Periodic pattern of liquid crystal molecular orientation induced by ultrasound vibrations

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Methods for controlling the periodic molecular orientation of liquid crystals using ultrasound vibrations and estimating the orientational direction are proposed. An ultrasonic liquid crystal cell was used, consisting of a liquid crystal layer sandwiched by two glass plates fitted with piezoelectric ultrasound transducers. The transmitted light intensity distribution through the cell was measured by changing the polarization direction to investigate the orientation direction of the liquid crystal molecules. The transmitted light distributions changed periodically owing to the flexural vibration of the cell at resonance frequencies of 43.9 and 70.7 kHz. The orientational direction of the liquid crystal molecules correlated with the vibrational distribution of the glass substrates, and the molecular orientation was changed periodically by the acoustic radiation force. The interval and intensity of the transmitted light could be controlled by the driving frequency and voltage amplitude, respectively. *Published by AIP Publishing.* https://doi.org/10.1063/1.5010213

Liquid crystals have both liquid properties and crystalline material anisotropies. Liquid crystals can be classified into thermotropic and lyotropic according to the type of phase transition from liquid to solid phases.[1] A molecule of thermotropic liquid crystals has an elongated, disk-like,[2] or banana-like[3] shape, and liquid crystals can be classified into three types (nematic, smectic, and cholesteric) according to the molecular aggregation state. Liquid crystal molecules have electric and magnetic dipoles; hence, the molecular orientation of a nematic liquid crystal with high liquidity can be controlled by an external field, and the optical anisotropy can be applied in optical devices, such as liquid crystal displays.[4] In terms of other optical applications, Sato and colleagues have used the birefringence of liquid crystals to develop an optical variable-focus lens[5,6] and investigated the optical characteristics of the lens.[7] These liquid crystal optical devices with no mechanical moving parts show advantages for downsizing electronic modules.

Liquid crystal optical devices require transparent electrodes so that the electric field can be applied through the liquid crystal layer to control the molecular orientation. In general, indium tin oxide (ITO) is used as the electrode material because of its high transparency. However, ITO contains the rare metal indium and ITO electrodes are fabricated by a sputtering deposition method, which has high equipment costs and complex processing requirements.[8] Furthermore, there is a trade-off between low resistivity and high transparency.[9,10] For flexible liquid crystal devices such as electronic digital paper, inorganic materials such as ITO would be unsuitable and alternative materials are required.[11] Ultrasound presents a promising solution to this problem. Several researchers have reported the effects of ultrasound on nematic liquid crystals.[12,13] Ultrasound propagation in liquid crystals can be observed optically, which means that the optical characteristics of liquid crystals are influenced by ultrasound. Our group has proposed a technique to control the liquid crystal molecular orientation using ultrasound vibrations,[14] which requires no transparent electrodes. The orientational direction can be changed by the acoustic radiation force generated by the flexural vibration of the transparent glass plate. In this paper, periodic control of liquid crystal molecular orientation with the use of ultrasound is discussed. It is difficult to realize a pinpoint control of molecular orientation in pixelated liquid crystal devices because this ultrasonic technique utilizes the entire resonance vibration modes of the device. However, a two-dimensional periodic change of the molecular orientation produces a periodic pattern of the effective refractive index, which can control the wavefront of the transmitted light and might have applications in microlens arrays,[15–17] optical waveguides, and photonic crystals.[18–20]

The effects of ultrasonic vibration on the orientational direction of liquid crystal molecules were investigated. An ultrasonic liquid crystal cell was fabricated (see Fig. 1). A nematic liquid crystal (RDP-85475, DIC, Japan; transition temperature of SN point: −10 °C; NI point: 123.7 °C; and viscosity: 93.7 mPa s) was used. Four piezoelectric lead zirconate titanate (PZT) transducers (Fuji Ceramics, Japan, $10 \times 10 \times 1\,\mathrm{mm}^3$) polarized in the thickness direction were bonded at the four corners of a transparent glass plate (a) ($80 \times 80 \times 0.7\,\mathrm{mm}^3$) using epoxy. A second glass plate (b) ($50 \times 50 \times 0.7\,\mathrm{mm}^3$) was bonded at the center of the glass plate (a) using epoxy containing silica microspheres with a diameter of 25 μm, such that a liquid crystal layer was formed between the two glass plates.

