Capture of microscopic objects by contour optical traps formed by 4-channel liquid crystal modulator

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Abstract. The efficiency of the contour optical traps generated by the 4-channel liquid crystal modulator for the manipulation with both transparent and absorbing particles has been experimentally studied. The maximum velocity of the substrate movement at which the captured particle is kept in the optical trap was used for the traps efficiency estimation. The obtained data show the ability of the effective capture of transparent objects with the ring traps even in the course of the objects boundary (periphery) being under the impact. The possibilities of a smoothly control of the size and the form of optical traps for increasing of the capture efficiency have been demonstrated.

1. Introduction
The object of this paper is an experimental study of the efficiency of the contour optical traps generated by a 4-channel liquid crystal (LC) modulator (LC focusing device). The LC focusing device is the spatial light modulator (SLM) characterized by the simplicity and compactness of the device and its control system, relatively low cost, sufficient energy efficiency and wide operating spectral range. The functionality of the 4-channel LC modulator is significantly lower as compared to the multi-pixel analogs. However, in problems of optical manipulation it can be effectively used for the generation of point traps, capable of capturing the transparent microobjects and their moving along a predetermined path within the focusing device aperture [1]. Besides, with the use of the focusing device the line segment traps can be formed applicable for the trapping and rotation of several particles or an elongated particle [1]. On taking into account a high practical interest to the capture and manipulation of absorbing microobjects including those of biological nature, we have considered the possibility of the formation and real-time control of the so-called contour traps [2] in the form of a ring, ellipse, and C-shaped.

Experiments on the optical manipulation by the traps in the form of light rings are described, for example, in works [3-6]. In [3] the behavior of silica microspheres moving under the influence of the periodic optical field is studied theoretically and experimentally. The axicon is used to form the Bessel beams with the intensity distributions in the form of concentric rings in the plane perpendicular to the direction of the beam propagation. The authors of [4] carried out experiments on the capture of absorbing and transparent microparticles with the use of hollow annular light beams. An array of such beams was formed by using a phase diffractive optical element (DOE), realized with the use of photolithography technique. The use of the stationary DOE is justified in researches where the dynamic changes of the beam are not required. And LC SLMs are the most promising in the studies where the control of light beams in real time is needed. The results of our experiments on the formation of optical traps of various types (including ring traps) with the use of the LC modulator
HOLOEYE HEO-1080P have been presented in [5]. In particular, the laser trapping of the 1.2 µm-diameter latex particles was fulfilled with the use of the ring-shaped optical trap that subsequently changed its shape from a ring to an ellipse. The experiments on the particles movement by the vortex optical trap in the shape of two concentric circulars have been also carried out.

By using the light modulator Holoeye LC - 2500R, the authors [6] have formed the Bessel beams of different orders and with different size of rings that allowed them to explore the behavior of transparent particles in such fields depending on the ratio of the particle radius and ring size, as well as the topological charge of the beam.

The 4-channel LC modulator application, on the one hand, allows to control the optical traps (their shape, dimensions) in real time, and on the other side – to create a compact and relatively inexpensive scheme of optical tweezers. The results of the implementation of this scheme and experiments on optical manipulation of both transparent and opaque objects with the use of contour traps are given in the article.

2. Formation of optical traps with a four-channel liquid crystal modulator

The LC focusing device is based on the integrated structure of crossed substrates of two cylindrical modal LC lenses. The nematic LC-layer is sandwiched between the two glass substrates covered with the transparent high-resistance coatings (the surface resistance ranges from 100 kOhm/square to several MOhm/square) and low-resistance non-transparent strip-shaped contacts. The substrates are oriented so that their contact electrodes are perpendicular to each other. The resulting device has a rectangular aperture. The LC-layer thickness is determined by the spacers and the initial planar orientation is ensured by the orienting coatings deposited onto the substrates. A detail description of the device principle of operation, its mathematical model and main operating regimes are given in [6-8]. In particular it has been shown that the frequency effect on the voltage distribution becomes negligibly small at the operating regime with a small modal parameter and as a result, the control of the voltage distribution is realized by means of the potentials amplitude and phase. In this case the equipotential lines of voltage distribution can only be of an elliptic and parabolic shape. The voltage distributions in the form of ellipses, circles and parallel straight lines generate the phase profiles of elliptic and circular truncated cones (due to the threshold nature of the voltage-phase dependence of LC-layer), as well as of cylindrical surface. While changing the amplitude and/or phase of the voltage fed to the contacts, it is possible to control both the location of the centers of circular and elliptic cones bases and the orientation of the elliptic cone axes and its eccentricity.

