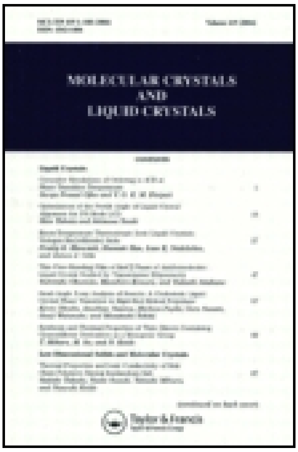

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Shape Measurements by Using a Liquid Crystal Lens

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Shape Measurements by Using a Liquid Crystal Lens

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We propose a microscope system for continuously taking the magnification images of a three-dimensional object by using a composite lens of a liquid crystal (LC) lens in addition to a relay lens and objective lens. The variable focal length of the composite lens can easily be controlled at the range of 3 mm by applying the voltages to both a circularly hole-patterned electrode and external flat electrode of the LC lens without any mechanical movements. The depth properties of the object can be estimated by using a Laplacian-Gaussian filter process of the all focused images.

Keywords Focal length; interference fringe; liquid crystal lens; microscope; three-dimensional measurement

1. Introduction

There are some measurement methods such as the depth-from-focus or depth-from-defocus methods with mechanical movements of the relay lens and objective lens for determining depth properties of three-dimensional geometric structure [1–3]. When the objective lens with a high magnification and numerical aperture of the microscope system is used, objects located closer to or farther from the focused object appear blurred. The blur increases with the distance from the object in focus and the geometry of a scene can be estimated by measuring the amount of the blur in an image. If a camera or an object is moved in the depth direction to adjust the focus, the image magnification variations occur. An inaccurate extraction of the image focus levels results from the variations.

Liquid crystal (LC) lenses with unique functions of a variable focal length and a beam deflection have been developed by S. Sato [4–9]. The structure of the LC lens with a circularly hole-patterned electrode and external flat electrodes is very simple. Since the LC directors in the homogeneous LC layer of the LC lens are aligned along the non-uniform electric field, the effective refractive index distribution can be obtained from the concave (negative) lens property and convex (positive) lens property. The bell-like wave-front distribution of the light through the LC lens can be controlled. When the circularly hole-patterned electrode of the LC lens is divided

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into the several same parts and the applied voltage to the each electrode is controlled, the transmission light can be deflected and focused in the three-dimensional positions. The circularly and elliptically laser spot can also be obtained by arranging the applied voltages to the several circularly hole-patterned electrodes. We have already demonstrated the laser tweezers system for optically manipulating the trapped microscopic particles dispersed into a water by using the LC lens with the variable focusing and deflecting functions [10,11]. The trapped slender micro-sized particles can be rotated in the clockwise and/or anticlockwise directions by rotating the elliptical laser beam spot. The positions of the trapped particles can also be moved by deflecting the focused laser beam spot.

In this study, we develop a microscope system by using a composite lens of the LC lens in addition to the objective lens and relay lens for continuously taking the magnification images at each focal length and analyzing the depth properties of the object. The focal length can be controlled by applying the voltages to the circularly hole-patterned electrode and external flat electrode of the LC lens without any mechanical movements. The three-dimensional distribution of the object can be estimated by using the Laplacian-Gaussian filter to compute the second derivation of each image.

2. Experimental

Figure 1 shows a schematic diagram of the microscope system with the composite lens. The composite lens consists of an LC lens, relay lens and microscope objective lens. The LC lens was inserted between the relay lens and objective lens (20×, numerical aperture: 0.4). Figure 2 shows the structure of the LC lens in this study. The LC lens was fabricated with one circularly hole-patterned electrode and external flat electrode on the glass substrate. The evaporated aluminium film coated on the glass substrate of the thickness 1.1 mm was chemically etched to be the circularly hole-pattern at the diameter of 2 mm by a photolithography technique. The surfaces of the polyimide films coated on the bottom transparent (ITO; Indium tin oxide) electrode and one side of the middle glass substrate with the circularly hole-patterned electrode were rubbed unidirectionally, and then the two rubbed surfaces were overlapped under anti-parallel directions by using glass ball spacers at the diameter of 110 μm. The LC material; MLC6080 purchased from Merck Co. was injected into the empty LC layer under the room temperature at 25°C. The physical properties of MLC6080 in this study are $k_{11} = 14.4$ pN, $k_{22} = 7.1$ pN and $k_{33} = 7.1$ pN; $\varepsilon_{\parallel} = 11.1$, $\varepsilon_{\perp} = 3.9$; $n_e = 1.710$ and $n_o = 1.507$. The pretilt angle of the LC molecule at the alignment surface on the substrate is 2 deg. The surface of the ITO film at

