Line optical traps formed by LC SLM

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Abstract. The methods for generation of optical traps in the form of line segments by means of liquid crystal modulators of two types are addressed in the paper, they are a multi-pixel modulator HOLOEYE HEO 1080P and a tunable liquid crystal focusing device (4-channel modulator) developed by the authors. The numerical and experimental assessment of the capture forces of the generated optical trap is fulfilled. The description of manipulation experiments with microobjects, including biological ones, carried out by the optical traps with the intensity distribution in the form of segments is offered. © 2015 Samara State Aerospace University (SSAU).

Keywords: optical manipulation; liquid crystal modulators; biological microobjects; light segment.

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References

1. H. Zhang, and K-K. Liu, "Optical tweezers for single cells," J. R. Soc. Interface 5, 671-690 (2008).
2. A. Banerjee, S. Chowdhary, W. Losert, and S. K. Gupta, "Survey on indirect optical manipulation of cells, nucleic acids, and motor proteins," J. Biomedical Optics 16, 051302 (2011).
3. K. Svoboda, and S. Block, "Biological applications of optical forces," Ann. Rev. Biophys. Biomol. Struct. 23, 247-285 (1994).
4. R. Skidanov, M. Rykov, G. Iannacchione, and S. Krivoshlykov, "The modification of laser beam for optimization of optical trap force characteristic," Computer optics 36**,** 377-386 (2012).
5. M. Rykov, and R. Skidanov, "Modifying the laser beam intensity distribution for obtaining improved strength characteristics of optical trap," Applied Optics 53(2), 156-164 (2014).
6. A. Korobtsov, S. Kotova, N. Losevsky, A. Mayorova, and S. Samagin, "Formation of contour optical traps with a four-channel liquid crystal focusator," Quantum Electronics 44(12), 1157-1164 (2014).
7. F. Cheong, C. Sow, A. Wee, P. Shao, A. Bettiol, J. van Kan, and F. Watt, "Optical travelator: transport and dynamic sorting of colloidal microspheres with an asymmetrical line optical tweezers," Applied Physics, 83, 121-125 (2006).
8. R. W. Applegate Jr, J. Squier, T. Vestad, J. Oakey, and D. W. M. Marr, "Fiber-focused diode bar optical trapping for microfluidic flow manipulation," Applied Physics Letter 92(1), 01394 (2008).
9. R. W. Applegate Jr, D. W. M. Marr, J. Squier, and S.W. Graves, "Particle size limits when using optical trapping and deflection of particles for sorting using diode laser bars," Optic Express 17, 16731 (2009).
10. R. Skidanov, and A. Porfir'ev, "Optical micromanipulation with using binary focusator," Computer optics 34, 214-218 (2010).
11. E. Spyratou, M. Makropoulou, and A. Serafetinides, "Red blood cell micromanipulation with elliptical laser beam profile optical tweezers in different osmolarity conditions," Proc. of SPIE-OSA Biomedical Optics, 8092, 80920T (2011).
12. R. Dasgupta, S.K. Mohanty, and P.K. Gupta, "Controlled rotation of biological microscopic objects using optical line tweezers," Biotechnol. Lett. 25(19), 1625-1628 (2003).
13. R. Applegate Jr., J. Squier, T. Vestad, J. Oakey, and D. Marr, "Optical trapping, manipulation, and sorting of cells and colloids in microfluidic systems with diode laser bars," Optics Express 12(19), 4390-4398 (2004).
14. R. Applegate Jr., J. Squier, T. Vestad, J. Oakey, D. Marr, P. Bado, M. A. Dugan, A. A. Said, "Microfluidic sorting system based on optical waveguide integration and diode laser bar trapping," Lab. Chip. 6(3), 422-6 (2006).

15. S. P. Kotova, V. V. Patlan, and S. A. Samagin, "Tunable liquid-crystal focusing device. I. Theory," Quantum Electron. 41(1), 58-64 (2011).
16. S. P. Kotova, V. V. Patlan, and S.A. Samagin, "Tunable liquid-crystal focusing device. II. Experiment," Quantum Electron. 41(1), 65-70 (2011).
17. S. P. Kotova, V. V. Patlan, and S.A. Samagin, "Focusing light into a line segment of arbitrary orientation using a four-channel liquid crystal light modulator," Journal of Optics 15(3), 035706 (2013).
18. M. Capitanio, G. Romano, R. Ballerini, M. Giuntini, F.S. Pavone, D. Dunlap, and L. Finzi, "Calibration of optical tweezers with differential interference contrast signals," Review of Scientific Instruments 73(4), 1687-1696 (2002).
19. A. Korobtsov, S. Kotova, N. Losevsky, A. Mayorova, V. Patlan, and S. Samagin, "Optical trap formation with a four-channel liquid crystal light modulator," Journal of Optics 16, 035704 (2014).

