Compact optical tweezer capable of dynamic control

Alexander Korobtsov[1], Svetlana Kotova[1,2], Nikolay Losevsky[1,2], Aleksandra Mayorova[1,2*], Sergey Samagin[1]

[1] Lebedev Physical Institute, 221 Novo-Sadovaya Str., Samara 443011, Russia

[2] Samara State Aerospace University (SSAU), 34 Moskovskoye Shosse, Samara 443086, Russia

[*] **e-mail:** mayorovaal@gmail.com

Abstract. The extension of capabilities towards the formation of controlled complex-shaped optical traps is demonstrated for the compact laser tweezer based on the four-channel LC modulator. The experimental results on the yeast cell manipulation, including the particles larger than 10 μm, are presented. The capture and confinement of the object with the dimensions 37 μm × 13 μm was realized by means of the use of the ellipse-shaped trap. The maximal escape velocity of this object was about 20 μm/s. © 2015 Samara State Aerospace University (SSAU).

Keywords: compact laser tweezers, optical manipulation, liquid crystal modulators, biological microobjects.

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1 Introduction

For technological applications of optical tweezers (e.g., their introduction into the clinical practice for solving particular biomedical problems) it is important to simplify the construction and the control system of these devices, to reduce their size and cost. From this point of view the semiconductor lasers seem to be attractive due to their high efficiency, compactness, and easy control of the radiation characteristics directly by varying the pumping current. The first publications on the use of laser diodes for fabricating a relatively cheap and compact optical tweezer appeared in the middle of nineties of the last century [1-3]. Later the semiconductor lasers have been used in laser tweezers based on optical fibres, which allowed the construction of a compact Raman tweezer. The laser diode-based optical tweezers have found wide application in microfluidic techniques.

On the other hand, the optical tweezers based on the semiconductor lasers possess a number of advantages exactly for biomedical applications, related, first of all, to the radiation wavelength range of the semiconductor lasers. The optical trapping stability in the infrared range with the possibility of significant reduction of the damage of living cells as compared to the visible range was clearly demonstrated in Ref. [4]. In the patent by Ashkin and Dziedzic it was recommended to use the lasers with the wavelength 0.8 – 1.8 μm for capturing the microobjects of the biological origin. There are a number of commercially available semiconductor lasers in this spectral range.

In this paper we present a brief review of the studies, devoted to the invention and development of optical tweezers based on semiconductor lasers, as well as to their use in biomedical applications. But it must be noted that due to laser techniques development not only semiconductor lasers but also small-size DPSS laser modules, including laser pointers, can be used as a source of radiation in compact inexpensive laser tweezers. In this paper we consider the specific technical features of the compact optical tweezer constructed by us, for which the capabilities of forming the traps with different shapes and dynamic manipulation can be essentially extended by means of using the four-channel LC modulator (LC focusing device).

2 Using semiconductor lasers in optical tweezers

2.1 Specific features of beam formation and technological advantages

The main problem discussed in the first papers on the use of semiconductor lasers in optical tweezers was the problem of sharp focusing of the beam from a semiconductor laser that possesses ellipticity and astigmatism. This problem was solved by correcting the beam asymmetry with anamorphotic prisms [2, 3], diaphragms, single-mode fibres, or objective aperture. In these methods the loss of up to 50% of power is observed, however, they all have been successfully used by the authors of Ref. [3] for trapping polystyrene particles, as well as the yeast and bacteria cells, by the optical tweezer based on the semiconductor laser. In Ref. [5] the problem of preliminary correction of the ellipticity and astigmatism for the beam from the laser diode was solved by means of using cylindrical optics. For the formation of the optical trap the laser diode with the miniature cylinder (Blue Sky Research) built in the case was used. An alternative approach was used by the authors of Ref. [1] who formed an optical trap using the aspheric CD lenses (Philips) specially manufactured for focusing strongly diverging beams. It was noted that the outgoing beam after the lens was elliptic, and the intensity profiles were more flat-top shaped in comparison with Gaussian beams. As sources of radiation, the single-mode gain-guided GaAlAs lasers with the maximal output power 40-50 W and the radiation wavelength 780 nm were used. The formation of traps was implemented using the microscope objectives (32×, NA=0.4) that allowed the focusing of the beam into a spot with the diameter 1.5 μm. The authors formed two types of traps, the single-beam trap and the double-beam one (in which two laser diodes were used). The optical manipulation experiments were performed with aqueous suspensions of polystyrene spheres having the diameter 9.6 μm and the refractive index 1.58, as well as with the human lymphocytes.