The optical transparency with the considered phase transmissions affects the plane uniform light wave in the following way. The light field with the central point maximum and concentric rings secondary maxima in the intensity distribution at the plane perpendicular to the light direction is formed in the far-field region when the phase delay has the shape of circle cone [7, 8]. For the case of the phase delay in the form of the cylindrical lens surface, the light in the focal plane is focused into the light segment with secondary maxima, and the central maximum intensity is substantially higher than secondary ones [9]. Thus it is possible to form point optical traps with the controlled position in the manipulation plane, as well as traps in the form of a segment with a given orientation [1]. In the field of the Fresnel diffraction at a short distance from the LC focusing device the following distribution of the light field is formed: the points of the maximum intensity are located on a curve similar to the shape of the lines of constant phase profile of the phase delay. Thus the contour optical traps in the form of rings and ellipses can be generated. The examples of possible optical traps formed with the use of the LC focusing device are presented in figure 1.
Figure 1. Different types of optical traps. The simulated (upper row) and experimentally obtained (second row) polarization interferograms; simulated (third row) and experimentally obtained (lower row) intensity distributions.

3. Experiments on optical capture

3.1. Experimental technique

In figure 2 the scheme of the laser manipulator with the integrated 4-channel LC modulator developed by the authors is shown. A solid-state diode-pumped laser with the emission wavelength of 0.53 µm and maximal output power of 500 mW was used to form the optical traps. The laser beam was directed through an interface collimator onto the LC focusing device. The LC focusing device and the lens form the required light field distribution in the specified plane. Then the beam was introduced into the 100x objective of an upgraded microscope XSP-104 and the result was a reduced intensity distribution reproduced in the manipulation plane. In order to visualize the working area of the experiment, an illuminator was placed under the cell with the microscopic objects. The imaging of the experimental procedure was made with the ocular digital camera DCIM-130 connected with the computer. The focusing device parameters were controlled via the graphical user interface that allowed specifying of the control voltage amplitude and phase in each of the channels.

The transparent microobjects (latex spheres of various diameters), nontransparent absorbing microobjects (particles consisting of a mixture of aluminum oxide and metal aluminum, silver particles, and their conglomerates) as well as microobjects of biological nature (е.coli and yeast Saccharomy cescerevisiae) were used for our experiments. The microparticles were suspended in water.

The efficiency of the traps was estimated by the maximum velocity of the substrate movement at which the captured particle is held in the optical trap. Microscopic objects were captured by the trap (either by the light ring boundary for transparent objects, or into a dark area for absorbing ones), then the microscopic stage was moved by a predetermined path with acceleration, and the velocity at which the particle was escaped from the trap was measured. It is evident that the particles separation from the trap occurs at the moment when the optical trap force is equal to the viscous force.
3.2. Capture and confinement of transparent objects
Transparent (non-absorbing) objects are trapped at the intensity maximum, i.e. they are captured by the light contour. The results of experiments on the capture and confinement of the latex microparticles with various diameters (d) by means of the ring trap with 5 μm diameter and 0.6±0.1 μm contour thickness are presented in table 1. The radiation power was 5 mW. The contact voltage was 6 V. The maximal velocity of microscopic stage relocation ($V_{max}$) at which the captured particle of a specified size is held in the optical trap are presented. One can see that the velocity is maximal for the particle of 2 μm diameter, i.e. the formed optical trap is more efficient for the objects of this size.