1 Introduction

Probable causes for the interest in the optical tweezers applications for the problems of biology and medicine (see reviews [1-3]) can be the unique capabilities of this toolkit, i.e. the possibility of contactless impact on the objects being studied, resulting in a high sterility, the possibility submicrometer precision of displacement control of the biological objects, etc. The sizes of objects that can be effectively trapped by the optical tweezers, range from a few nanometers to hundreds micrometers, and these very sizes are typical of the most biological cells and their organelles. The order of the applied forces, from 10^{-12} to 10^{-9} N, is sufficient for the effective capture and manipulation of biological objects. In view of the diversity of sizes and shapes of biological objects, as well as a wide range of biomedical problems solvable by means of specified tools, the capture and manipulation of biological objects is fulfilled with the aid of not only the point optical traps representing sharply focused Gaussian beams, but also the traps of other configurations. It is important to search the optimal form and parameters of the trap to solve a specific biomedical problem. Thus the traps with the intensity distribution in the form of Crescent are proposed by the authors of [4, 5] for the manipulation of biological microobjects. Such traps can effectively capture objects while acting on their periphery, not the center. This property is important for the maintenance of the functional state of the cells. The corresponding intensity distributions can be formed either through modification of the Gaussian beam or superposition of vortex beams with the use of stationary diffractive optical elements. The contour optical traps (in the form of rings, ellipses and C-shaped) formed with the LC focusing device [6] can also be used to minimize the radiation effects. The advantage of this method for the traps formation is the possibility of real-time control of their shape and size.

The optical traps with the intensity distribution in the form of line segments allow to capture simultaneously several objects, locate them in the required position, sort them by size and refractive index [7-9], move them along the trap [10] and align the elongated objects along the trap [11]. It is obvious that all these capabilities are of interest for biomedical applications. The techniques of generation of traps in the form of a line segment with the use of the LC modulators, in particular multi-pixel modulator HOLOEYE HEO 1080P and a tunable liquid crystal focusing device (4-channel modulator) developed by the authors are discussed in the article. A comparative analysis of the forces occurring in the point trap and the trap in the form of a segment was carried out. The results of experiments on manipulations of microscopic objects with formed traps are set forth below.

2 Methods for the line optical traps generation

The most simple, effective and inexpensive technique of the line optical trap (LOT) generation is that based on the use of a cylindrical lens placed in the path of the beam forming the trap. For the first time this method was proposed by R. Dasgupta et al. in 2003 [12]. The authors realized the rotation of the trapped objects (in particular the bacteria *E.coli*) by means of the lens rotation. Two cylindrical lenses were used for the formation of the LOT with asymmetrical (non-uniform) intensity profile by the authors of [7]. The generated LOT capabilities for the transportation and sorting of colloidal microspheres were demonstrated. As the advantages of the proposed optical tweezers scheme, the simplicity of its implementation and low cost were pointed out. The scheme for the formation of the optical trap in the form of a line segment with the use of two cylindrical lenses was also described in [11]. The LOT dimensions were 1 X 20 μm and it was used for the simultaneous capture of several RBCs and their orientation along the line segment.

The methods for such traps formation through the use of binary diffractive optical elements (DOE) are known [10]. First the corresponding DOE was computed so that the phase changed linearly along the line segment and then it was obtained with the aid of the photolithographic technique on the glass substrate. The authors described the experiments on the polystyrene microspheres (individual and multiple) capture and their further relocation along the generated line segment.

A large number of studies is devoted to the formation of LOTs by means of the laser diode bars [8, 9, 13, 14]. The optical trap in the shape of a line segment was realized with the use of the 1 μm-wide

linear single laser emitters that ranged in length from 25 μm to 1 mm. The authors noticed the technique simplicity, its low cost, possibilities for creating of a long linear trapping area for micromanipulation and easy embedding of diode bars into flowing microfluidic systems. The microparticles sorting in a fluid flow and also the capture of large particles (up to 200 μm-size) were realized with the generated optical trap.