The authors of Ref. [6] presented the so called compact optical tweezers (COT) based on laser diodes. The specific feature of their tweezer is that the laser diode (Sanyo DL-8031-031A, radiation wavelength 808 nm, maximal power 200 mW) together with the correcting optics (aspherical lens, anamorphotic prism, mirrors) was inserted directly into the microscope tube

between the ocular and objective. The optical system was optimised by means of the original program (Zemax optical program) to provide the sharp (optimal) beam focusing. The power stability in the focus was provided by the temperature stabilisation of the laser diode using the special module Supercool PE-017-06-11. The authors use the term COT for the entire construction, including all elements mentioned above. The COT was designed to provide the minimal size, simplicity of the use, and modularity. The system was installed into the inverted microscope (Olympus IX-70, 100x), the objective of which formed the optical trap. The trapping was demonstrated for polystyrene particles with the size from 0.5 μm to 30 μm, suspended in water, and for the yeast cells.

Semiconductor lasers were successfully used for the construction of multiple traps. For the first time this technique was described in Ref. [7]. For optical trapping the authors used an array of vertical-cavity surface-emitting lasers (VCSEL array). In particular, they used the 8×8 VCSEL array (NTT Photonics Laboratory) with the radiation wavelength 854±5 nm, the output power exceeding 3 mW, the aperture diameter 15 μm, and the mesh 250 μm. The advantage of such tweezer is the possibility of controlling the radiation of every laser independently, which allows flexible manipulation of microscopic objects. Besides that, the, VCSEL array is easily combined with microoptics, the control of the displacement is implemented by switching on and off the appropriate elements, which allows the technological simplification of the system. The experiments on simultaneous trapping and moving of two microscopic objects (polystyrene microspheres with the diameter 6 μm and 10 μm) with two elements of the array switched on were demonstrated. The displacement of the particles in the liquid was implemented by moving the substrate. The power of radiation in the trap was less than 10 mW. It was also shown that the microobject can be moved along a certain trajectory (in particular, the L-shaped trajectory was realized) by switching the individual elements of the array. In Ref. [8] the multiple-beam optical trap for manipulating of several objects at once was formed using the acoustooptical deflector (AOD). The beam of the semiconductor laser with the radiation wavelength 780 nm and the output power 90 mW was incident on the AOD and then the first diffraction order was focused on the sample. The multiple trapping was implemented by fast scanning of the beam over the AOD. The aqueous suspensions of polymer spheres were used as samples.

Semiconductor lasers were used in optical fibre laser tweezers, both in the double-beam one based on two single-mode fibres and two diode lasers with the wavelength 980 nm [9], and in the single-beam tweezer developed by the research team from Japan [10,11]. In the latter the sharply focused beam was formed at the output from the optical fibre with high numerical aperture. Such optical tweezer was proposed by the authors in Ref. [12]. The laser semiconductor module was used for the first time in their tweezer for the experimental study of the dependence of trapping efficiency upon the distance (along the z-axis) between the fibre and the substrate [13]. The radiation wavelength was 1.48 μm. The role of microscope objectives was played by polystyrene and silicon particles with the diameter 10 and 5 μm, respectively, dispersed in ethanol. In these experiments the 2D trap was implemented. Later the 3D trapping was achieved at the expense of the specially shaped tip of the optical fibre. The chemical etching method was used to form the sharp tip (17°) [10] or axicon [11]. In these papers the laser module with the wavelength 980 nm was used, which allowed one to perform experiments with biological objects.

The use of a low-power laser diode (the wavelength 785 nm) simultaneously for optical trapping and for exciting the Raman scattering allowed the authors of Ref. [14] to create a compact laser tweezers Raman spectroscopy (LTRS) system. To provide the trap formation, the beam from the semiconductor laser was introduced into the inverted microscope with high numerical aperture of the objective (100×, NA=1.3). The same laser could be used to excite the Raman scattering from the trapped particle. The scattered radiation was collected by the same objective and entered into a spectrograph. The laser was switched from one power value to another; for trapping the power of 2 mW (directly on the sample) was used, and to excite the scattering the power was switched to 15 mW for a short period of time. The experiments were performed with the aqueous suspensions of RBCs and yeast cells (living and dead). The spectral difference between the different types of cells was observed. It is worth noting that the studies on combining the optical trapping methods with IR and Raman spectroscopy have been carried out by other authors too, and not only for identification of biological objects. The specific feature of the studies performed by the group of Ch. Xie is just the use of a semiconductor laser for this goal.