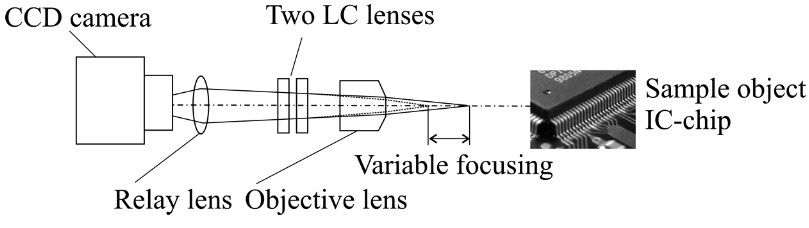

Figure 1. Schematic diagram of the microscope system with two LC lenses.

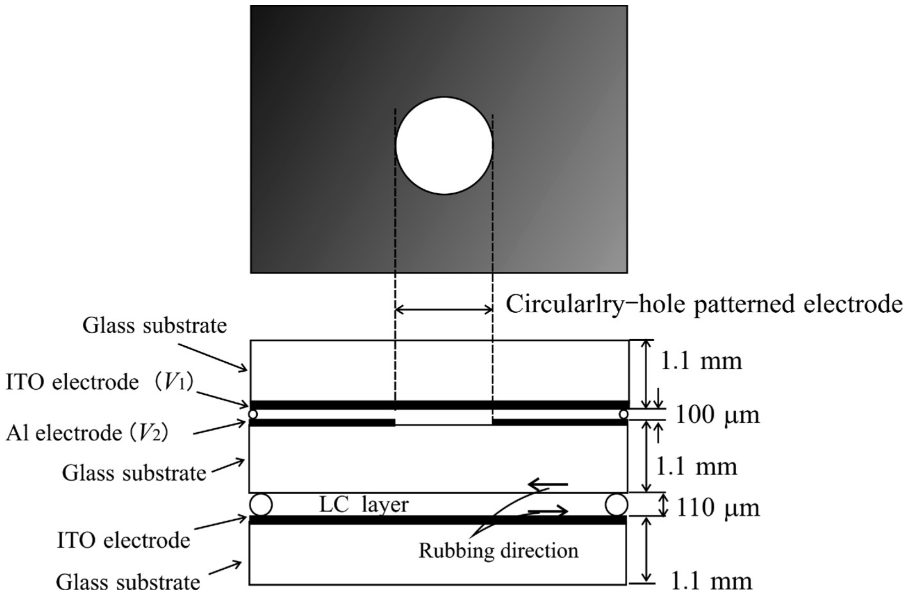

Figure 2. Structure of the LC lens.

the top glass substrate faced with a thin glass substrate of 100 µm, and then it was attached on the middle glass substrate with the circularly hole-patterned electrode. The same structural LC lenses were combined orthogonally with two rubbing directions of the homogenously aligned LC layer in the LC lens as shown in Figure 1. The voltages to the circularly hole-patterned electrode and flat transparent electrode of the LC lens were applied by using a function generator at a frequency of 1 kHz and an amplifier with the amplification factor of an approximately 10 times higher.

3. Image Processing

The combination focal length $f_{\rm all}$ through the composite lens is deduced by the following equations:

$$f_{\rm all} = \frac{\frac{f_1 \cdot f_{\rm LC}}{f_1 + f_{\rm LC} - d_1} \cdot f_2}{\frac{f_1 \cdot f_{\rm LC}}{f_1 + f_{\rm LC} - d_1} + f_2 - d_2} \qquad (1)$$

where f_1, $f_{\rm LC}$ and f_2 are focal lengths of relay lens, LC lens and objective lens. The distance from the primary principal point of the relay lens to the secondary principal point of the LC lens is defined as d_1, and the distance from the principal point of the composite lens such as relay lens and LC lens to the third principal point of the objective lens is d_2. In this equation, the combination focal length can be changed by controlling the focal length of the LC lens.

The images are continuously taken by the CCD camera with each applied voltage to the electrodes of the LC lens. The calculated results of the Laplacian-Gaussian filter processing of the all experimental images are obtained by using a National Instrument's Laboratory Virtual Instrument Engineering Workbench (NI

LabVIEW) and NI vision development module kit. The Laplacian-Gaussian filter is widely used for the edge detection of an image and $L(x, y)$ of an image with pixel intensity values $I(x, y)$ is given by

$$L(x,y) = \nabla^2 I(x,y) = \frac{\partial^2 I(x,y)}{\partial x^2} + \frac{\partial^2 I(x,y)}{\partial y^2}. \qquad (2)$$

Since the input image is represented as a set of discrete pixels, we have to find a discrete convolution kernel that can approximate the second derivatives in the definition of the Laplacian-Gaussian filter.