Not only the generation of the light line segment but also its dynamic control can be achieved with the use of spatial light modulators. The typical scheme of the experimental setup for the generation of the dynamical optical traps is presented in Fig.1.

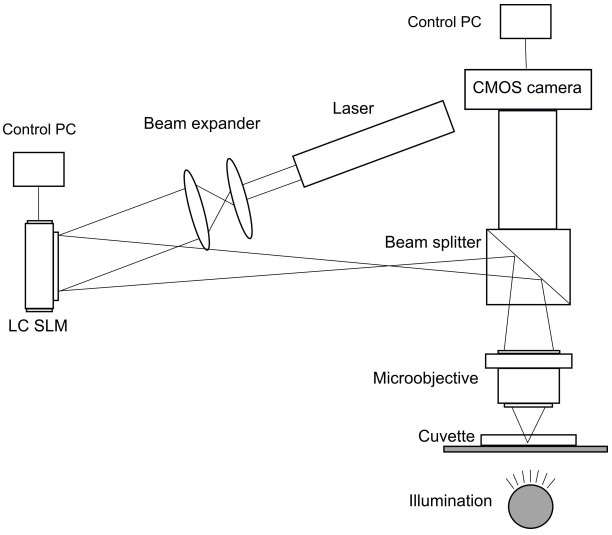

Fig.1 Scheme of optical tweezers with the implemented SLM.

We used a multi-pixel LC SLM HOLOEYE HEO 1080P for the intensity distribution generation in the form of a line segment. The used modulator had 1920 × 1080 addressable pixels and allowed to specify 256 phase gradation of the phase within the range from 0 to 2π. The line segment in the microscope working plane was obtained as a result of the formation of an astigmatic Fresnel lens by the transparency. The segment length could be controlled by the change of the astigmatism value. The transparency was illuminated with a uniform plane wave.

The four-channel LC focusing device can be used for the generation of dynamically controlled line optical traps as an alternative to multi-pixel liquid crystal modulators. In this case the optical scheme presented in Fig.1 can be used. However, the peculiar feature of the LC focusing device is its ability to operate in the transmission regime (note that the reflection regime is also possible if necessary), thus simplifying structurally the scheme of its integration into the manipulator. The principle of the LC focusing device operation was described in detail in [15-17]. The modulator under consideration is the device constructed on the basis of crossed substrates of the cylindrical modal LC lenses joint into the integrated structure. The device had four control contact electrodes and allowed to focus illumination into a point or segment. To focus the light into a segment, it was necessary to determine the voltage distribution with the equipotential lines in the shape of parallel lines. In this case the profiles of the phase delay in the form of the cylindrical lenses surface could be created. The optical transparency with such phase transmission will focus plane wave into light segment which position and orientation can be controlled by means of change of amplitude and/or phase of voltage applied to contacts [17]. The dimension of the generated line segment was determined by the focusing device aperture and parameters of the optical system, providing the input beam entry into the microscope.

It is clear that the LC modulators method for the line optical trap generating is significantly higher in price than the techniques based on the use of cylindrical lenses or laser diode bars. However, the use of the LC modulators widens the scope of opportunities for the formation and dynamic control of optical traps of different types. Besides, the precise mechanical movements of the active element are not required. It should be noted that the use of the 4-channel LC focusing device is considerably low-price as compared with the commercial multi-pixel liquid crystal modulators because of its significantly simpler design and control system. The device is characterized by quite a high energy efficiency and a wide working spectrum range, simplicity of its integration into the manipulator scheme due to the mode of transmission, and also by the ability to form a smooth continuous profile of the phase delay and to smoothly control it. The last-named ability is attainable due to the use of solid electrodes.

The results of the microscopic objects (including biological ones) manipulation experiments, carried out with the use of the generated optical trap are given in Section 4.

3 Analysis of the line optical trap capture force

The optical trap force was estimated experimentally with the use of the so-called drag-force method [18], which was for the first time presented in [3]. The optical trap force can be estimated by the viscous force determined by the formula:

$$F = V \times \beta, \tag{1}$$

where V is the velocity of particle motion in the liquid, β – the coefficient of viscosity. For a spherical particle of the radius r located close to the bottom of the cell, subject to the distance h between the particle center and the cell bottom, β is defined by the Faxen's formula:

$$\beta = \frac{6\pi\eta r}{1 - \frac{9}{16}(\frac{r}{h}) + \frac{1}{8}(\frac{r}{h})^3 - \frac{4}{256}(\frac{r}{h})^4 - \frac{1}{16}(\frac{r}{h})^5},$$

where η is the fluid viscosity.

