Liquid-crystal panel with microdots on an electrode used to modulate optical phase profiles

Koichiro Kishima, Naoko Yoshida, Kiyoshi Osato, and Nobuyoshi Nakagawa

The optical characteristics of a liquid-crystal (LC) panel with microdots on an electrode are investigated. Although 3 μm is larger than 1 molecule of LC material, microdots with a 3 μm diameter are sufficiently small to produce a smooth index profile. We use an electrode patterned in a new way to modulate the index profile of the LC panel, which allows us to modulate the optical phase of the passing light. © 2006 Optical Society of America

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1. Introduction

Nematic liquid-crystal (LC) panels are widely used as display devices. LC panels are also used as optical-phase-modulating devices because they control the index profile of LC material by varying the applied voltage.[1] The LC panels used as phase-modulation devices control the phase of the light passing through the device. The panels have applications in many fields, for example, spatial-phase-modulating systems,[2,3] optical phase gratings,[4] lenses with variable focal length,[5] and optical data storage systems.[6,7] A typical phase-modulation device controls the phase of the passing light without changing its direction; thus the device is composed of two parallel glass substrates with patterned electrodes and LC material sandwiched by the substrates because the thickness of the LC must be uniform.

The principle of phase modulation is adjusting the optical path of the passing light by controlling the index of the LC material by applying different voltages to different electrodes.[2,3] Figure 1 shows the structure of a phase-modulating device now in widespread use. It is not possible to obtain a full (continuous and accurate) phase profile with this device even if the layout of the electrodes and the voltages to be applied are optimized.

We believed there might be a way to obtain a full profile if we looked closely at the LC material itself. It is clear that, because LC materials partake of the characteristics of both liquids and crystals, the continuum theory can describe their characteristics.[8,9]

To obtain a full phase profile, we redesigned the LC device as in Fig. 2. The newly patterned electrode shown in Fig. 2(b), with its dense and sparse areas of microdots (microareas where an electrode is removed), can create the ideal voltage profile for LC molecules by allowing the density of the microdots to be adjusted. The orientation of the LC molecules cannot follow the voltage profile when the applied voltage is varied by very small increments by using the microdots. So orientation of the LC molecules is averaged over the profile of the applied voltage, and the phase profile of the passing light is smooth and full.

2. Optical Phase Modulation by Using Microdots

Figure 3 is a schematic diagram of the orientation of LC material with dots (areas where the electrode is removed) patterned on the electrode. When the dots are too large for the LC material, as shown in Fig. 3(a), the orientation of the molecules of the LC material follows the voltage applied. Therefore the index profile of the LC panel is not continuous. Moreover the passing light is lost by the diffraction caused by deviation from the index of the LC panel when the number of dots is large. On the other hand, the orientation of LC molecules is averaged when the size of the dots is small enough for the LC material, as shown in Fig. 3(b). Consequently the index profile would be smooth, and diffraction

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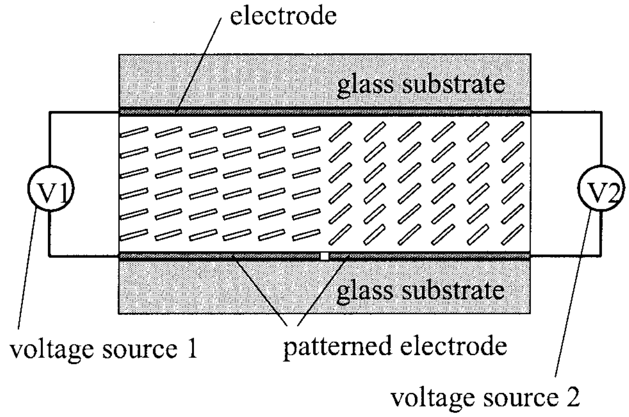


Fig. 1. Structure of a typical phase-modulating device. Phase modulation is performed by applying a different voltage to different electrodes; thus the phase profile is not continuous (not full).

would not occur. The average orientation of the molecules of LC in Fig. 3(b) is smaller than the orientation of the LC molecules of the LC panel without the dots at the same applied voltage because the effective supplied voltage in Fig. 3(b) is decreased by decreasing the area of the electrode caused by the adopting dots.