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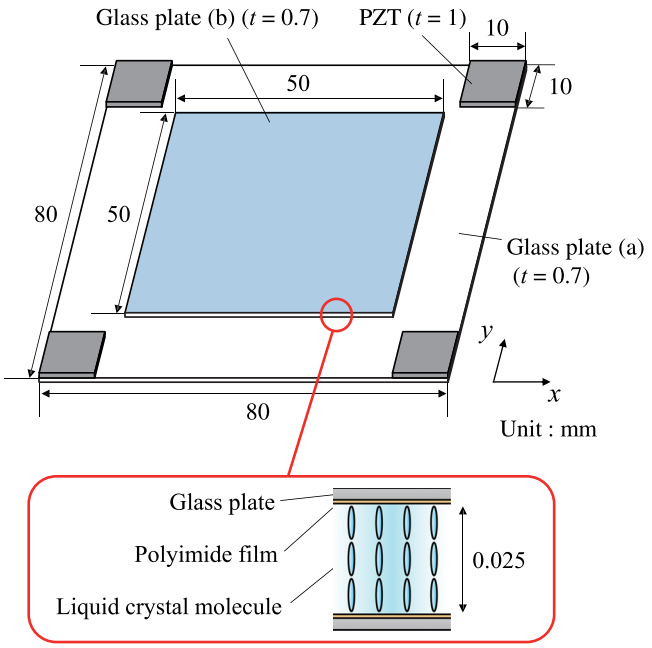

FIG. 1. Configuration of the ultrasonic liquid crystal device.

After injecting the liquid crystal into the gap, the liquid crystal layer was completely sealed using epoxy. The liquid crystal molecules were oriented perpendicular to the glass plates owing to the orientation effect of the polyimide films (vertical alignment type, SE-5811, Nissan Chemical, Japan) formed on the glass plates. By exciting the transducers with an in-phase electric continuous sinusoidal signal at certain resonance frequencies, flexural vibration modes were generated on the liquid crystal cell. The acoustic radiation force,[21,22] which is a static force caused by the difference in the acoustic energy densities between the liquid crystal layer and the glass plates, allows the collective molecular orientation of the liquid crystal to be changed.

The transmitted light through the ultrasonic liquid crystal cell was measured under crossed Nicol conditions to investigate the optical characteristics and molecular orientation. A polarizer and an analyzer were arranged orthogonally, and the liquid crystal cell was installed between them. A He-Ne laser beam ($\lambda = 632.8$ nm) with a beam width of 2 mm was passed through the cell, and the transmitted light of the analyzer was received by a photodetector (2051-FS, Newport) with a detector diameter of 0.9 mm. The vibrational amplitude distribution on the upper surface of the glass plate (b) was measured using a laser Doppler vibrometer (NLV-2500, Polytec) to investigate the relationship between the transmitted light and the mechanical vibrations of the glass plate.

There are several resonance frequencies for flexural vibration modes of the liquid crystal cell over 20 kHz, and the optical and vibration characteristics of the cell were measured at two resonance frequencies, namely, 43.9 and 70.7 kHz. The polarization direction of the incident light to the liquid crystal cell θ was changed by rotating the polarizer and analyzer in the in-plane direction under the crossed Nicol conditions to investigate the birefringence of the liquid crystal cell. At $\theta = 0°$ and 90°, the polarization direction corresponds to x and y axes in Fig. 1, respectively. The area of $30 \times 30\,\text{mm}^2$ at the center of the cell was observed by scanning a laser with a measurement pitch of 0.5 mm. In the case without ultrasound excitation, the transmitted light was filtered under the crossed Nicol conditions because the liquid crystal molecules oriented perpendicularly to the glass plates in the default condition. Figure 2 shows the transmitted light intensity distributions at θ of 0° to 90° at resonance frequencies of 43.9 and 70.7 kHz. The light intensities were normalized to the maximum value of each. By applying an input voltage of 50 V_{pp}, flexural vibration modes were generated on the glass plates, and the transmitted light distributions of the cell changed considerably. The maximum vibrational displacement amplitudes of the glass plate (b) in the observational area were 0.91 and 0.88 μm at 43.9 and 70.7 kHz, respectively. The periodic patterns of the transmitted light were rotated and changed gradually with the polarization direction; rhombic and lattice patterns appeared at $\theta = 0°$ and 45°, respectively, at the two frequencies. It should be noted that the same patterns appeared at $\theta = 0°$ and 90° at both frequencies; however, the light intensity distributions were inverted with respect to each other.