Optical tweezers based on laser diodes have found wide application in microfluidic systems. Thus, a series of papers [15-18] by R. Applegate Jr., D. Marr, J. Squier, S. Graves et.al. (USA) are devoted to the microfluidic flow manipulation of microobjects using a bar of diode lasers. The authors of the paper report the simple and relatively cheap technique that allows the control of a large capture zone without the necessity of laser beam scanning or varying its phase. In Ref. [15] the trap in the form of a light segment was formed by using a bar of laser diodes (JDS Uniphase, SDL-6300) with the dimensions 100 μm×1 μm, radiating at the wavelength 980 nm and having the power up to 3W. To form sharply focused beams the microscope objective 40× with the numerical aperture 0.65 was used. The resulting segment allowed simultaneous trapping and alignment of several particles along the light line. The results of such experiments were demonstrated for polystyrene particles having the diameter 1.8 μm, 10 μm, as well as for red blood cells. Increasing the dimensions of the diode lasers bar to 460 μm×1 μm with

the maximal output power 5 W at the wavelength 808 nm made it possible to trap and sort larger (exceeding 100 μm) particles [18]. The proposed technique was further developed by using an optical fibre instead of the microscope objective for focusing [16]. This allowed R. Applegate Jr. et al. to construct a portable optical tweezer for using in microfluidic techniques and to make the injection of radiation into the microfluidic systems and the control of the optical trap inside them easier by using the optical fibres. To form the optical trap in the form of a light segment, the bar of diode lasers (Snoc Electronics, LD-005) with the built-in cylindrical microlens was used. The bar dimensions were 200 μm× 1 μm, the mean power was 3 W, and the radiation wavelength was 808 nm. The output radiation was projected directly onto the sample through the polymer fibre with the diameter 1 mm with the refractive index 1.49 (Industrial Fiber Optics), placed perpendicularly to the beam trajectory. A unique module for optical manipulation was presented in Ref. [19]. A specific feature of the device is that the microfluidic channels are formed directly in the laser active medium. The module is fully portable and does not require alignment. In the module four lasers were used placed in pairs against each other. The counter-propagating optical beams in each pair formed the optical trap. The device was based on the GaAs/AlGaAs heterostructure with InAs quantum dots and radiated at the wavelength 1290 nm. A similar system operating at the wavelength 980 nm was fabricated on the base of the heterostructure with GaAs quantum wells. The microchannels were etched chemically inside the structure. The authors experimentally demonstrated the capabilities of the module for solving many manipulation problems. In particular, one particle or a few particles of polystyrene with the diameter of 5 μm were captured and trapped. The trapped particle was then released from the trap by switching on and off the appropriate pair of lasers forming the trap. The possibility of transferring the particles from one trap to another between the traps separated by 100 μm in the direction, perpendicular to the flow, was demonstrated. The possibilities of trapping a biological particle, aligning a few colloid particles along the line, perpendicular to the flow, etc., were also demonstrated.

The so called optical travolator (horizontal transporter) for transporting and dynamical sorting of colloid particles in aqueous suspensions was presented in Ref. [20]. The travolator is an optical trap in the form of a light segment with the asymmetric intensity profile, shaped using the diode laser (SUWTech LDC-2500) with the radiation wavelength 1064 nm and the maximal output power 400 mW in combination with cylindrical lenses. The laser beam was split into two beams using a beam splitter. Each beam was passed through a cylindrical lens (the lenses were tilted and shifted with respect to the optical axis) and then the light from two arms was collected and sent to the microscope. In the setup the inverted microscope (Nikon TE300) with the immersion objective (100×, NA=1.3) was used. The samples were aqueous suspensions of negatively charged particles of polystyrene or silicon. To create a liquid flow in the cuvette with the sample the voltage from 0 to 110 V was applied using the picoamperemeter to the especially built-in copper electrodes in the cuvette. The applied electric field provided a uniform flow, and the velocity of the particles motion was controlled by the value of the applied voltage. Using the formed light segment, the authors carried out the experiments on transporting silicon microspheres with the diameter 1.58 μm along the segment. Moreover, they placed two segments at some angle to each other to redirect the particles (polystyrene spheres with the diameter 1.2 μm) and to concentrate them in the bounded volume. In the paper the results of the experiment on sorting the particles of two sizes, 1.2 μm and 3.2 μm, were also presented. The possibility of manipulating the objects of biological origin was demonstrated by the authors by the example of yeast cells.

An interesting technique of trapping and manipulating the microobjects of different nature (polystyrene particles, yeast cells, *Bacillus cereus* bacteria) was described in Ref. [21]. To tear the microobjects from the substrate the authors used the infrared (the wavelength 1.06 μm) pulsed laser. The great gradient force (up to 10^9 N) arising for the short time (about 45 microseconds) allowed the particle to overcome the substrate adhesion. Then the continuous-wave low-power diode laser with the radiation wavelength 785 nm was used to trap and manipulate the particle, lifted above the substrate.