Thus by measuring the microobjects escape velocity, it is possible to estimate the maximum or escape force of optical trap (the capture force). In our experiments the microobjects relocation in the liquid was attained by means of the microscope stage motion while the particle was held with the optical trap. For this purpose the microscope stage was equipped with stepper motors (SY 35ST26-0284A) and the corresponding actuators with the movement step of 0.15 μm, operated from the computer. The developed software (graphical user interface) allows to control the operation of the stepper motors in real-time from the screen monitor that displays the working field of the microscope. In particular, the system enables to place the cell in its original position for the initial capture of the micro-object and move the stage with the cuvette of samples with a given initial velocity and constant acceleration. Then the image of the operating field and the parameters of the cell moving are recorded in real time in the video file. The subsequent processing of the recorded data allows get the information about the optical trap force.

The experimental dependences of the escape velocity and capture force of the microoobjects on their radius for the line optical trap are shown in Fig. 2 and Fig. 3 respectively. The received dependences are compared with those for the point optical trap. The latex spheres of a certain size were used in these experiments as microobjects. The beam waist radius for the focused point beam and the half-width of the formed line segment in the manipulation plane were 1 μm. The radiation power in the trap was 10 mW.

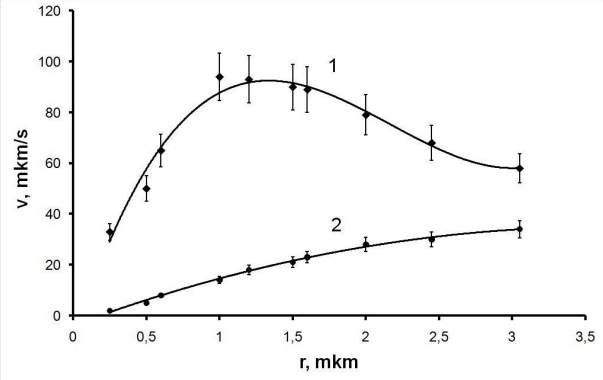

Fig. 2 The dependences of the escape velocity on the microsphere size for the point trap (1) and the LOT (2).

As mentioned above, the traps in the form of light segments are successfully used for the microparticles sorting [7, 9, 13]. The received dependences justify this possibility. Indeed, the analysis of the calculated graphs shows that the trap in the form of a segment allows a wider-range sorting of microparticles and a higher sensitivity to the microparticles size than the point trap. This fact can be explained as follows. The placed in a viscous fluid microbjects are trapped by the LOT. The objects motion in the liquid results in the viscous force appearance. The particles detachment from the trap occurs at the moment when maximal force of the optical trap is equal to the viscous force. Thus the value of the escape velocity is determined by the equilibrium between the optical trap force and the viscous force. The viscous force is increased linearly with the increasing particle size, leading to the velocity decrease. And the behavior of the dependences of the optical trap forces on the particle size differs for the point optical trap and line optical trap as it is seen from Fig. 3. The difference is explained by the fact that in case of the LOT the amount of the light flux intercepted by the particle continuously grows with the increasing of the particle size. And for the point trap the growth of the intercepted light flow is stopped when the particles size becomes equal to the trap size, and consequently the growth of escape velocity is also stopped. Thus for the case of point traps, the extremum appears in the dependence of the escape velocity. So for the case of the point trap, as you can see from Fig. 2, the escaped velocity can be equal for microspheres of different radius. There is no extremum observed in the dependence of the velocity on the particle size in case of line optical trap.

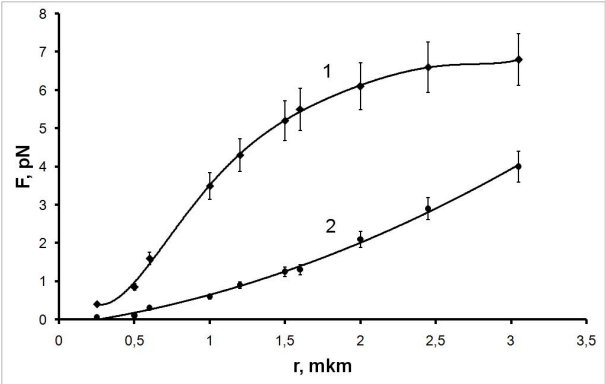

Fig. 3 The dependences of the capture force on the microsphere size for the point trap (1) and the LOT (2).