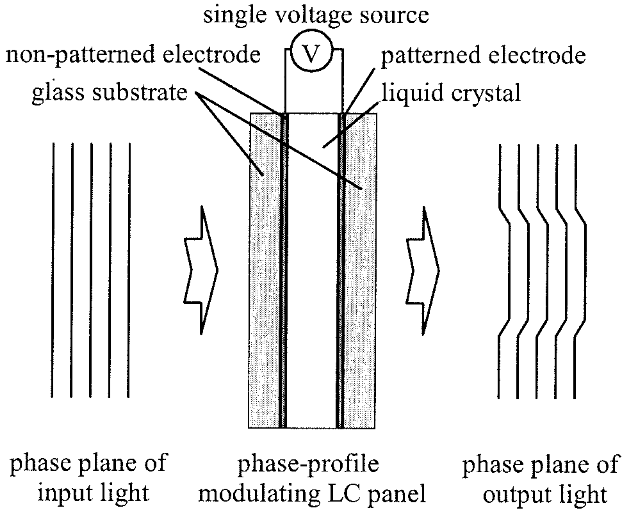
The concept of our phase profile modulation when very small dots, are used which we call microdots, on an electrode is shown in Fig. 2. This concept makes use of the averaging of the orientation of LC molecules by employing sufficient microdots, and the average orientations of the LC molecules is controlled by the density of the microdots. Therefore, as shown in Fig. 2, the phase of the passing light through the LC panel where the density of the microdots is sparse is delayed.

Using this technique, we can obtain a valid functional profile by adjusting the density of the microdots.

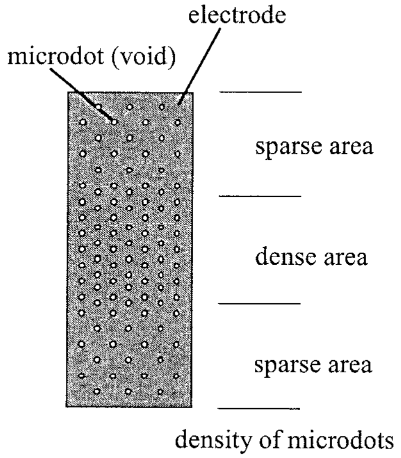
3. Experiments

A. Sample Preparation

The structure of the LC panel in our experiments is shown in Fig. 4. To execute precise measurements, two optically polished glasses are adopted as the substrates that sandwich the LC material. The glass substrates are 0.25 mm thick; 8 nm thick indium tin oxide (ITO) is used as the electrodes that apply the voltage to the LC material. The microdots are fabricated by wet etching the electrode layer of one side of the LC panel, and there is no microdot on the opposite electrode. The microdots are 3, 6, and 12 μm in diameter. To attain designed microdot patterning, we employed a glass photomask by using e-beam patterning and a contact mask aligner on a lithography process of liquid photoresist. A 37 nm thick anchoring film made from polyimide is coated on the electrode and normalized in the polarized direction by mechanical rubbing. Considering the thicknesses of the electrode and the anchoring film, the step at the edge of the microdots is negligible for the LC material.