2.2 Applications in biomedical studies

In fact, the authors of all the papers mentioned above pointed out the promising potentialities of the optical tweezers based on laser diodes of the infrared range for biomedical applications and demonstrated the possibility of optical manipulation for the objects having the biological origin, e.g., bacteria [3, 21], yeast cells [3, 6, 10, 14, 20], human erythrocytes [14, 22, 23] and lymphocytes [1]. In Ref. [10] the experiments on isolating the symbiotic chlorella from *Paramecium Bursaria* were described. The dependences of the stretching of single-layer liposome membranes upon the radiation power and the relative refractive index were studied by the authors of Ref. [9]. The liposomes were stretched by means of the double-beam optical fibre tweezer, the power being varied from 30 mW to 53 mW. To change the refractive index of the aqueous solution the special polymer (polyethylene glycol, PEG) was added in different concentrations. The results of the experiments on erythrocyte stretching both in stagnant fluid and in the flow, obtained using the technologically simple asymmetric optical trap based on an inexpensive diode laser, are presented in Refs. [22, 23]. Interesting results for biomedical applications were obtained using the compact LTRS system. The technique proposed in Ref. [14] and described above in Section 2.1 acquired further development, namely, the variations of Raman

spectra of cells and yeast depending on the solution temperature were studied, the *in vivo* spectra were measured for the living pine cells, e-coli, and a number of other biological objects [22].

Of particular interest are the studies performed by the authors of Ref. [25], where the advantages of laser diode-based optical tweezers with the wavelength 830 nm are discussed in comparison with those using the Nd:YAG laser (1064 nm). The authors point out the drawbacks of using the radiation at the wavelength 1064 nm in optical tweezers. These drawbacks include the heating of water, the formation of temperature gradient close to the radiation focus, and the production of active forms of oxygen (in the presence of a stabiliser) that lead to the destruction of the biological samples. In particular, the destruction of nucleic acids and phosphodiester bonds was reported. It was asserted that there are two optimal wavelengths for the trapping of living cells, 830 nm and 970 nm. Just at these wavelengths the phototoxicity is minimal. Besides that, the authors ascribe to the drawbacks of the radiation wavelength 1064 nm the high transmittance of silicon at the wavelengths exceeding 1 μm, which leads to problems with the response of silicon detectors. As already mentioned, the experiments were carried out using two lasers, 830 nm and 1064 nm, respectively. A double-beam trap was formed, in which two diverging beams propagated towards each other. This trap was used to stretch the RNA. The experiments on trapping the mammary gland cells were also performed. It was shown that the cells did not die, in spite of relatively high power delivery (the observations were carried out during a few hours). Besides that, the authors experimentally found that at the wavelength of 830 nm the two-photon excitation of green fluorescence in the protein molecules occurs. This is expected to allow the future study of single protein molecules in a living cell.

Note, that the studies devoted to the comparative analysis of optical tweezers based on laser diodes of the visible range and the laser of the infrared range have been carried out significantly earlier. Thus, the paper by H. Schneckenburger, et al. [26] presents the results of direct comparison of the viability of the cultivated Chinese hamster ovary cells under different doses of irradiation in the course of trapping with optical tweezers based on the laser diodes, emitting in the visible range (670-680 nm), and on the Nd:YAG laser (1064 nm). On the one hand, the experimental results demonstrated the advantages of IR range, when the radiation doze is large (2.4 GJ/cm^2). On the other hand, it was shown that no cell destruction occurs also for the visible-range radiation with the dose of 340 MJ/cm^2.

The authors of Ref. [27] have found that for the same powers of radiation the gradient force in the trap using a pulsed laser is much larger as compared to the continuous-wave laser. To the opinion of the authors, this fact allows one to expect easy formation of optical tweezers for operating with biological samples, since the trap based on pulsed laser diodes is simultaneously characterised by sufficient rigidity (from the point of view of optical trapping) and softness (from the point of view of minimal damage of the samples).

2.3. Possible prospects

In the context of optical manipulation the beams with nonzero angular momentum are of particular interest. Due to the angular momentum transfer, the so called vortex beams are able to rotate the microobjects, move them along the predetermined trajectories, and cause different types of deformation. From this point of view the wide-aperture surface-emitting semiconductor lasers with vertical cavity are rather interesting, since in their cross section stable arrays of vortices arise. The construction of such semiconductor lasers provides the generation of a single longitudinal mode and a large number of transverse modes. The nonlinear interaction between high-order transverse modes gives rise to the appearance of complex optical field structures, in particular, to the formation of regular arrays of optical vortices and spiral waves. The spontaneous (without additional optical elements) formation of such stable structures was experimentally observed in Refs. [28-30]. For example, in Ref. [28] the variation of the transverse structure of a wide-aperture vertical-cavity laser under the variation of the pumping current was studied experimentally. It was found that with the growth of the pumping current beyond the threshold values the arrays of vortices can be observed. In Ref. [30] P. Genevet et al. experimentally demonstrated that the localised states in wide-aperture lasers can possess the orbital angular momentum. A number of papers were devoted to the studies, aimed at the development of a complete theory explaining and describing the dynamics of birth, existence and destruction of complex structures in wide-aperture lasers [31-34].