Generally, the birefringence characteristics of transparent materials are measured by rotating a polarizer and an analyzer under the crossed Nicol conditions. If the orientation direction of liquid crystal molecules is uniform in the thickness direction, the light intensity distributions should correspond at $\theta = 0°$ and 90° under the crossed Nicol conditions because the transmitted light intensity can be expressed as a function of $\sin^2 2\theta$. The maximum light intensity is observed at $\theta = 45°$ and 135° since the transmitted light is polarized elliptically through the liquid crystal layer. Therefore, these experimental results imply that the liquid crystal molecules were twisted in the thickness direction; however, there have been few reports describing the methods of precisely measuring liquid crystal molecular twisting orientation. When we focus on one observation point changing the polarization direction θ, the maximum light intensity was obtained for the case where the polarization direction of transmitted light through the cell corresponded to the orientational direction of the analyzer. Under this hypothesis, we can assume that the orientation direction at the upper surface of the liquid crystal layer corresponds to the same direction. Figure 3 shows the orientational direction of the liquid crystal molecules and the vibrational amplitude distributions of the glass plate. The vibrational amplitudes are expressed using a color scale and normalized by each maximum value. The distributions of the orientational direction expressed using bars were obtained by measuring the polarization direction of the incident light θ which gives the maximum light intensity of the transmitted light at each measurement point in Fig. 2. When applying the input voltage at resonance frequencies, the composite vibration modes of the lattice and concentric flexural vibration, with half wavelengths of 8.9 and 6.5 mm, were generated on the glass plates at 43.9 and 70.7 kHz, respectively. The vibrational distributions of the glass plate and the molecular orientation were correlated; the molecular orientations flowed out from the loop positions and aligned along the nodal lines of the flexural vibration. A high frequency flexural vibration produced an orientational pattern with a shorter period. These results indicate that the molecular orientation in

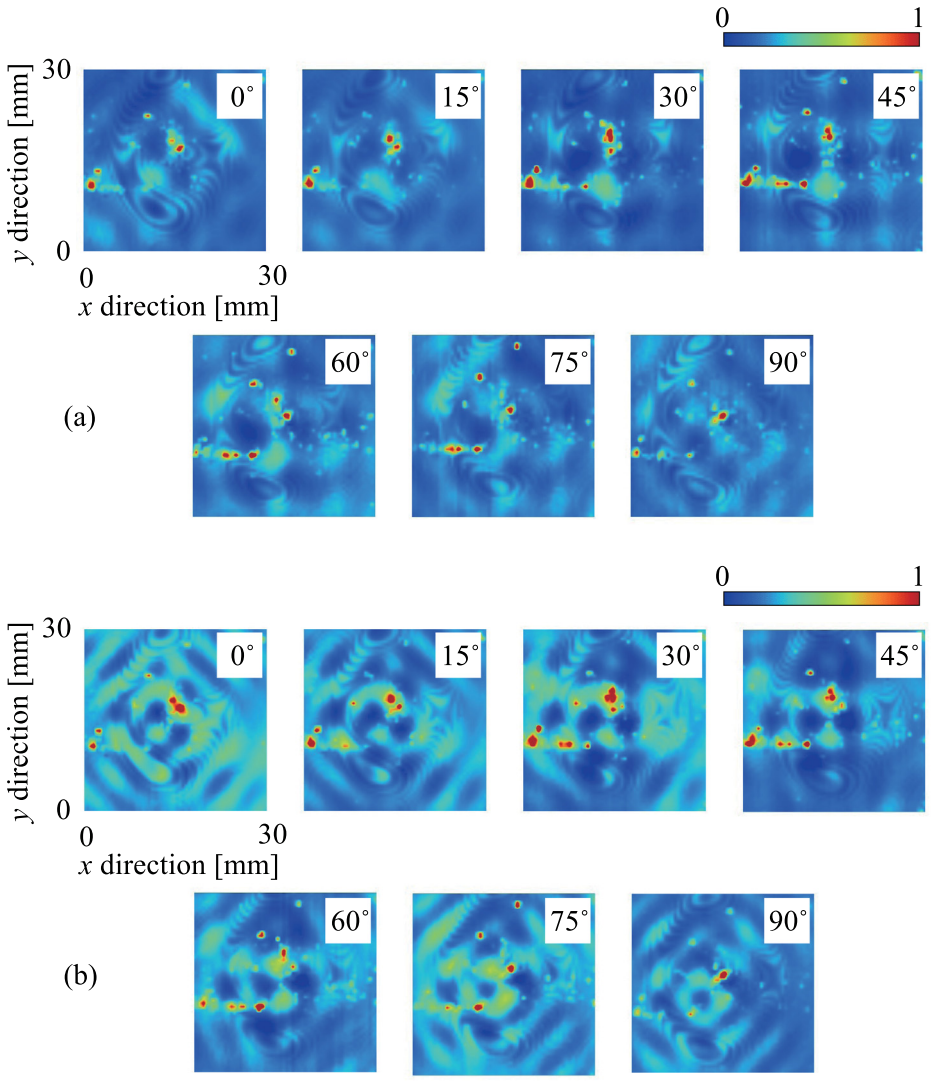

FIG. 2. Distributions of the transmitted light intensity at several polarization directions at (a) 43.9 and (b) 70.7 kHz.

the liquid crystal layer was changed by the acoustic radiation force generated by the flexural vibrations of the glass plate. Although the structure of the ultrasonic liquid crystal layer was symmetric in the thickness direction, the liquid crystal molecular orientation was twisted asymmetrically. The asymmetric twisting orientation is attributed to the impedance mismatching between the glass plates (a) and (b) and the ultrasound attenuation in the liquid crystal layer. In fact, the ratio of the vibrational amplitude of the glass plate (b) to that of the glass plate (a) was 0.90 at 43.9 kHz.