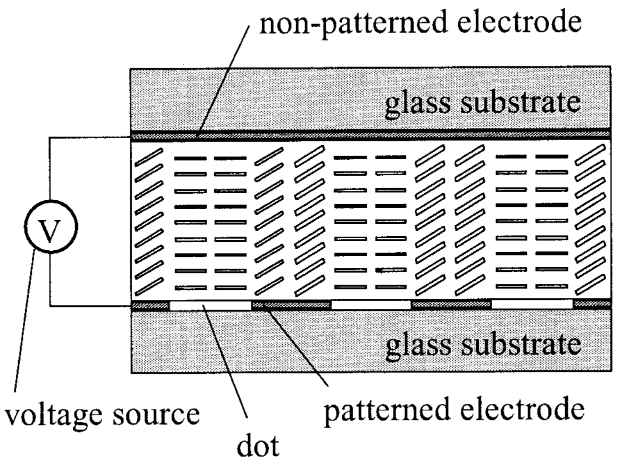
(a) function of phase-profile modulating device



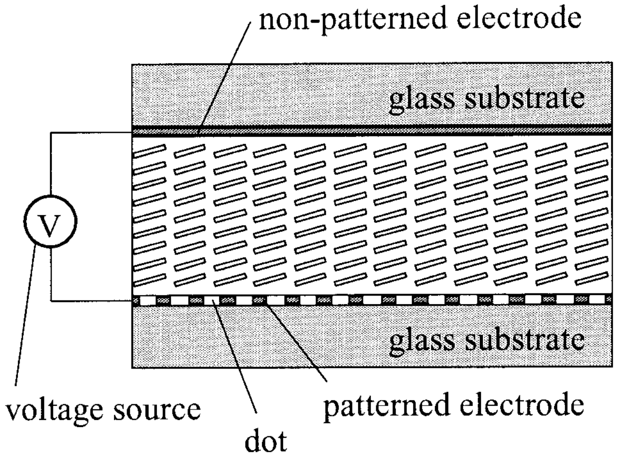
(b) patterned electrode structure

Fig. 2. Concept of phase profile modulation by microdots on the electrode: (a) schematic diagram of the phase-profile modulation device; (b) microdot-density-modulated patterned electrode.

Figure 5 is a scanning electron microscopy (SEM) photograph of the microdots on the electrode. The diameter and average distance between the microdots are 6 and 12 μm, respectively, and the microdots were randomly located. We define the density of the microdots as the proportion of the electrode taken up by the dots themselves; thus the density in Fig. 5 is 20%. The nematic LC material is supplied by Chisso Corporation; its threshold voltage is 1.94 V, $\Delta\varepsilon = 6.9$, and $\varepsilon_{\perp} = 3.6$, and its optical parameters are $\Delta n(n_e - n_o) = 0.116$ and $n_o = 1.489$ at $\lambda = 589$ nm. We employ this LC material, considering its durability against short-wavelength laser radiation. The gap in the LC panel is set at 6 μm. The plotted shape of the applied voltage is rectangular, and its frequency is 1 kHz.



(a)



(b)

Fig. 3. Concept of the orientation averaging of LC material: (a) orientation of LC molecules not averaged with dots that are too large; (b) orientation of LC molecules averaged with dots that are small enough.

B. Measurements of Diffraction and Retardation

To investigate the averaging of the orientation of the LC molecules with the microdots patterned on the electrode, we measured the diffraction characteristics and retardation characteristics. The experimental results from diffraction loss and the retardation characteristics of the LC panel with microdots on the electrode are shown in Figs. 6 and 7, respectively. The microdot diameters are 3, 6, and 12 μm, and the microdot density is 20% in these experiments. In Fig. 7 retardation of the LC panel without microdots is also plotted as a reference. In both measurements a GaN laser diode with a wavelength of $\lambda = 407$ nm was used as a light source. A collimated laser beam with a diameter of 3 mm was normally illuminated on the LC panel. In the measurement of the diffraction characteristics the polarization angle of the incident beam was adjusted to the extraordinary ray of the LC material, i.e., the polarization angle of the incident beam is parallel to the direction the anchoring film was rubbed. To obtain the diffraction loss, we used a combination of the $f = 50$ mm focusing lens and the $\phi = 0.2$ mm aperture in front of the photodetector into the beam passing through the LC panel. In measuring the retardation characteristics, we adopted the polarizer rotating method,[10] and we set enough distance between the LC panel and detector to remove the diffracted light.