Obviously, the arrays of optical vortices arising in wide-aperture semiconductor lasers are of a certain interest for the problem of optical manipulation, however, no papers on the implementation of optical tweezers using such lasers could be found.

3 Compact setup for manipulating microscopic objects

Figure 1 presents the compact laser micro-manipulator based on the optical microscope XSP-104.

In the manipulator any small-size semiconductor laser module, or small-size DPSS laser modules, including laser pointers, can be used as a source of radiation. To apply a certain type of the laser module with definite wavelength, it is necessary to adjust the appropriate dichroic mirror in the especially fabricated adapter together with the corresponding optical filters at the input of the adapter and the input of the digital camera. The particular experiments were carried out with the semiconductor laser module DMH-650-60 (the wavelength 650 mn, the maximal power 60 mW), DPSS module DME-532-80 (the wavelength 532 nm, the maximal power 80 mW), portable DPSS module (laser pointer) LPH-532-150star (the wavelength 532 nm, the

power 50 mW, and the wavelength 1.06 μm, the power 90 mW). When operating with LPH-532-150star, the selection of radiation at the desired wavelength was implemented using the appropriate optical filters.

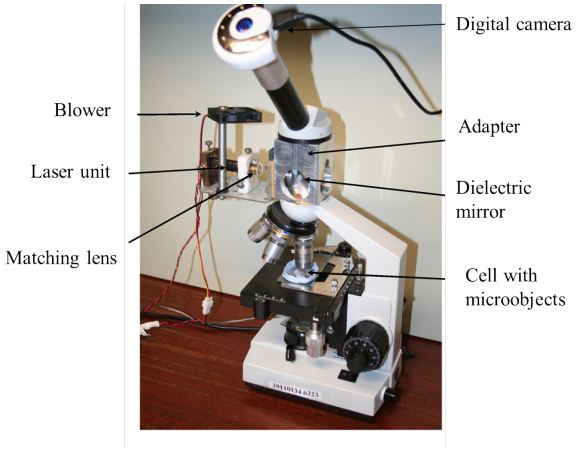


Fig. 1 Photograph of the compact laser tweezer.

The cooling of the laser module is implemented by means of the miniature blower attached to the stage with the supply voltage 12 V. The negative lens with the optical power 6 dioptres is glued to the output face of the laser module coaxially with the beam, output from the module. This lens provides the matching of the laser radiation focusing plane and the plane where the microobjects are found within the operating zone of the manipulator. Moreover, this lens expands the laser beam to the diameter of the entrance aperture of the microscope objective, which allows the reduction of the focusing spot. The module is supplied from the standard power supply unit, providing the control of the laser output power.

The microscope was upgraded by installing the especially fabricated adapter between the ocular unit and the microscope objective unit. Inside the adapter the adjustable bushing is placed, to which the dielectric mirror (the reflection coefficient 70% at the wavelength 0.65 μm for the light incident at the angle of 45°) is attached, tilted by the angle 45° with respect to the optical axis of the microscope. The adapter also incorporates the additional bushing for mounting optical filters that provide the attenuation of laser radiation, coming from the working zone to the photodetector of the digital camera. On the outside the rigid metallic plate is attached to the case of the adapter, on which the laser module alignment device is assembled. The alignment device provides the translational movement of the laser module in two mutually perpendicular transverse directions and the tilt of the module in two angles. The video recording is implemented using the ocular digital camera DCM-130 with the resolution of 1.3 megapixels, from which the image is transmitted to the computer.

The cell with microobjects suspended in a liquid is placed on the object stage of the microscope. The laser beam passing through the microscope objective (100×, NA=1.25) is focused into a spot with the diameter about 1.5 μm, thus forming a point optical trap. The calibration of the optical trap using the force drag method, the direct measurement of the optical trap forces depending on the parameters of the captured objects, their position, and also the characteristics of the trap itself, the quantitative assessment of micromechanical properties of complex liquid media (polymers, membranes, biotissues), and a number of other problems imply the implementation of the controlled movement of the microscope object stage with sub-micrometre accuracy. For this goal the stage of the microscope XSP-104 was equipped with the step motors (SY 35ST26-0284A) and the appropriate drives with the step 0.132 μm of the displacement in the horizontal plane. The especially designed control unit and the developed software (graphic user interface) allow the real-time control of the step motors operation from the monitor screen, where the operating field of the microscope is displayed. In particular, the system allows one to put the cell into the starting position for the initial capture of the microobject and to move the stage with the cell with microobjects with given initial velocity and constant acceleration. Similarly, a special module provides the movement of the stage with the cuvette and particles along the z axis with the step 125 nm. Thus, the considered compact manipulator allows the formation of point optical traps and the control of their position with high precision.