4. Results and Discussion

The refractive index distribution at the circularly hole-patterned region can be changed by applying the voltages to the electrodes as shown in Figure 2 and then the focal length of the LC lens can be controlled without any mechanical movements. Figure 3 shows the focal length property of the composite lens in the microscope system, when the voltage V_1 to the flat ITO electrode changes from 15 V to 30 V and the applied voltage V_2 to the circularly hole-patterned electrode is a constant value ($V_2 = 20$ V). The composition focal length at each applied voltage can be estimated by means of a Modulation Transfer Function (MTF) measurement, where the MTF is the contrast magnitude ratio to test the performance of the optical system [12]. The focal length can be obtained from 5.5 mm to 8.5 mm at the spatial frequency under 40 cycles/mm.

Figures 4a–4c show the microscope images of the sample object such as an IC-chip of lead flame parts with the depth of 1500 μm and the width of 300 μm by changing the applied voltage V_1 to the external flat electrode during $V_2 = 20$ V. The focal length increases as increasing the V_1. When the voltage $V_1 = 20$ V as shown in Figure 4a, the top of the lead flame parts is adjusted in focus and the other regions are blurred. The focused and defocused areas of the each image at the different height can be obtained without variations of the image magnification and position shift.

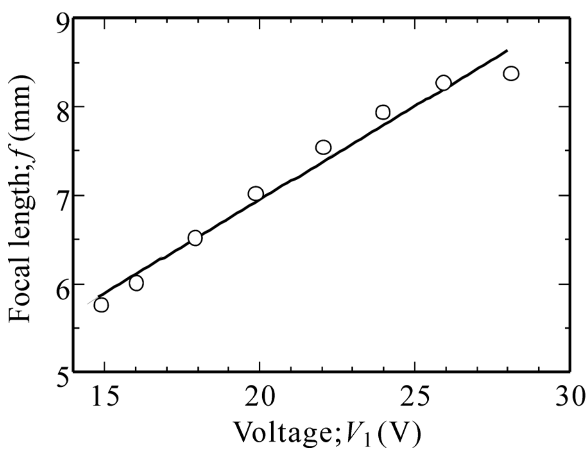

Figure 3. Focal length property of the composite lens.

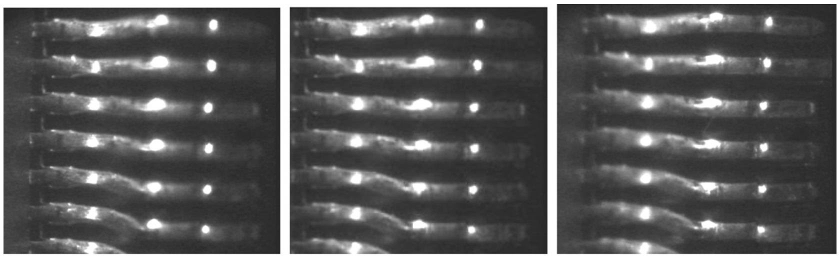

Figure 4. Microscope images of the IC chip at several focal planes.

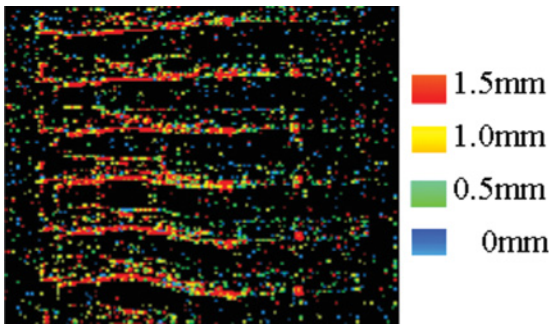

Figure 5. Depth mapping result by analyzing the microscope images of the IC chip.

Figure 5 shows the depth property analyzed by using the Laplacian-Gaussian filter process of the series images in the depth direction. The depth property of three-dimensional structure about 1.5 mm height such as the lead flame parts of the IC-chip can be determined. The total reflection light from the object with strong light intensity is influenced into the fluctuations of the calculated results. The resolution along the depth direction and the reduce of the total reflection light are now in progress.

5. Conclusion

The three-dimensional shape microscope system by using a composite lens of an LC lens and high magnified objective lens without any mechanical movements has been developed. The focal length through the composite lens can be varied and its value is about 2.5 mm. The depth of three-dimensional structure with the 1.5 mm height such as the lead flame parts of the IC-chip can be estimated by using our system.

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