From the experimental results of adopting a 3 μm diameter microdot sample, we observed a restrained diffraction loss and a reduction in index change (a reduction in retardation). The restrained diffraction loss indicates that the index profile is smooth, and consequently the orientation of the LC molecules is averaged. The reduction in the index change indicates that the average LC orientation is controlled by the applied voltage that is decreased from the supplied voltage by decreasing the area of the elec-

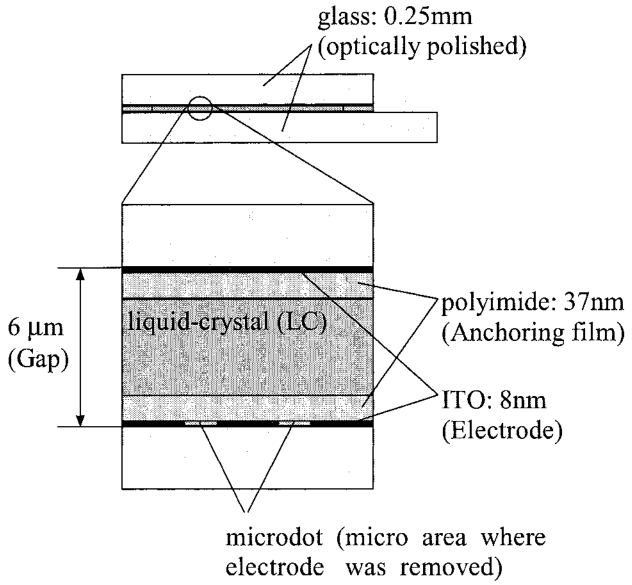


Fig. 4. Structure of the LC panel.

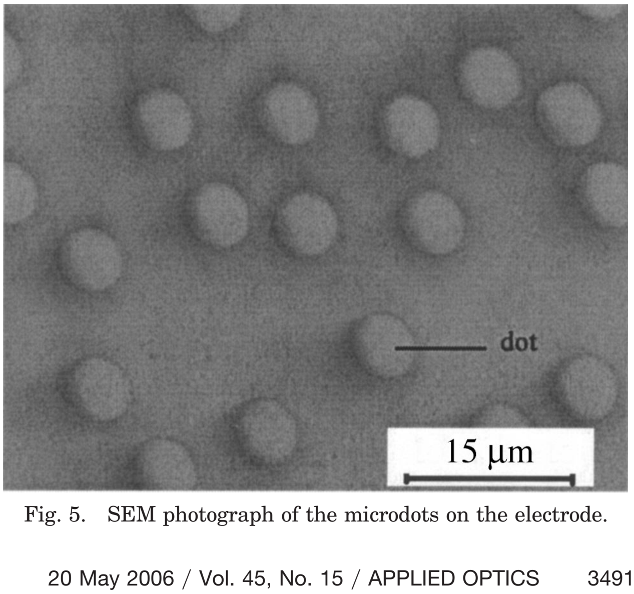


Fig. 5. SEM photograph of the microdots on the electrode.