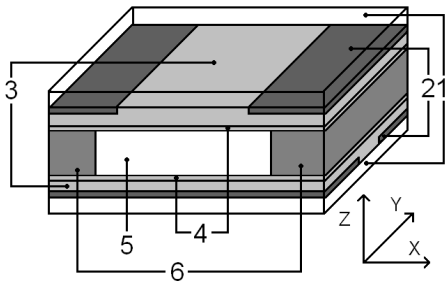
4 Contour trap formation

In some problems it is required to form optical traps with the shape more complex than the point trap, namely, with the shape of rings, ellipses, light segments, etc. In biomedical studies the interest to such optical traps is related, first of all, to the problem of minimising the negative effect of laser radiation on the trapped object. As mentioned above, the essential reduction of this effect is possible at the expense of the optimal choice of the wavelength, in particular, using the diode lasers operating in the infrared range. Nevertheless, as it was correctly pointed out in Refs. [35, 36], for trapping of single eukaryotic cells with the size greater than the point trap, the maximal impact is at the nucleus as the most dense structure of the cell. Hence it is desirable to provide the stable capture of a cell by its peripheral part using the traps having the shape of rings, ellipses, or arcs. Correspondingly, the interest to the traps having the form of light segments can be related to the necessity of capturing and orientation of elongated objects.

The multi-pixel liquid crystal spatio-temporal light modulators (LC STLMs) possess unique capabilities for forming complex-shaped traps and dynamic control of their configuration, so they are widely used in the optical manipulation. However, their use in compact, technologically simple and relatively inexpensive optical tweezers can be unreasonable. Alongside with the high cost and the operation in the reflected light (which leads to the increase of the dimensions of the

optical tweezer system), the drawbacks of the LC STLMs include the relatively low diffraction and energy efficiency. As an alternative to the multi-pixel modulator, we use the four-channel LC modulator (LC focusing device) for the formation of complex-shaped traps in the compact optical tweezer setup. The schematic diagram illustrating the construction of LC focusing device is presented in Fig. 2 and considered in detail in Refs. [37-43]. The device consists of two cylindrical modal LC lenses, joined into a single unit. The layer of nematic LC is enclosed between two glass substrates with transparent high-resistance coatings and low-resistance strip contacts deposited on them. The substrates are placed so that their contact electrodes are perpendicular to each other. By controlling the electrophysical parameters of the device one can vary the distribution of the electric voltage over the aperture. Under the action of the voltage the reorientation of molecules (S-effect) occurs in the LC layer. This leads to the change of the spatial distribution of the phase shift, contributed by the LC layer to the phase of the transmitted light wave.

a



b

Fig. 2 Exterior view (a) and schematic diagram (b) of the LC focusing device: 1 – glass substrates, 2 – contact electrodes, 3 - high-resistance conducting layer, 4 – orienting coating, 5 - LC layer, 6 – spacers. The diameter of the white case is 5.5 cm, the area of the small spot in the centre of the device (aperture) is 1 mm×1 mm.

The scheme of experimental setup is presented in Fig. 3. The specific feature of the optical trap formation using the four-channel LC modulator is that the device operates in the transmission mode. This fact allows the simplification of the optical tweezer scheme and the reduction of its dimensions. In order to get the complex-shaped optical traps in a compact optical tweezer the device is placed after the laser module and collimator. For controlling the LC focusing device we used the computer-controlled four-channel generator of sinusoidal oscillations [38]. The control unit allows the application of four independent potentials having the same frequencies, the controlled amplitudes in the range from 0 to 12.5 V, and the phase shift from 0 to 2π to the contacts of the focusing device. Thus, using only four control contacts one can produce different intensity distributions, control their shape and size, and move them across the focusing device aperture.

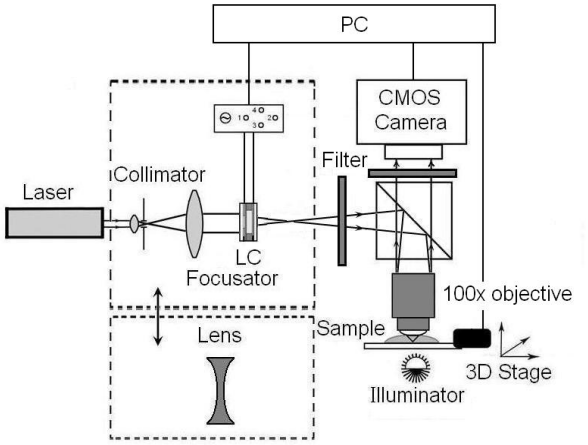


Fig. 3 The scheme of experimental setup. The frame with collimator and LC focusing device is used for the contour traps formation and the frame with diverging lens is used for the point trap formation.

