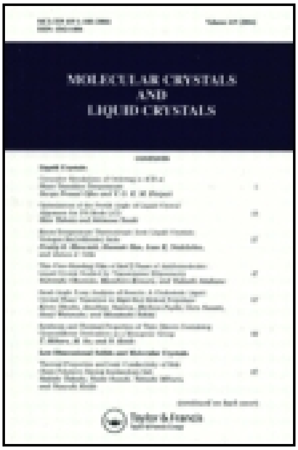
MOLECULAR CRYSTALS AND LIQUID CRYSTALS

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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Version of record first published: 22 Sep 2010

Mol. Cryst. Liq. Cryst., Vol. 488, pp. 238–245, 2008

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400802240680

Laser Manipulator for Rotating Microscopic Trapped Particles by Using Liquid Crystal Optical Devices

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We propose a laser manipulator for controlling positions and rotation of trapped microscopic particles suspended in water by using a liquid crystal (LC) device. This LC device has unique functions such as an anamorphic lens property, variable-focusing and deflection properties. The trapped slender particle can be aligned along the major axis of the elliptically shaped laser beam spot and the position of the particle can be controlled. Furthermore, the positions of multiple microscopic particles can also be controlled along the interference fringe patterns of a wedge LC cell.

Keywords: interference fringe pattern; laser beam deflection; laser manipulator; liquid crystal optical device; microscopic particle; variable-focusing

1. INTRODUCTION

Laser manipulation system has been used to trap dielectric spheres, biological samples such as viruses, bacteria and living cells, organelles by using a single-beam gradient force [1]. The optical pump and valve with colloidal particles in micro-fluidic channels have also been widely used by activating the focused leaser beam [2].

Electro-optic liquid crystal (LC) devices such as LC lenses [3,4], LC micro-lenses [5], LC gratings [6] have been studied and demonstrated. The focal length of the LC lens and LC micro-lens can be tuned by applying a voltage. We reported three-dimensional microscopic

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particle manipulation by using a composite lens of an objective lens and an LC lens with two functions of variable focusing and beam deflection properties. The trapped particles such as polystyrene balls can be shifted in the longitudinal direction as well as the transverse direction without any use of mechanical parts [7].

In this paper, we demonstrate the optical trapping for controlling the positions and rotations of the trapped particles suspended in water by using the LC optical device.

2. EXPERIMENTAL

Figures 1(a) and 1(b) show top and side view structures of the LC optical device for controlling the position and rotation of the microscopic particles. A thin LC (ZLI-6080, Merck) layer (110 μm) with a positive dielectric anisotropy is sandwiched between two glass substrates. The lower glass substrate is coated with a transparent indium tin oxide (ITO) film and its surface with the ITO faces the LC layer. The outer surface of the upper substrate is coated with eight-divided-circularly-hole-patterned aluminum thin film electrodes and its diameter is 3.8 mm. The surfaces of the substrate which face the

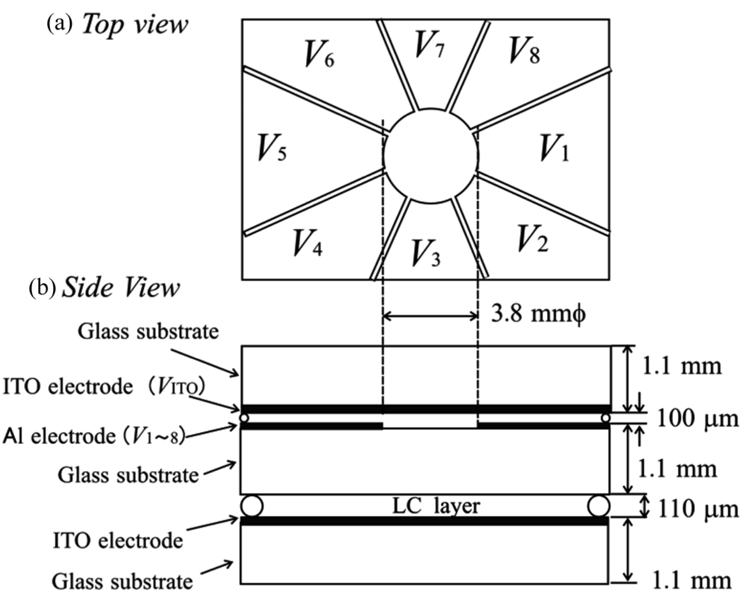


FIGURE 1 LC optical device with eight-divided-circularly-hole-patterned electrodes and external control electrode.