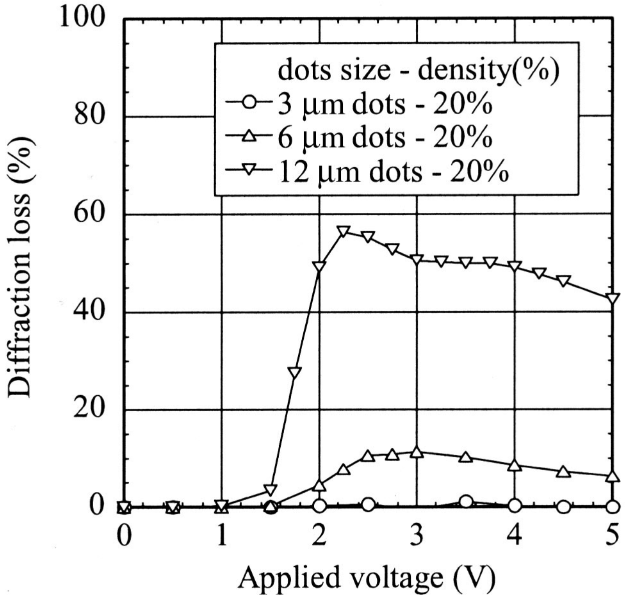


Fig. 6. Diffraction characteristics of the LC panel with microdots.

trode caused by adopting microdots, as we explain in Fig. 3(b). Therefore, from the orientation-averaging point of view, 3 μm diameter microdots are small enough for the LC material. Concerning the results of retardation characteristics, the data of a 3 μm diameter microdot sample is shifted to the right by comparing the data without microdots with the effect of this decrease in the supplied voltage.

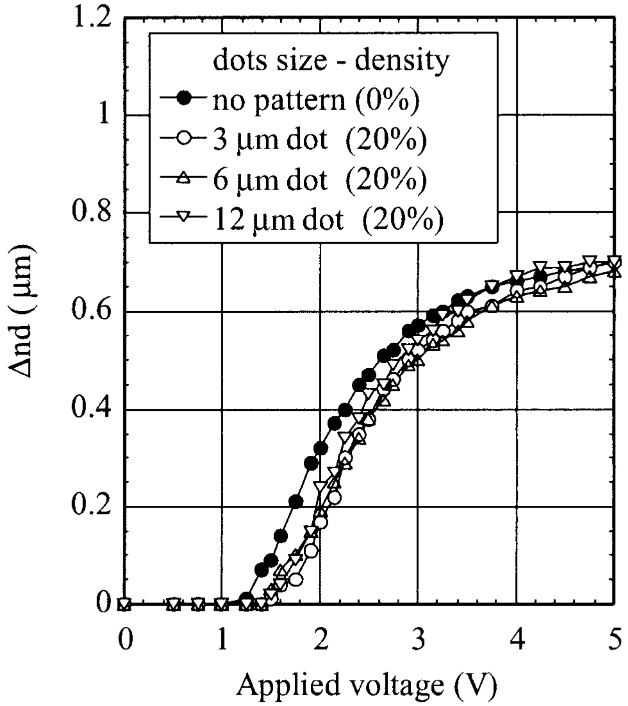


Fig. 7. Retardation characteristics of the LC panel with microdots.

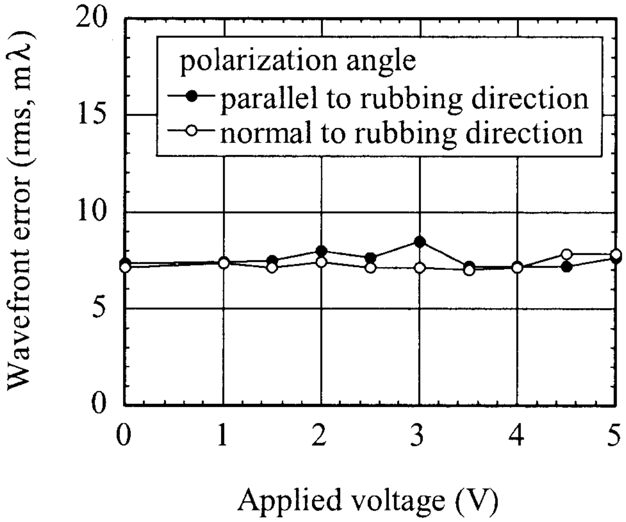


Fig. 8. Wavefront error when light is passing through the LC panel with microdots.