Table 1. The experimental results of the study of the efficiency of the ring optical trap with 5 μm diameter and 0.6±0.1 μm contour thickness for the capture of latex spheres of various diameters (d).

| d, μm | d/ contour thickness | $V_{max}$, μm/sec |
|-------|----------------------|-------------------|
| 0.9   | 1.5                  | 3.5±0.4           |
| 1.2   | 2.0                  | 8.5±0.9           |
| 2.0   | 3.3                  | 25.0±2.5          |
| 2.9   | 4.8                  | 13.9±1.4          |
| 5.0   | 8.3                  | 11.2±1.1          |
| 6.1   | 10.2                 | 1.9±0.2           |

The capture of transparent objects of the size substantially smaller than the diameter of the ring trap, is visually illustrated in figure 3. It is seen that the latex spheres of 2 μm-size and e.coli of the 0.7-0.9 μm-size are captured. The particles are arranged along the light contour (boundary) of the ring. The number of the particles captured by the optical trap is determined by their size and radiation power in the optical trap.

A qualitatively different picture for the capture is observed when the particle sizes are comparable to the size of the dark area of the ring (the diameter of the ring trap). In this case it is possible to capture the micro-object into the center of the trap. When the microscopic stage is moved with low speed the object is held in the trap center. The increase of the velocity results in the shift of the trapped
The capture and confinement of the transparent objects of the size comparable with the diameter of the ring trap is illustrated in figure 4.

**Figure 3.** The capture of transparent objects of a size substantially smaller than the diameter of the ring trap a) e.coli; b) latex spheres.

**Figure 4.** The capture and confinement of transparent object of the size comparable to that of the optical trap. Frames of video: different stages of capture (the arrow shows the direction of movement of the cell with particles).

The yeast *Saccharomyces cerevisiae* are used as the objects having the size comparable to the size of the dark region (intensity minimum) of the ring. The yeast is a weakly absorbing object at the used wavelength of 0.53 μm. The experiments were carried out at the radiation power of 3 mW. The dependence of the maximum velocity of the substrate relocation when the microobjects (with dimensions of 5.7 X 4.6 μm and 4.7 X 3.7 μm) were kept in a ring trap, on the change of its diameter (D) is presented in tables 2 and 3, respectively.

**Table 2.** The experimental results of the study on the efficiency of the ring optical trap for the capture of yeast cells with size 5.7 X 4.6 μm (d_{mean} = 5.15μm).

| D (μm) | d_{mean}/D | S_{particle}/S_{ring} | V_{max}, μm/sec |
|--------|-------------|-----------------------|-----------------|
| 3.1    | 1.66        | 2.70                  | 9.0±0.9         |
| 3.3    | 1.56        | 2.40                  | 6.9±0.7         |
| 3.6    | 1.43        | 2.02                  | 5.7±0.6         |
| 4.1    | 1.25        | 1.56                  | 4.7±0.5         |
| 4.4    | 1.17        | 1.35                  | 4.7±0.5         |

**Table 3.** The experimental results of the study of the efficiency of the ring optical trap for the capture of yeast cells with size 4.7 X 3.7 μm (d_{mean} = 4.2μm).

| D (μm) | d_{mean}/D | S_{particle}/S_{ring} | V_{max}, μm/sec |
|--------|-------------|-----------------------|-----------------|
| 3.1    | 1.35        | 1.81                  | 3.7±0.4         |
| 3.3    | 1.27        | 1.60                  | 3.5±0.4         |
| 3.6    | 1.17        | 1.34                  | 3.5±0.4         |
| 4.1    | 1.02        | 1.03                  | 3.5±0.4         |
| 4.4    | 0.95        | 0.89                  | 3.5±0.4         |
It is seen from table 2 that the maximal velocity of the microscopic stage motion at which the microscopic objects escaped from the optical trap is $9.0\pm0.9$ μm/sec for the 5.7 X 4.6 yeast cell. This value is significantly lower than the corresponding velocity for the microobjects capture by means of the point optical trap. The maximal velocity is $27\pm2.7$ μm/sec for the point optical trap (with beam waist 0.7-0.8 μm) with power radiation 3 mW. However, the obtained data show that the traps in the form of a ring can be effectively used for the capturing of transparent objects. The advantage of such traps as compared to the point traps for manipulation of biological objects consists in their ability to minimize the impact of the laser radiation on biological object by reducing of the power density, and impact on the periphery of the object. The relevance of the problem under consideration is discussed in [10], for example.

