Control of liquid crystal molecular orientation using ultrasound vibration

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We propose a technique to control the orientation of nematic liquid crystals using ultrasound and investigate the optical characteristics of the oriented samples. An ultrasonic liquid crystal cell with a thickness of 5–25 μm and two ultrasonic lead zirconate titanate transducers was fabricated. By exciting the ultrasonic transducers, the flexural vibration modes were generated on the cell. An acoustic radiation force to the liquid crystal layer was generated, changing the molecular orientation and thus the light transmission. By modulating the ultrasonic driving frequency and voltage, the spatial distribution of the molecular orientation of the liquid crystals could be controlled. The distribution of the transmitted light intensity depends on the thickness of the liquid crystal layer because the acoustic field in the liquid crystal layer is changed by the orientational film. © *2016 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4943494]

Liquid crystal is an intermediate state between the liquid and solid states. There are various types of materials with different components and aggregation states that form the liquid crystal states; these are known as liquid crystals. Liquid crystals are composed of elongated anisotropic molecules with an electric or magnetic dipole and can be classified into three types according to their collective molecular orientation: nematic, smectic, and cholesteric. Compared with the other two types, nematic liquid crystals have regular, symmetric collective molecular orientation, and both their molecular orientation and optical characteristics can be readily controlled by applying an electric or magnetic field. Nematic liquid crystals are suitable for use in optical devices and contribute to the downsizing of various optical devices such as liquid crystal displays (LCDs).[1–3] These optical devices require transparent electrodes to generate an electric field through the liquid crystal layer. Indium tin oxide (ITO) is generally used as the electrode material in such devices. However, ITO contains the rare metal indium, and ITO electrodes are fabricated by sputtering, which requires expensive equipment and multiple steps. In addition, the light intensity transmitted through the electrodes is attenuated,[4,5] and it is difficult to realize a high electric conductivity and transparency simultaneously.[6]

Here, we propose a technique to control liquid crystal molecular orientation using an ultrasound vibration. By using an acoustic field rather than an electric or magnetic field, ITO electrodes are not required. Several groups have reported the effects of ultrasound on nematic liquid crystals.[7–9] Sato and colleagues used the birefringence of liquid crystals to develop an optical variable-focus lens[9–11] and then investigated the optical characteristics of the lens.[12] Our group has also investigated variable-focus lenses using an ultrasound vibration and two immiscible liquids[13] or a transparent viscoelastic material.[14] The surface profile of a lens can be deformed by the radiation force of ultrasound, so that its focal point can be controlled, as with the crystalline lenses in the human eye. By utilizing the resonance vibration modes of the glass substrate, optical lens arrays in which both the focal length and lens pitch can be controlled have been developed.[15–17] Using an ultrasound vibration to induce the resonance vibration modes of substrates, we aim to develop new optical liquid crystal devices with no mechanical moving parts, such as variable-focus lenses. In this paper, as a first step, we investigate the fundamental optical characteristics of a nematic liquid crystal controlled by ultrasound and the change of the molecular orientational direction of the liquid crystal caused by ultrasound.

The optical characteristics of liquid crystals exposed to ultrasound were investigated. Figure 1 shows the configuration of the ultrasonic liquid crystal cell. Polyimide orientational films (vertical alignment type, SE-5811, Nissan Chemical, Japan) were formed on two rectangular glass plates with dimensions of (a) $120 \times 5 \times 0.7$ mm and (b) $50 \times 5 \times 0.7$ mm. Two rectangular ultrasonic piezoelectric lead zirconate titanate (PZT) transducers (Fuji Ceramics, Japan, $30 \times 5 \times 1$ mm) polarized in the thickness direction were bonded at both ends of glass plate (a) using epoxy. The edges of glass plates (a) and (b) were bonded using epoxy containing silica glass microspheres with a diameter of 5, 10, or 25 μm, so that a thin chamber for the liquid crystal layer was formed between the two glass plates. After injecting a nematic liquid crystal (RDP-85475, DIC, Japan; transition temperature of SN point: $-10\,^{\circ}$C; NI point: $123.7\,^{\circ}$C; and viscosity: 93.7 mPa s) into the chamber by the capillary effect, the liquid crystal layer was completely sealed using