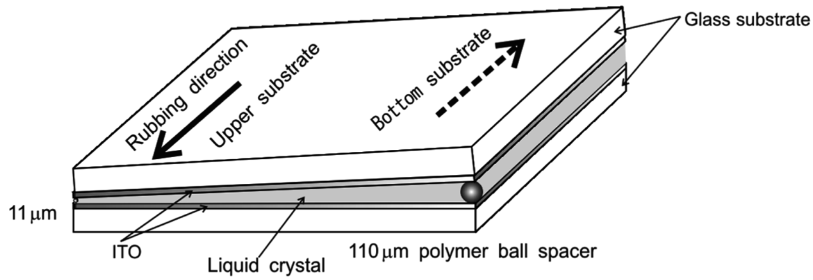


FIGURE 2 Structures of a wedge LC cell.

LC material are coated with polyimide (PI) film and is unidirectionally rubbed to align the LC directors. The top glass substrate with ITO film and the substrate with eight-divided-circularly-electrodes is attached in parallel by using cover glass (100 μm). Each voltage of eight-divide-electrodes $V_1 \sim V_8$ and external electrode V_{ITO} can be applied independently.

Figure 2 shows a schematic diagram of a wedge LC cell for simultaneously controlling the multiple microscopic particles by using the interference fringe patterns. The LC layer is sandwiched between

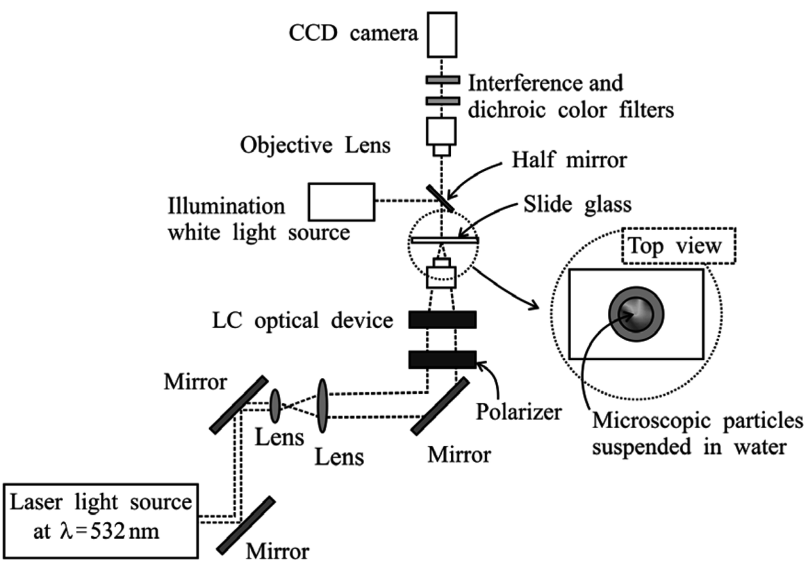


FIGURE 3 Three-dimensional controllable and rotatable manipulation system of microscopic particles by using the LC optical device.

two glass substrates at two different diameters of polymer ball spacers (11 μm and 110 μm). The surfaces of the ITO film are coated with polyimide film and its film on the upper and bottom substrates is unidirectionally and homogeneously rubbed.

Figure 3 shows the schematic diagram of laser manipulation system for rotating microscopic trapped particles by using liquid crystal optical devices. The manipulation system consists of a laser source at a wavelength of 532 nm, two lenses, polarizer, LC optical device and condenser lens (40×, NA = 0.45). The microscopic particles such

