nanohole in a dielectric mesoscale particle allows one to "compress" the optical field near its rear surface and to obtain superlocalization of the optical field intensity to dimensions of this nanohole, which is typical for PNJs.

Based on these investigations, we proposed the concept of the easily implementable "optical vacuum cleaner" [29]. The main idea is to use a nanostructured dielectric mesoscale particle (with a spherical,

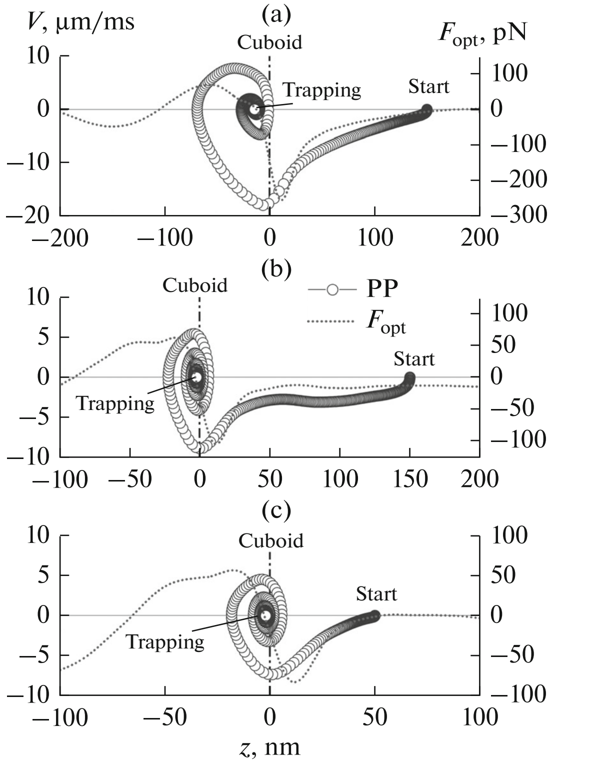

Fig. 2. Phase portraits (PPs) of the trajectory of a 15-nm gold sphere initially positioned near the shadow surface of a cubic particle (Start) on the same axis with the hole (the boundary is labeled as Cuboid) [29]. The length of the particle's face side is equal to the wavelength (600 nm); the refractive index of the material n = (a) 2.0, (b) 1.8, and (c) 2.2 nm. The radiation is incident in the direction of the z axis. For reference, the distribution of the z-component of the optical power of the trap is presented.

cylindrical, or cubic shape) for redirecting the optical pulse and reaching desirable optomechanical effects for manipulation of a metal nanosize object. Based on numerical simulation, it was shown that optical forces F_{opt} acting on a gold nanosphere are multiply amplified near the nanohole in a mesoscale dielectric particle, which leads to effective motion of metal nanoparticles towards the nanohole. For example, analysis of the phase portrait of the nanoparticle motion, i.e., the dependence of the velocity of the particle V on its coordinate z (focused lens with NA = 0.5 at $\lambda = 600$ nm and power of 10 W), demonstrates [29] that the Au nanoparticle moves to the final point of its trajectory after several milliseconds from the beginning of the light impact. The final point is positioned at a distance of ~20 nm inside the hole of the cubic dielectric particle (Fig. 2).

It follows from the figure that, in particular, the hole in the dielectric microparticle can be blind and have a small depth from the shadow surface of this particle because the force gradient is always maximum near the hole. Moreover, it is seen that an increase in the refractive index of the particle above the characteristic level for the formation of a photon jet (for example, equal to 2.2 in Fig. 2) leads to a significant decrease in the distance for trapping a metal nanoparticle (by ~3 times). This is related to the fact that if the refractive index of the particle material exceeds 2, the electromagnetic field is localized inside this particle and does not go beyond its shadow surface [16].

Numerical simulation demonstrates that the proposed nanostructured dielectric mesoscale particle can be used for optomechanical trapping of metal nanoparticles. In comparison with traditional optical methods, it is very promising in biomedical, chemical, and technological applications, in air cleaning systems, and in air filters [30–34].