In addition, the quality of the beam passing through the LC panel with 3 μm diameter microdots on the electrode with a dot density of 20% was measured by a phase interferometer (Zygo Corporation DVD-400, λ = 405 nm). Figure 8 shows the wavefront error of the LC panel as the applied voltage changes. The power element and skew element are removed from the plotted data. This result shows that the quality of the output beam of the LC panel in both polarization angles is not affected by the 3 μm diameter microdots on the electrode.

C. Phase Profile Modulation by Microdot Density Modulation

To test our concept of phase profile modulation, we examined an LC panel with microdot-density modu-

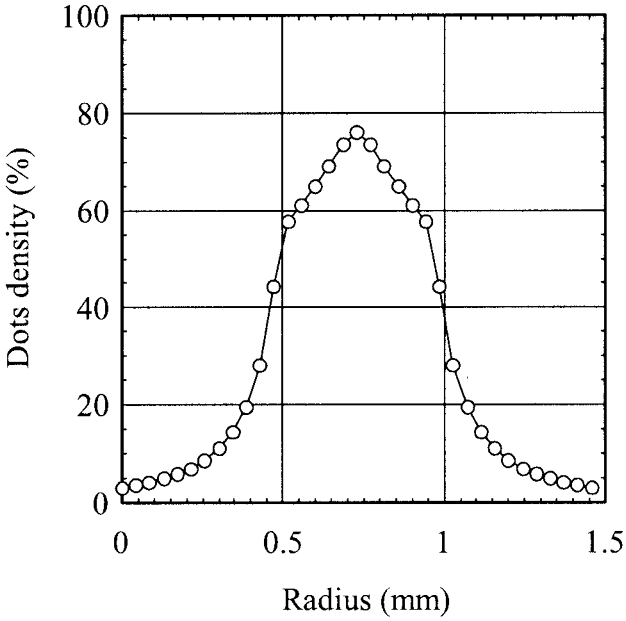
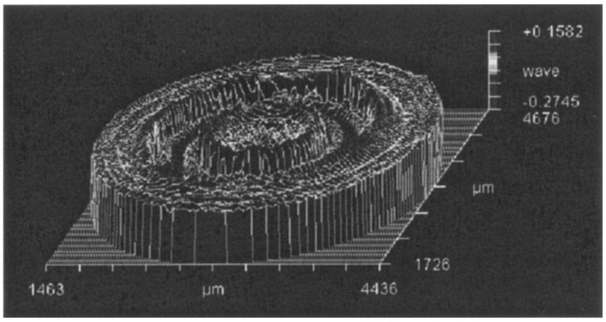
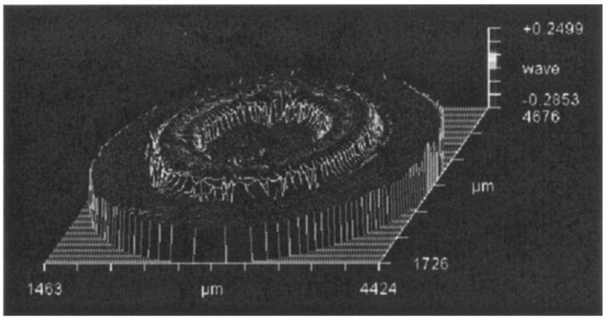


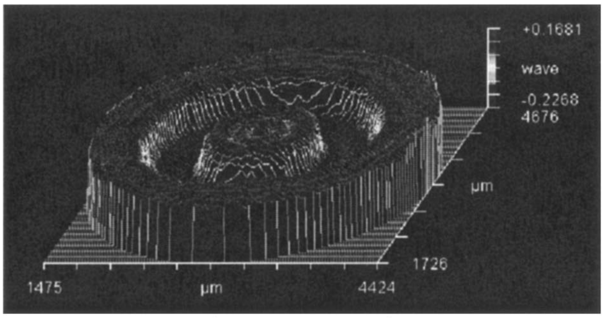
Fig. 9. Microdot density profile on the LC panel.