At the same time, the line-shaped trap provides a higher sensitivity of the capture force to the particle size. This fact is confirmed by both theoretically and experimentally obtained values of the capture forces for the traps in the form of a segment. Note that the calculations are performed in the framework of geometric optics subject to the geometry of the light beam in its waist. The simulations are based on the idea of an impulse flow transferred by the light wave, and the Fresnel formulas for the coefficients of reflection and refraction of light at the interface of two media. The initial field is defined in the plane perpendicular to the beam axis and tangent to the top point of the particles. Its intensity and phase are determined by the evolution of a Gaussian beam during propagation. Further the ray paths are set by the laws of geometrical optics. The diffraction of the laser beam on the microobjects as well as wave interference inside the microparticles are not taken into account during the simulation.

Both the simulated and experimental results for the capture force of the LOT for two values of the particle radius are presented in Table 1. The difference of the

calculated and experimental results is not exceeding 20%.

Table 1. The capture force for the LOT.

r, μm	F, pN (simulated)	F, pN (experimental)
0.6	0.30±0.03	0.24±0.04
1.6	1.30±0.13	1.25±0.18

As you can see from the table the strong dependence of the capture force on the particles size is observed for the LOT. The capture force for the 1.6 μm radius particles by 4-5 times exceeds the capture force for 0.6 μm-radius particles. The obtained results were compared with those for the point optical trap. As shown by simulations, for the case of the point traps the force values are higher, they are 1.6 pN and 5.5 pN for particles with the radius of 0.6 μm and 1.6 μm respectively for the same value of the radiation power in the trap. However, their ratio is less and is about 3.4.

Thus, the optical trap in the form of a segment can effectively capture micro-objects. And our simulations confirm that the sensitivity of the capture forces to the particles size for LOT is somewhat higher than for the point trap. So there is good reason to assert that the line optical traps can be more efficiently used for the micro-objects sorting by their size as compared to the spot traps.

4 The experiments on the microobjects manipulation

4.1 Experiments with the use of SLM HOLOEYE HEO 1080P

The experiments on the LOT-aided manipulation have been carried out by means of the experimental setup presented in Fig.1 with the SLM HOLOEYE HEO 1080P as the LC modulator. 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 SLM HOLOEYE HEO 1080P. 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 computer-operated ocular digital camera DCM-130. As the microobjects of various diameters (0.9 ÷ 3.2 μm), the latex spheres suspended in water were used. The velocity of the microscope stage relocation was about 5 μm/sec. The particles captured into the beam are held there under the impact of gradient force of light pressure. Since the light segment was placed at the 45^0-angle to the direction of the stage movement, the particles moved along the beam generated and escaped at its edge. Thus, the area "covered" by the light line segment remained free from any particles. The optical force was not sufficient to capture the particles of different size and these particles passed through the optical trap without deflection.

The usability of the LOT as the optical shield for the formation of a pure area in the fluid flow is illustrated by Fig. 4. The 1.2 μm-latex spheres were used for this experiment. The LOT geometry was 18 μm X 1 μm. The black arrows indicate the direction of the particle motion along the line segment (short arrow) and the direction of the LOT movement due to the microscope stage motion (long arrow).

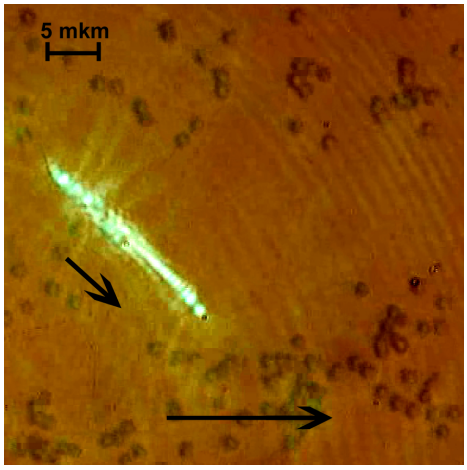

Fig. 4 LOT used as the optical shield for formation of a pure area.