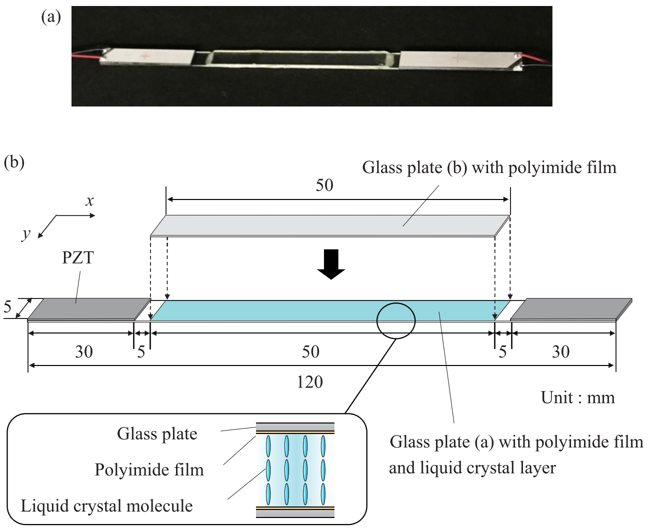

FIG. 1. Ultrasonic liquid crystal cell: (a) photograph and (b) configuration. The liquid crystal layers with thicknesses of 5, 10, and 25 μm were fabricated.

epoxy. The injected liquid crystal molecules were oriented perpendicularly without contacting the orientational polyimide films. By applying a continuous sinusoidal electric signal to the PZT transducers at the resonance frequency of the glass plates, an in-phase flexural standing wave is generated on the glass plate in the length direction (x direction in Fig. 1). The standing wave has several nodal lines every half wavelength, which is suitable to be supported. The acoustic radiation force[18] caused by the sound wave radiated from the flexural vibration acts on the liquid crystal layer, allowing the collective orientational direction of the liquid crystals to be changed. Since acoustic radiation force is a static force that is generated by a difference in the acoustic energy densities of different media, it is possible that the acoustic radiation force acts on the boundary between the liquid crystal layer and the glass plates, not to an individual liquid crystal molecule directly. Because the periodic change of the molecular orientation of the liquid crystal correlates to the wavelength of the flexural vibration on the glass substrate, the spatial distribution of the molecular orientation and the transmitted light through the liquid crystal layer can be modulated by varying the resonance frequency of the glass substrate.

The transmitted light distributions through the liquid crystal cell were measured by the crossed Nicol's method in which the polarizer and analyzer are arranged orthogonally. The liquid crystal cell was installed between the polarizer and analyzer and a He-Ne laser beam ($\lambda = 632.8$ nm) with a beam width of 2 mm was passed through the liquid crystal layer in the thickness direction. The transmitted light with or without an ultrasound vibration was received by a photodetector (2051-FS, Newport) with a detector diameter of 0.9 mm.

There were several resonance frequencies of the in-phase flexural vibration modes of the glass substrate between 20 and 200 kHz. Figure 2 shows representative experimental results for the transmitted light intensity distributions through the liquid crystal cell without and with ultrasound at 59 and 189 kHz (see photographs in supplementary Figure S1[21]). The laser beam was scanned around the center of the cell (measurement area of 30×1 mm). In the case without ultrasound excitation (Fig. 2(a)), the transmitted light intensity in the measurement area was very small because the liquid crystal molecules that oriented in the vertical direction did not affect the incident light, and the transmitted light was filtered through the polarizer and analyzer under the crossed Nicol conditions. By exciting the two PZT transducers in-phase at an input voltage of 20 V_{pp} at 59 and 189 kHz (Figs. 2(b) and 2(c), respectively), the transmitted light intensity distributions were increased with periodic sinusoidal patterns in the length direction. The average intervals of the transmitted light peaks at 59 and 189 kHz were 9.0 and 5.0 mm, respectively, and the transmitted light distribution was changed by the driving frequency. These results indicate that the molecular orientation of the liquid crystal was changed by ultrasound irradiation inducing the flexural vibration of the substrate. The liquid crystal molecules recovered to homeotropic alignment after a series of ultrasonic excitation since the transmitted light distribution returned to the default distribution (Fig. 2(a)).

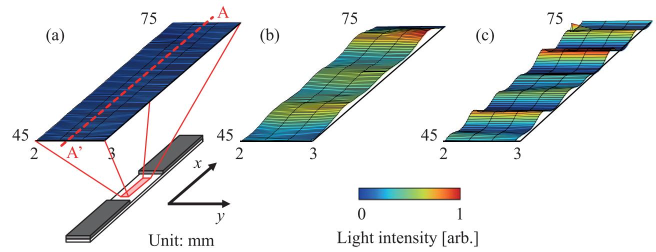

FIG. 2. Distributions of the transmitted light intensity (a) without, and with ultrasound excitation at (b) 59 kHz and (c) 189 kHz. Measurement area is around the center of the cell (30×1 mm).