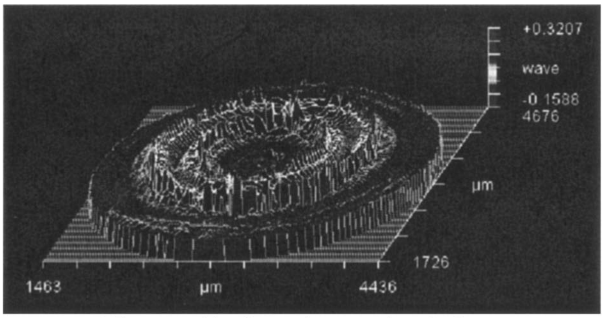
(a) applied voltage is 2.00V



(b) applied voltage is 2.25V



(c) applied voltage is 2.75V



(d) applied voltage is 3.25V

Fig. 10. Phase-modulation profiles with microdot density modulation.

lation. In this experiment the diameter of the microdots is 3 μm, small enough for LC material. We made the LC panel with 18 levels of microdot density by adjusting the distance between the microdots. The density profile of the microdots on the LC panel is plotted in Fig. 9. We set the minimum and the maximum of the microdot density to 3% and 76%, respectively. The phase-modulation profiles obtained by a phase interferometer (DVD-400, $\lambda = 405$ nm) when voltage is applied to the LC panel of 2.0, 2.25, 2.75, and 3.25 V are shown in Figs. 10(a), 10(b), 10(c), and 10(d), respectively.

From the results in Fig. 10 the phase-modulation profiles of light passing through the LC panel corresponding with the microdot-density-modulation profile in Fig. 9 are shown. In this way the concept of phase profile modulation by microdot density modulation is confirmed. Although a single voltage is applied to the LC panel, a modulated phase profile is obtained.

Figure 11 shows the phase difference in the light passing through the LC panel between a microdot density of 3% and 76% when the results are measured by an interferometer. We consider that there is one additional λ difference between the applied voltages of 2.25 and 2.75 V shown in Figs. 10(b) and 10(c) because the phase interferometer cannot express a phase difference larger than 1.0λ, and the phase difference between a microdot density of 3% and 76% must be the largest. From Fig. 11 the value of 1.5λ is obtained as the maximum phase difference when 3.0 V is the applied voltage.

D. Effect of Anisotropic Microdots

To further consider this concept, we investigated the diffraction loss of the LC panel by using the anisotropic microdots on the electrode. Figure 12 shows the elongated shape of the anisotropic microdots and the direction of the microdot elongation and the rubbing direction. In sample A the long axis of the microdots is parallel to the rubbing direction. In sample B the long axis of the microdots is normal to the rubbing direction. The width and the length of the anisotropic microdots are 3 and 12 μm, respectively. In this experiment the microdot density is 40%. The diffraction characteristics of the LC panel having anisotropic microdots are shown in Fig. 13. Figure 13 shows that

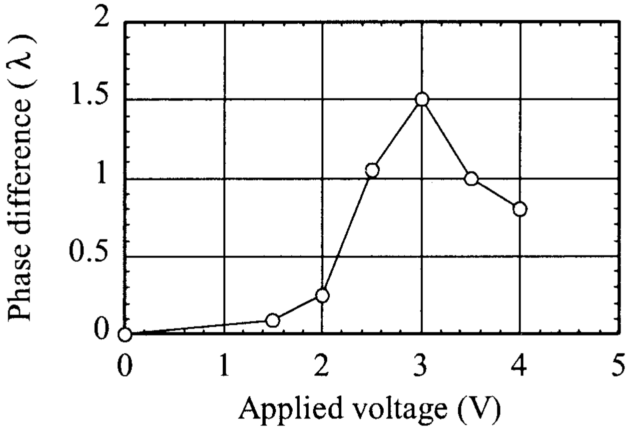
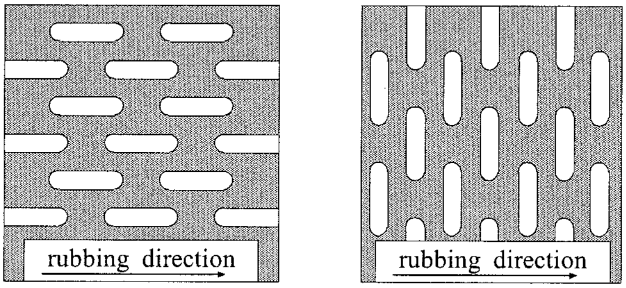