4.2 Experiments with the use of the 4-channel LC focusing device

As already mentioned, the formation of the optical traps with the LC modulators allows to generate the defined intensity distributions and also dynamically control them. This functional property of the trap in the form of a line segment was obtained with the use of the LC focusing device. The solid-state diode-pumped laser and XSP-104-microscope described in paragraph 4.1 were used. The aperture of the focusing device was 1×1 mm^2. The applied voltages changed within the range from 3 to 8 V. The laser beam was directed through the interface collimator onto the LC focusing device where the required light field distribution in the specified plane was formed. Then the beam was introduced into the 100x-objective of the microscope and as a result the reduced intensity distribution was reproduced in the manipulation plane. The line segment in the plane of manipulation in our experiments had the following parameters: 7 μm-length and ~ 0.7 μm-width. The line segment planar orientation was achieved by the proper choice of the amplitude and phase of voltages applied to the focusing device contacts. The voltage generator used in the experiments allowed setting of the voltage amplitude accurate within 0.1 V, and phase – within 6 degrees. Under these conditions the discreteness of specifying the trap rotation angle was 15 degrees. A

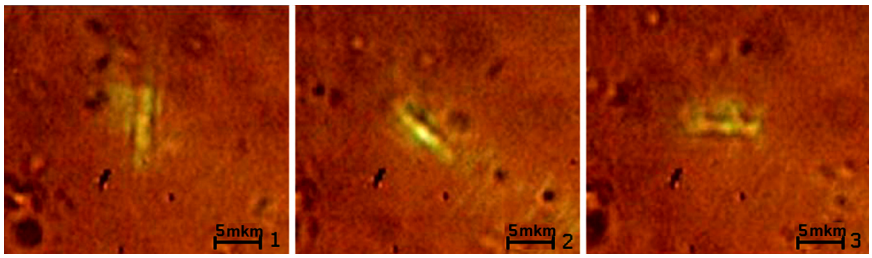

Fig. 5 LOT-aided capture, alignment and the rotation of the *E.coli* bacterium.

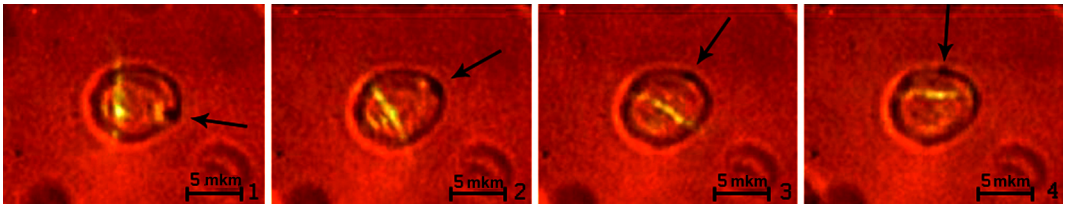

Fig. 6 LOT-aided capture, alignment and rotation of yeast cell.

more detailed description of the LC focusing device operation in this mode can be found in [17, 19].

The experiments with biological microobjects, in particular *E.coli*-bacteria and yeast *Saccharomy cescerevisiae* have been carried out. The yeast cells were previously held at 24^0 C for 13 hours in water. And the process of the *E.coli* preparation was as follows: the *Colibacterin siccum* was suspended in physiological solution, after that the glucose was added to the solution and the obtained mixture was additionally held for 12 hours at 36^0 C. The constant temperature was maintained with the aid of a thermostat.

The frames from the video presented in Fig. 5 and Fig. 6 illustrate the manipulation experiments for the *E.coli* and yeast *Saccharomy cescerevisiae* respectively. In both cases the microobjects were trapped with the LOT and kept in the trap during its rotation. The colibacillus (dark stripe in Fig. 5) having the form of a rod was aligned along the light segment.

The yeast cell size significantly exceeds the width of the light segment. However the rotation of the cell with the trap was obtained. A slight heterogeneity in the cell is marked with a black arrow in Fig. 6. And it is seen that the rotation of the LOT led to the cell rotation.

5 Conclusion

The techniques of the LOT generation with the use of the LC SLM are discussed. The capabilities and advantages of the optical traps of this shape in manipulation experiments have been studied both experimentally and numerically. The experimentally proved capabilities for the formation of a pure area in the fluid flow as well as for the alignment and rotation of biological microobjects afford a basis to talk about the prospects of the LC focusing device use in optical manipulation, including, biomedical applications.

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