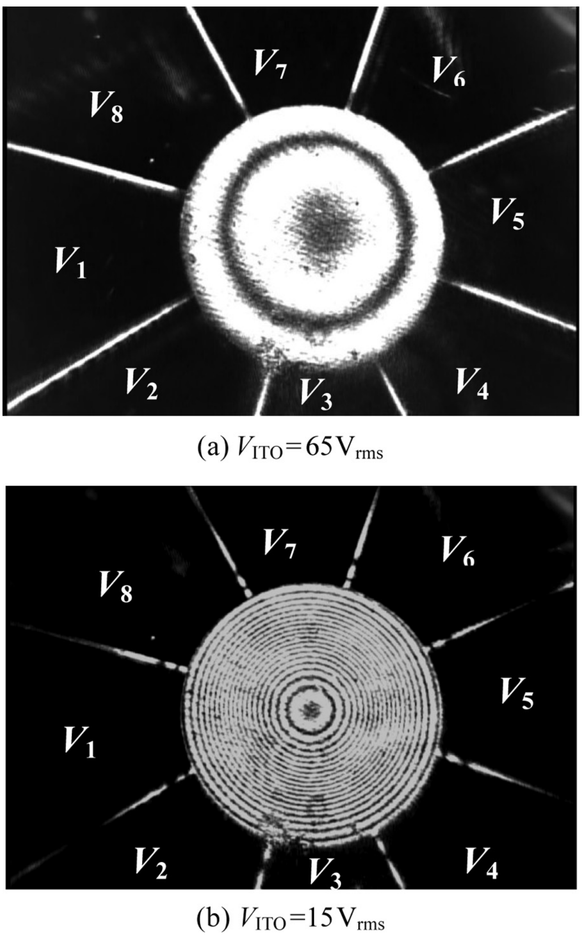
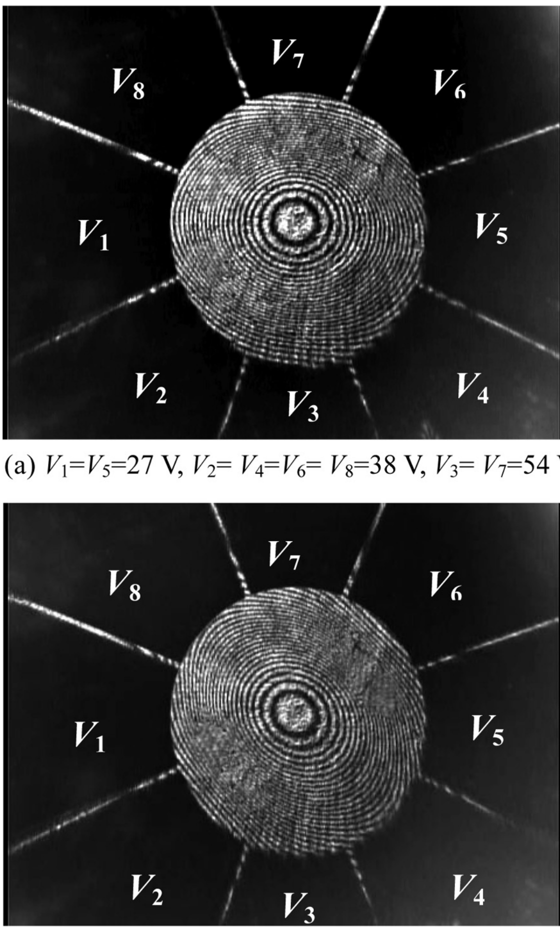


FIGURE 4 Circular interference fringe patterns of the LC optical device. ($V_{1\sim8} = 55\,V_{rms}$).

as slender glass rod particles (length: 30 ~ 50 µm, diameter: 11 µm) or polymer ball particles (diameter: 5 µm) are suspended in water on the slide glass. The positions of the particles trapped by the focused laser beam are monitored by using an imaging system through an objective lens, interference and dichroic color filters and CCD camera. When the three-dimensional positioning or rotating the particles are demonstrated by using the LC optical device as shown in Figure 1, the polarization direction of the polarizer is adjusted along the rubbing direction of the LC optical device. On the other hand, the direction



(a) V_1=V_5=27 V, V_2= V_4=V_6= V_8=38 V, V_3= V_7=54 V

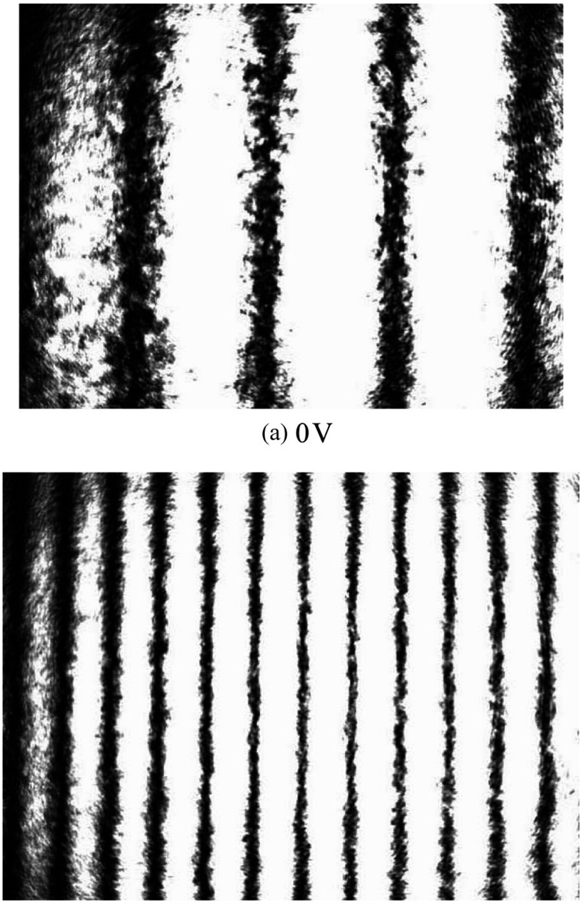
(b) V_1= V_3=V_5= V_7=38 V, V_2=V_6=54 V, V_4=V_8=27 V

FIGURE 5 Elliptical interference fringe patterns.

of polarizer and rubbing directions is set with 45 degree when the wedge LC cell as an LC optical device shown in Figure 2 is used in the laser manipulation system.