Note, that the light field intensity distributions having the contour shapes are typically produced at the distance from 3 to 6 cm from the focusing device. The distance and the form of the contour trap depend on the phase shift profile, the deflection value, and the distribution width. To get the desired light distribution in the plane of microobject manipulation, one has to match the microscope observation plane with the plane where the contour filed is formed after the LC focusing device. Thus one can create optical traps having the shape of a segment, ring, ellipse, arc, etc. [40, 41, 43]. Examples of the possible types of optical traps are presented in Fig. 4.

Surely, such intensity distributions and the corresponding optical traps can be successfully synthesised using the stationary diffraction optical elements (DOEs). However, due to the variety of shapes and sizes of biological objects it seems important to have the possibility to vary the shape and size of the trap in real time, depending of the trapped objects. The displacement, size and shape of the traps, produced by the focusing device, can be controlled very smoothly (in theory - continuously). This is due to such important feature of the LC focusing device, as the use of a solid electrode for creating the voltage distribution within the aperture limits, which allows the formation of a smooth continuous profile of the phase delay and the smooth change of the voltage distribution at the focusing device aperture at the expense of varying the potentials at the

contact electrodes. Practically, the possibility of smooth control of the ring size is limited by the discreteness of the controlling voltages, applied from the control unit, and can be improved by decreasing the discretization step. The possibility of continuous phase profile formation leads to the reduction of diffraction losses. Moreover, the device possesses sufficiently high radiation resistance: in the experiments the radiation power density, incident on the focusing device, approached 30 W/cm ^{2}.

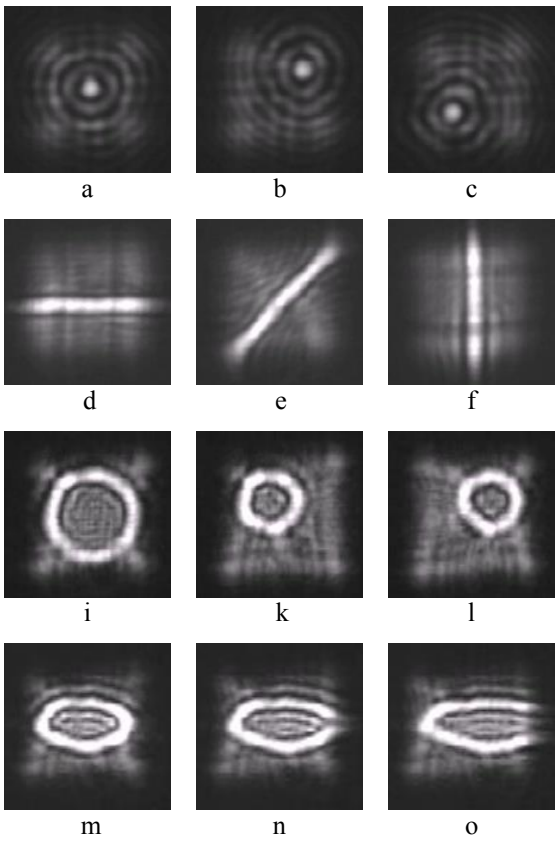


Fig. 4 Possible shapes of optical traps: controllable point traps (a-c), controllable trap in the form of a segment (d-f), ring trap (j-l), ellipse-shaped trap (m), C-shaped traps (n, o). The wavelength is 870 nm (a-f), and 650 nm (j-o).

As an example of using the compact optical tweezer based on the LC focusing device, let us present the results of the experiments, in which the *Saccharomy cescerevisiae* yeast cells suspended in water were used as the objects for micromanipulation, and the optical trap had the shape of an ellipse. The experiments were carried out at the radiation wavelength 532 nm. The radiation power in the optical trap amounted to 5.6 mW. The so called escape velocities were measured, i.e., the maximal velocities of the object stage motion for which the microobject remained to be captured by the optical trap. The measurements were performed with the displacement of the stage along the major semiaxis of the ellipse and along the minor one. Figure 4 presents the fragments of the video record, illustrating the capture and confinement of an individual yeast cell by the ring optical trap. The dependence of the escape velocity of the microobject upon its size for different directions of the displacement is presented in Table 1.

As seen from Table 1, the ellipse-shaped trap formed by means of the compact four-channel LC modulator allows the confinement of the trapped microobjects under the motion of the stage with the velocities of nearly 15 μm/s. If the dimensions of the trapped particle are smaller than the dimensions of the trap, then the shape of the trap plays an essential role. The escape velocity under the displacement along the minor semiaxis is greater than that in the case of moving along the major semiaxis (see the third row of Table 1). Similar results were obtained for trapping the latex microspheres with the diameter 2.4 μm. These particles were captured by the ellipse with the dimensions 3.9 μm × 4.8 μm. The escape velocity was 8.2±0.8 μm/s when moving along the major semiaxis of the ellipse and 14.0±1.4 μm/s when moving along the minor semiaxis.