2. PHOTONIC HOOK: A NEW SUBWAVELENGTH SELF-BENDING STRUCTURED LIGHT BEAM

At present, optical transport and trapping are being actively developed. Many new effects suitable for trapping were investigated. For example, in 2015, a new type of a subwavelength structured light beam was discovered; it was called the photonic hook (PH) [35]. The light from a photonic hook is localized not along a straight line but on a curvilinear trajectory [35–39] due to diffraction of the electromagnetic wave on a mesoscale dielectric spatially structured (Janus) particle made in the form of a cuboid with broken symmetry [35, 36, 38]. The distinctive features of the PH are that the transverse size and curvature radius of the beam are a fraction of the incident radiation wavelength and the side lobes do not follow the shape of the main beam and are not bent [36–39]. Note also that generation of well-studied curved Airy beams usually requires expensive and complicated optical elements with a cubic phase, which often makes optical elements unfit for building into an optical system.

Recent investigations of families of PH-beams made it possible to implement them for different types of wave interactions including optics [37–39], THz [38], surface plasmonic waves [40], and acoustics [41]; in general, they gave fresh impetus to the development of mesoscale photonics by providing new opportunities in manipulation of particles on subwavelength scales [37, 39] owing to the scaling effect. As known from optics, if there are two objects having the same shape and the same properties of the material but their sizes are different, they scatter the electromagnetic wave incident on them in the same way provided that the similarity is preserved, when the ratio of linear dimensions of these objects to the radiation wavelength is the same.

The photonic hook [42–48] formed by a structured dielectric cylinder with a built-in glass cube was discussed based on numerical simulation in [42]. Specially designed five-layer dielectric cylinders allow one to obtain double PHs [44]. Recently, it was proposed to generate photonic hooks by dielectric broken symmetry particles consisting of materials with different refractive indices [45, 46] and numerically investigated in [45–47], as well as by bielliptic cylindrical particles [48].

Generation of a curved region of radiation localization based on a metalens in the visible range was also described recently in [49]. Those investigations are not related to photonic hooks because metalens dimensions do not satisfy the mesoscaling condition stated above and the structure of the localized field is not adequate to characteristic features of a photonic hook [35–39]: the beam curvature significantly exceeds the wavelength and the spatial structure of the field, including the structure of side maximums is similar to the distribution of Airy beams.

In general, the studies demonstrated the possibility to generate spatially structured electromagnetic and acoustic fields allowing one, in addition to trapping, to implement more various kinds of optical manipulations of nanoobjects. In particular, they led to the concept of the optical hook based on an optomechanical manipulator which allows one to control the motion of trapped particles along a curved trajectory even around dielectric obstacles [37, 50].

Simulation [51] demonstrates that in the approximation where the particle is an electric dipole, i.e., a Rayleigh particle, the target nanoparticle moves around the dielectric obstacle plate. This allows one to better manipulate target nanoparticles around, e.g., glass obstacles. At the same time, a metal (Au) plate completely disrupts both the formed localized field and the trajectory of such target nanoparticles [37]. One of possible biomedical applications of this concept in vitro is to direct cells along a curved trajectory for the further analysis [50]. The concept of the photon hook presupposes the precision control over the particle motion for manipulation and sorting of cells on lab-on-chip platforms and microfluidic devices without the necessity of multiple trapping of the ray.

One more interesting application area of mesoscale dielectric particles is optical traps based on standing waves. Trapping and manipulation of nanoparticles in a standing wave (which can be generated using two counterpropagating coherent PNJs) in the transmission regime were considered in [52]; in the reflection regime, they were studied for the first time in [53].

CONCLUSIONS

Basic functional capabilities of optical tweezers are determined mainly by the spatial structure of the optical traps and degree of radiation localization. However, the electromagnetic radiation has its own characteristic scale, the wavelength. For present-day problems of physics and biology, this is a rather large scale. For the effective work and control by nanoparticles, the corresponding optical controlling elements must provide the operating capacity on subwavelength scales—less than the wavelength [54–60]. These problems belong to a new modern research direction—structured subwavelength beams. The main problem solved using such beams is to manipulate nanoobjects on scales less than the wavelength, i.e., to do what was believed to be essentially impossible in traditional optics.

Recently, mesoscale dielectric photonics is being intensely developed. It deals with small (about several wavelengths) optical elements distinguished by relative simplicity of technical implementation. In the field of optomechanical manipulations by nanoparticles, systems based on principles of mesoscale photonics can be easily integrated into a small lab-on-chip platform. Using a new subwavelength structured beam, it becomes possible to perform operations of manipulation of objects at the subwavelength level.

In addition, using the effect of the optical photonic hook, microparticles can be directed (transported) to distances on scales of the optical radiation wavelength, e.g., for purposes of sorting subcellular biological material. In particular, particles can be sorted by the refractive index, shape, and size. Based on the concept of the photonic hook, one can also design different shapes of the ultraprecise laser scalpel [61].

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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