The efficient capturing under the influence on the objects periphery is confirmed by the last two lines of table 2. It is seen that the velocity values do not change and are $4.7\pm0.5$ μm/s at the decrease of the ratio of particle diameter to the diameter of the trap from 1.25 to 1.17. The ability of a further increase of the trap diameter without having to reconfigure the optical scheme was limited by the aperture of the LC focusing device. However, the experiments with the microobject of a smaller size (see table 3) proved the possibility of the capturing and retention under the impact actually on the border of the object: $d_{\text{mean}}/D=1.02$ and $d_{\text{mean}}/D=0.95$. The maximum moving speed of the substrate for these cases was $3.5\pm0.45$ μm/s. A similar result was obtained by the authors [4] for the capture of transparent (non-absorbent) particles in a dark area of light rings formed with the use of a stationary diffraction optical element. It is observed that for the effective capturing the size of the particles should exceed the radius of the ring.

You can also see from table 2 that $V_{\text{max}}$ depends on the diameter of the trap provided that this diameter is sufficiently large (for our experiments $d_{\text{mean}}/D=1.43\div1.66$). Thus the reducing of the trap diameter from 4.4 μm to 3.1 μm, during the capture of the yeast cells 5.7 X 4.6 μm resulted in double increase of $V_{\text{max}}$ (from 4.7 μm/sec to 9.0 μm/sec). So we can suppose that there exist the possibility to control the capture efficiency by means of the optical trap size.

The capture efficiency depends not only on the dimensions of the contour trap, but also on its form. This is confirmed by the experiments presented by movie frames in figure 5.

![Movie frames showing particle behavior in ring and ellipse traps](image)

**Figure 5.** Behavior of the particle in the trap depending on the shape of the trap. Upper row: the ellipse trap – the object is moving along the trap contour. Lower row: the ring trap – the microobject is stably held by the trap. The arrow shows the instant direction of movement of the cell with particles. The black dashed lines at the frames 1 are similar to the form of the intensity maximum of contour traps.
Yeast cells were used as micro objects. The microobject was captured by the contour trap and the microscope stage was moved along an arbitrary trajectory defined by the user. The shape of the trap was transformed from ellipse to ring during the experiment. You can see (upper line of figure 5) that for the ellipse trap the microscopic stage moving resulted in the relocation of the particle along a path (the particle does not leave the limits of the optical trap, but inside the trap it is moved by the fluid flow). Then the trap was transformed to the ring shape. In this case the microobject was kept by the traps and its relocation was not observed (see lower line of figure 5). Thus, the capture by the ring trap is more stable as compared to the trap in the form of an ellipse.

3.3. Experiments with absorbing objects

The traps with a minimum intensity inside (in the form of rings, ellipses, and so on) are the most interesting for the capture of absorbing objects into the dark region. In our experiments as the absorbing microobjects we used suspended in water microparticles (of 0.5-1.5 μm size) and their conglomerates (of 5-6 μm size) consisting of a mixture of aluminum oxide Al₂O₃ and metallic aluminum obtained in the process of electrical explosion of aluminum wires and also suspended particles of silver (Ag) obtained by the laser ablation. To capture the absorbing object it is necessary to move the trap closer to the object to overlap the radiation and open it again after the objects appears in the center of the optical trap. The shutter was used for radiation overlapping and the objects were delivered to the virtual marker on the screen that indicates the position of the center of the light ring.

The capture of particles by a trap in the form of a crescent (C-shaped optical trap) with its subsequent transformation into the ring is more easy-to-use for a number of tasks. The LC 4-channel modulator allows to form C-shaped optical trap and to transform it into the ring trap due to the change of applied voltage. For the formation of traps in the form of circle or ellipse arcs it is need that the lines of constant phase profile of the phase delays would not be closed within the aperture (that is, had the shape of an arc of a circle or ellipse). Since the light field distribution with the intensity maxima located along the contour of similar curve is generated in the near-field region of LC modulator, it is possible to form the corresponding C-shaped traps. The line of the constant phase will be not closed provided that the phase delay distribution is formed in the shape of a cone with the circle or ellipse base with dimensions slightly larger than the aperture or the generated distribution is shifted to the edge of the aperture.