Fig. 11. Phase difference in light passing between microdot densities of 3% and 76%.



(a) sample A (b) sample B

Fig. 12. Schematic diagram of anisotropic microdots on the electrode and relations between the directions of the anisotropic microdots and rubbing directions: (a) the long axis of the microdots parallel to the rubbing direction; (b) the long axis of the microdots normal to the rubbing direction.

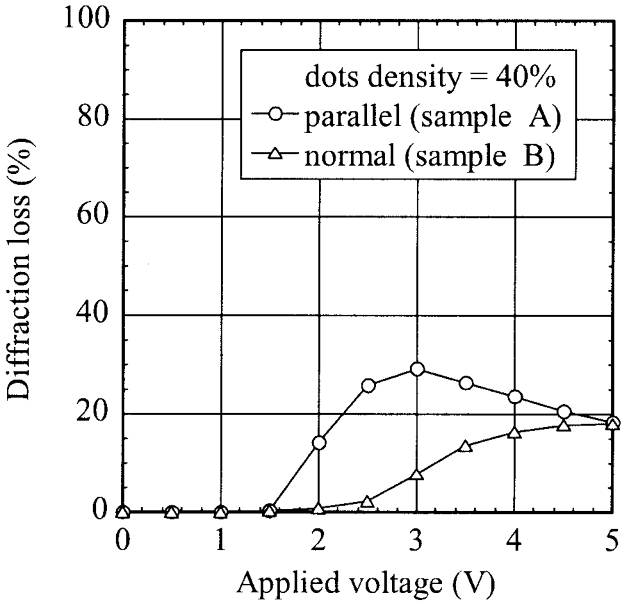


Fig. 13. Diffraction characteristics of the LC panel with anisotropic microdots.

sample A has a larger diffraction loss than sample B in spite of their having identical microdots. We therefore consider that the diffraction characteristics of the LC panel are sensitive to the long axis of the anisotropic microdots.

4. Conclusion

The optical characteristics of an LC panel with microdots on the electrode have been precisely investigated. The experimental result of restrained diffraction loss from the LC panel with 3 μm diameter microdots on the electrode indicated that the orientation of LC molecules was averaged and that the index profile was smooth. The reduction in the index change indicates that the average orientation of the LC molecules can be controlled by applying a voltage decreased from decreasing the area of the electrodes by adopting microdots. Therefore 3 μm diameter microdots are regarded as small enough for LC material from the orientation averaging point of view.

The phase-profile-modulating LC panel with microdot density modulation has been demonstrated. The diameter of the microdots in the LC panel was 3 μm, and the microdot density ranged from 3% to 76%. The corresponding phase profile modulation of light passing through the phase-profile-modulation LC panel with the profile of density-modulating microdots on the electrode was obtained. We obtained a maximum phase difference of 1.5λ between a microdot density of 3% and 76%. However, applying voltage to the LC panel was from a single voltage source.

Our experimental results indicate that the phase-profile-modulating LC panel with microdot density modulation can yield a full phase profile when the density of the microdots is continuously adjusted.

In addition, this phase-profile-modulating LC panel is applicable to a wide wavelength range, such as all visible wavelengths and IR wavelengths, because the diffraction loss characteristic is more sensitive when the light source has a shorter wavelength.

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