Figure 6 presents the selected frames from a video record, demonstrating the possibility of capture and confinement of a relatively large particle. The object was the yeast cells, aggregated into a single particle with the dimensions 37 μm × 13 μm. The velocity of detachment of the object from the elliptic trap with the dimensions 4.8 μm × 4.2 μm for the displacement along its minor semiaxis amounted to 18.8±1.9 μm/s. The importance of manipulating large objects was repeatedly discussed in the literature [18, 44]. In biomedical applications this problem is related to the variety of sizes of the biological objects. The possibility of trapping and moving the microobjects larger than 10 μm by means of a contour trap will make it possible to avoid the nucleus damage when trapping the nucleated cells.

5 Conclusion

We demonstrate the scheme of a compact optical tweezer, in which the small-size semiconductor laser modules and small-size DPSS laser modules, including laser pointers, are used as a radiation source. It is shown that the use of the four-channel LC modulator (LC focusing device) in the scheme of the compact optical tweezer allows essential extension of its functional capabilities, namely, the formation of tuneable traps with a variety of shapes and the control of their position. The technological features of the four-channel LC modulator allow saving compactness and technological simplicity of the device. The operability of the compact laser manipulator with extended capabilities is demonstrated in the experiments with yeast cells.

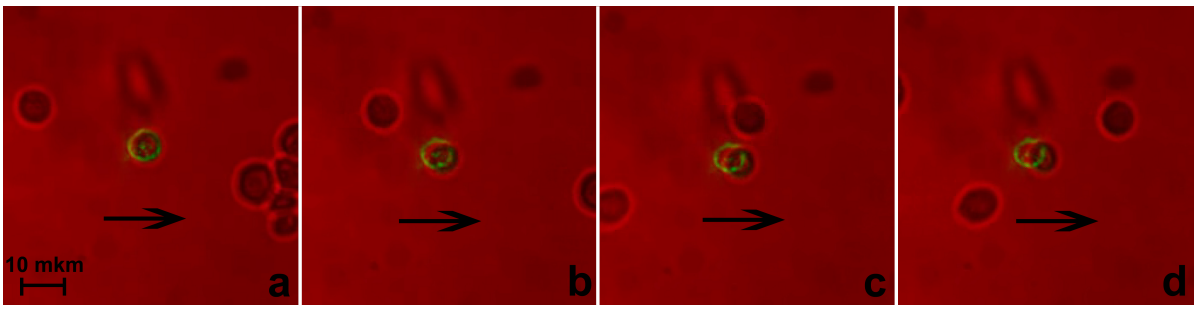


Fig. 5 Capture and confinement of a single *Saccharomy cescerevisiae* cell. The arrow shows the direction of the microscope stage movement.

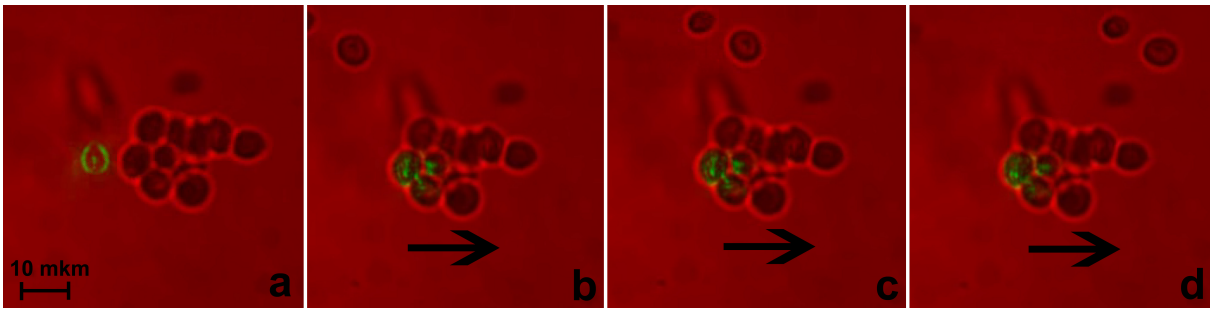


Fig. 6 Trapping and confinement of a large microparticle. The arrow shows the direction of the microscope stage movement.

Table 1 Escape velocities versus the size of the microobject (*Saccharomy cescerevisiae* yeast cells).

Particle size	Contour trap size	Escape velocity of the trap, μm/s	
		Displacement along the minor semiaxis	Displacement along the major semiaxis
5.0 μm × 5.6 μm	4.8 μm × 4.2 μm	15.3±1.5	15.0±1.5
4.9 μm × 6.3 μm		17.1±1.7	16.4±1.6
3.1 μm × 3.4 μm		16.7±1.7	12.7±1.3

Acknowledgments

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