The experiment on the capture and confinement of microparticles in this way is illustrated in figure 6. Microobjects are moved to the C-shaped trap formed by the focusing device (frame 1). The trap is transformed into the circle and the particles are captured with the trap (frame 2) and kept in it during the substrate motion (frames 3-4).

![Figure 6](image)

Figure 6. The capture and confinement of aluminum particles (of 1.5 μm diameter) by C-shaped trap transformed into the ring trap. The arrow shows the direction of movement of the microscopic stage.

The maximum velocity of the substrate relocation ensuring the confinement of the aluminum particle (with diameter 1.5 μm) in the ring trap of 8 μm diameter and 0.9 μm contour thickness at radiation power 10 mW was 2.5±0.3 μm/sec. This diameter of the trap was achieved due to the optical scheme reconfiguration which provided the input of the generated intensity distribution in the working area of the microscope.
The frames of the movie illustrating the argentum (Ag) particle confinement by the ring optical trap are presented in the figure 7. The outside diameter of the ring was 3.2 μm, the contour thickness was 0.9 μm and the Ag particle size was 2.7 X 1.1 μm.

Figure 7. Ag particle (2.7 X 1.1 μm) confinement by the ring optical trap (diameter - 3.2 μm, the contour thickness - 0.9 μm) during the substrate motion. The arrow shows the direction of movement of the microscopic stage.

The maximal velocity of the microscopic stage relocation ($V_{\text{max}}$) when the argentum particles of various sizes are still kept in the optical trap are given in table 4.

Table 4. The experimental results of the study on the efficiency of the ring optical trap with 3.2 μm diameter and 0.9±0.1 μm contour thickness for the capture of absorbing Ar particles of various size.

| Size, μm   | $V_{\text{max}}$, μm/sec | P, mW |
|------------|---------------------------|-------|
| 4.3 X 2.5  | 1.9±0.2                   | 3     |
| 2.7 X 1.1  | 1.9±0.2                   | 3     |
| 2.7 X 3.7  | 5.7±0.5                   | 2     |

The results of capture the Ag particle with the size 2.7 X 1.1 μm depending on the change of the trap size (ring diameter) are presented in table 5. It is seen that for the ring diameter equal to 3.5 μm the maximal velocity of the substrate movement was achieved. For the mentioned parameters of the particle and trap this velocity was 8.1 μm under the radiation power 2 mW.

Table 5. The experimental results of the study on the efficiency of the ring optical trap for the capture of absorbing Ar particle with the size 2.7 X 3.7 μm ($d_{\text{mean}} = 3.2$ μm).

| D, μm | $d_{\text{mean}}/D$ | $S_{\text{particle}}/S_{\text{ring}}$ | $V_{\text{max}}$, μm/sec |
|-------|---------------------|--------------------------------------|---------------------------|
| 3.2   | 1.00                | 0.98                                 | 5.7±0.5                   |
| 3.5   | 0.91                | 0.83                                 | 8.1±0.8                   |
| 4.2   | 0.76                | 0.56                                 | 5.7±0.5                   |
| 4.4   | 0.73                | 0.52                                 | 5.7±0.5                   |

Our experimental results show that there exists an optimal size of the ring traps, when the capture efficiency is maximum. This size is determined by the parameters of the captured micro-object (its size, shape, refractive index, absorption coefficient and so on) and this dependence is quite complicated even for transparent objects [3, 6, 11]. So it can be concluded that from a practical viewpoint the use of the 4-channel LC modulator for the absorbing microobjects capturing is reasonable and convenient since it allows to ensure a smooth control of the shape and size of the optical trap owing to the control voltage parameters change.
4. Conclusion
The experiments on the optical manipulation of transparent and absorbing particles by the contour traps generated with the use of the 4-channel LC light modulator have been carried out. The capture efficiency was estimated by the maximum velocity of the substrate that ensures the particles confinement in the trap. This value depends both on the parameters of traps and the geometrical and physical properties of micro objects. It has been shown that the ability of the LC focusing device to smoothly control the shape and size of the optical trap in real time allows to optimize the size of the trap to the size of the captured particles thus improving the capture efficiency. This can be useful, for instance for manipulation of the objects of biological nature (both transparent and absorbing), because of the variations in size, even within a single sample, attributable to them.

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5. References
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