3. RESULTS AND DISCUSSION

Figures 4(a) and 4(b) show the circular interference fringe patterns of the circularly hole-patterned region in the LC optical device as shown in Figure 1 when the applied voltages to the eight-divided electrodes are same values under crossed polarizers observed using the CCD



(a) 0 V

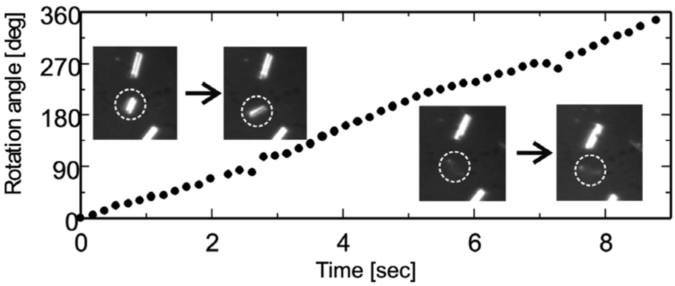
(b) 2.0 V

FIGURE 6 Fringe patterns of the wedge LC cell.

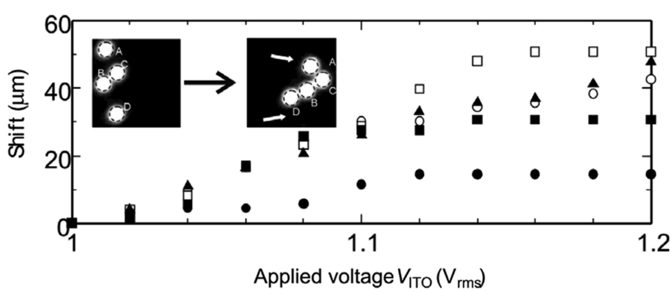
camera. Since there is a phase difference of 2π between the neighboring fringes, the phase difference properties of exiting ray from hole-patterned region can be estimated and the phase difference profile varies with the applied voltage. Then the parabolic profile of the effective refractive index distribution is attained. The LC director distributions, that is the profile of phase retardation in the hole-patterned region can easily be arranged by the external voltage. The optical property seems to be a lens-like distribution of the refractive index.

The elliptical interference fringe patterns of the hole-pattern region in the LC optical device are shown in Figures 5(a) and 5(b). The direction of the major and minor axes in the fringe patterns can be rotated, where each applied voltage to eight-divided electrodes is arranged to be $V_{\mathrm{major}} = 38\,\mathrm{V}$, $V_{\mathrm{minor}} = 54\,\mathrm{V}$ corresponding to the major and minor axes of the elliptical interference fringe and $V_{\mathrm{side}} = 27\,\mathrm{V}$ to other directions.

Figures 6(a) and 6(b) show the fringe patterns of the wedge LC cell shown in Figure 2 under crossed polarizers. Since the LC material faces in the ITO electrode as shown in Figure 2, the applied voltage



(a) Rotation control of trapped particle



(b) Position control of plural particles

FIGURE 7 Rotation and position control of trapped particles.

of the wedge LC cell is smaller than that of the LC optical device with eight-divided-circularly-hole-patterned electrodes and external control electrode. When the voltage is applied to the upper and bottom electrodes, the fringe pattern is seems to be shifted from left side to right side.

Figures 7(a) and 7(b) show demonstrations of the rotation and position control of the trapped microscopic particles. In Figure 7(a), the glass rod particles is trapped and rotated in the clockwise direction by using the LC optical device with eight-divided-circularly-hole-patterned electrodes and external control electrode. Since the trapped slender particle aligns along the major axis of the elliptical intensity profile at the focusing point, the particle can be rotated by controlling each applied voltage to the divided electrode and setting the major axis direction of the ellipse. The trapped particle can also be rotated in the anticlockwise direction. In Figure 7(b), the positions of the multiple polymer ball microscopic particles at a diameter of 5 μm can also be controlled by the interference fringe pattern shifts of the wedge LC cell shown in Figure 6.

4. CONCLUSION

The laser manipulation system for controllable and rotatable trapping the microscopic particles are developed by using an LC optical device with eight-divided-circularly-hole-patterned electrodes and external control electrode. The positions of the trapped particles can be shifted by using the beam-steering function of the LC optical device. The trapped particles can also be rotated in clockwise or anticlockwise directions by adjustable laser spot profile. Furthermore, the multiple microscopic particles can be moved by changing the interference fringe patterns with the application of the voltage to the wedge LC cell.

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