The vibrational amplitude distributions at the surface of the glass plate were measured using a laser Doppler vibrometer (NLV-2500, Polytec) to investigate the relationship between the transmitted light intensity and vibrational distributions. Figure 3 depicts the cross-sectional distributions of the transmitted light and out-of-plane vibrational amplitude of the glass plate at (a) 59 and (b) 189 kHz along line A-A′ in Fig. 2. At the resonance frequencies of 59 and 189 kHz, the wavelengths of the flexural vibration on the glass substrate were 5.8 and 3.0 mm, respectively. These distributions are correlated with those of the transmitted light. The higher driving frequency gives flexural vibration of shorter wavelength and shorter periodic patterns of the transmitted light; the ratios of the period of the transmitted light to the half-wavelength of the vibration were 1.55 and 1.67 at 59 and 189 kHz, respectively. These results mean that the molecular

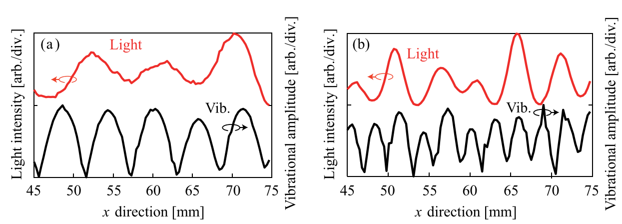

FIG. 3. Distributions of the transmitted light (red) and vibrational amplitude of the glass substrate (black) at (a) 59 kHz and (b) 189 kHz along line A–A′ in Fig. 2(a).

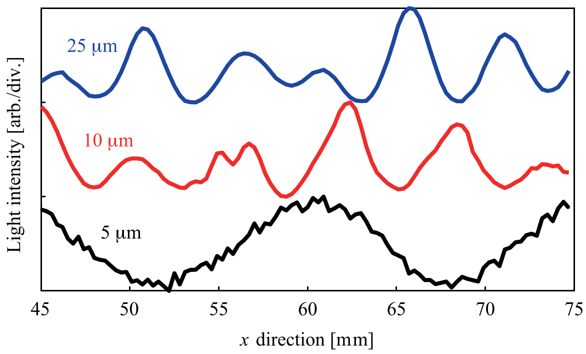

FIG. 4. The transmitted light intensity distributions for the liquid crystal layers with thicknesses of 5 (black), 10 (red) and 25 μm (blue) with an input voltage of 20 V_{pp} at 189 kHz.

orientation of the liquid crystal was changed by an ultrasound vibration.

The optical characteristics of the liquid crystal devices depend on the thickness of the liquid crystal layer.[19] The transmitted light distributions for the liquid crystal layers with thicknesses of 5, 10, and 25 μm with an input voltage of 20 V_{pp} at 189 kHz were measured (Fig. 4). The results indicate that the periods of the transmitted light decreased as the thickness of the liquid crystal layer increased; the periods are 14.9, 5.8, and 5.0 mm for thicknesses of 5, 10, and 25 μm, respectively. This tendency is attributed to the anchoring strength of the liquid crystal layer to the orientational polyimide film increasing as the thickness of the liquid layer decreases.[20] In principle, the half-wavelength of the flexural vibration should be equal to the period of the transmitted light. However, it should be noted that the acoustic field in the liquid crystal layer, not the vibrational distribution, directly affects the transmitted light distribution. The results in Fig. 4 suggest that the sound velocity in the liquid crystal layer increased as the anchoring strength increased, resulting in the longer periods of the transmitted light.

In summary, a technique to control the orientational direction of nematic liquid crystal molecules using acoustic radiation force from ultrasound was proposed. The molecular orientation and transmitted light distribution through a liquid crystal device were changed by the ultrasonic flexural vibration of the glass substrate. The interval of the transmitted light narrowed as frequency increased. By changing the thickness of the liquid crystal layer, the distribution of the transmitted light intensity through the liquid crystal layer was changed. The results indicated that the distribution of sound pressure in the liquid crystal layer depended on the thickness of the liquid crystal layer.

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[21]See supplementary material at http://dx.doi.org/10.1063/1.4943494 for patterns of the transmitted light through the cell.