The transmitted light intensity of the liquid crystal cell at the loop position of the vibration was measured at two

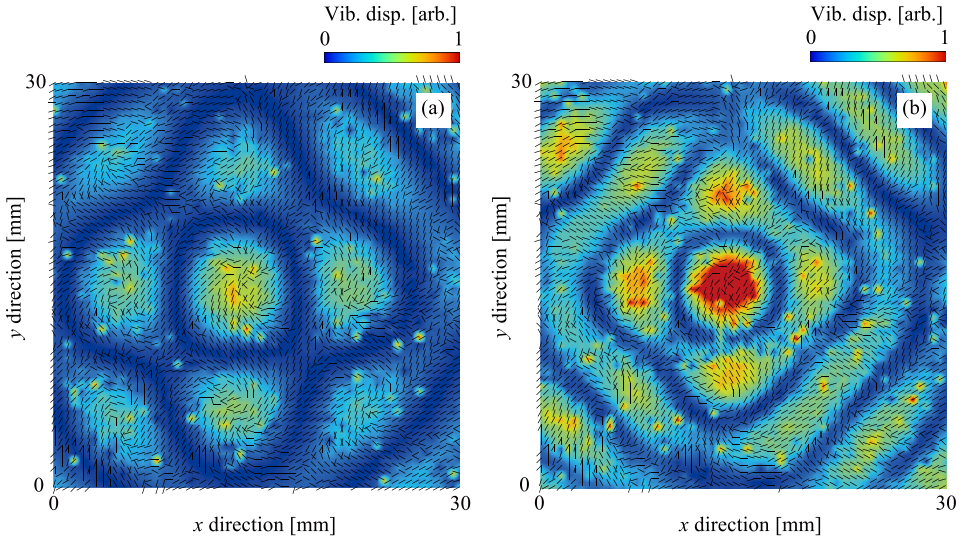

FIG. 3. Distributions of the vibrational amplitude of the glass substrate and the orientation direction of the liquid crystal molecules at (a) 43.9 and (b) 70.7 kHz.

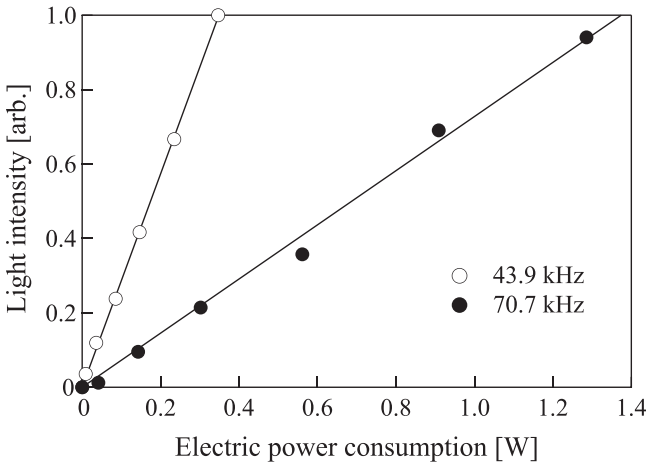

FIG. 4. Relationship between the electric power consumption and the transmitted light intensity at 43.9 and 70.7 kHz.

resonance frequencies by changing the voltage amplitude. Figure 4 shows the relationship between the electric power consumption of the one PZT transducer and the transmitted light intensity, and the light intensities were proportional to the electric consumption. These linear dependences imply that the molecular orientation is changed by the acoustic radiation force, which is a function of the square of the sound pressure amplitude, which in turn varies as the square of the input current to the transducer. The gradients of the straight lines indicate the electric control efficiencies of the liquid crystal molecular orientation, and the larger change in the light intensity was observed at the lower resonance frequency with the same electric consumption. These results imply that the refractive index distribution of the liquid crystal can be controlled by the driving frequency and amplitude.

In summary, a technique to control the orientational direction of liquid crystal molecules periodically by an acoustic radiation force was proposed. The molecular orientation was changed periodically by flexural vibration of the glass plates. The period and the transmitted light intensity could be controlled by the driving frequency and amplitude, respectively, so that the refractive index of the liquid crystal layer could be controlled in two-dimensions.

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