Vertical Alignment Technology of Fine LC Pixels Based on Elastic Alignment Effect for Electronic Holography

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ABSTRACT

To achieve electronic holography with a wide field of view, we proposed the elastic alignment technique for liquid crystals (LCs) using a lattice-shaped wall structure. We showed that the shape of the microscopic space filled with LCs enables vertical alignment control of the LC without conventional alignment films.

1 Introduction

Since 3-dimensional (3D) displays are capable of expressing depth, they are expected to be applied not only in the fields of broadcasting, communications, and entertainment but also in a wide range of fields such as medicine and industry. As one of 3D displays, electronic holographic displays reproduce the wavefront of object light. This feature enables a natural stereoscopic vision for human beings [1][2]. They reproduce the wavefront of object light using spatial light modulators (SLMs). SLMs using liquid crystals (LCs) are capable of modulating the phase distribution of the incident light and reproduce the phase hologram, which realizes high light utilization efficiency. Furthermore, phase hologram has the advantage of suppression of higher-order diffraction images leading to degradation of image quality [3]. Therefore, we focus on the phase-type LC-SLM in this paper.

Although electronic holographic displays are attractive 3D display modes as mentioned above, they have a problem that a field of view is too narrow for practical use. Since holography uses light diffraction to reproduce an image, a field of view is restricted by the maximum diffraction angle. To increase the diffraction angle, the pixel pitch of the SLM needs to be reduced. Assuming a desktop environment, the SLM should have a field of view angle of 30°. This field of view angle requires for pixel pitch of 1 μm in the SLM [3].

However, when the pixel pitch of an LC-SLM is 1 μm, it is difficult to drive pixels independently due to leakage of electric field and penetration of the LC elastic force among adjacent pixels. To overcome this problem, we have earlier suggested a dielectric shield wall structure so far [3]. The lattice-shaped wall structure has dielectric barriers between adjacent pixels and suppresses the electric field leakage and penetration of LC elastic force by dividing the LCs into pixel regions. To achieve uniform LC alignment in a pixel structure with lattice-shaped walls, partition plates are inserted parallel to the rubbing direction of the parallel alignment film. Giving anisotropic shape to the space filled with LCs causes the space to strain, resulting in an elastic alignment effect based on the minimization of elastic free energy [4][5]. The LC is aligned along a direction that minimizes the elastic free energy of the elastic alignment effect and the parallel alignment film anchoring. Thus, uniform LC alignment has been achieved in a micropixel structure with lattice-shaped walls of 1 μm pitch [6].

In recent years, a field of view angle wider than 30° is required for applications such as TV broadcasting where multiple people are expected to watch. To expand more of a field of view angle, the pixel pitch of the SLM needs to be finer than 1 μm. However, the behavior of LC alignment in fine pixel structures of less than 1 μm has not to be clarified.

In this study, we aimed to control the LC alignment of the lattice-shaped wall structure for pitches of less than 1 μm.

2 Proposed Fine LC Pixel Structure

In general, LC molecules are aligned by anchoring forces from the wall or the substrate surface. Here, we used nanoimprinting technology to form the wall structure. The formation of alignment films and rubbing treatment or ultraviolet irradiation to the wall structure is difficult. Because if the alignment films are coated, the material fills the cavities of the lattice-shaped wall. Therefore, the LC molecules are more strongly affected by the alignment film with strong anchoring strength formed on the upper substrates than on the wall surface.

To realize fine pixels with a pitch of less than 1 μm, the pitch of the wall structure must also be formed to less than 1 μm. When using highly birefringence LC materials with refractive index differences of 0.37 [7], the thickness of the LC layer required for sufficient phase modulation from 0 to 2π is 1 μm. When the thickness of the LC layer is 1 μm and the pitch of the walls is reduced, the space filled with LC surrounded by the wall structure and the substrate has a long shape along the thickness direction, as shown in Fig. 1. In such a shape, the area occupied by the alignment becomes small. Hence, the effect of surface anchoring by the wall becomes dominant, and it will be difficult to control LC alignment.

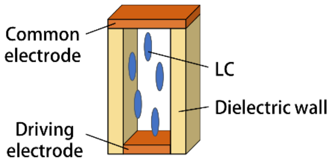


Fig. 1 Schematic illustration of designed dielectric shield wall structure with a pitch of less than 1 μm

For the above background, we propose a method to align the LC molecules vertically to the substrate by using elastic alignment with the fine lattice-shaped wall structure. The vertical alignment prevents the elastic alignment of orthogonal walls from competing with each other, which is considered to be suitable for higher resolution of pixels. Furthermore, by realizing a shape with a smaller elastic free energy than the surface anchoring of the wall, stable LC alignment can be achieved using only elastic alignment without using an alignment film. When the formation of the alignment film is not necessary, it helps simplify the manufacturing process of the phase modulator and reduces the cost.

Based on the above, we examined to control the vertical alignment of LC using only elastic alignment of a lattice-shaped wall structure.

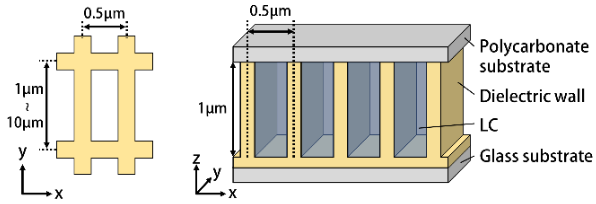
3 Results and Discussion

3.1 Relationship between Shape of LC-Filled Space and LC Alignment

Elastic alignment is largely related to the shape of the space in which the LC is filled. To control the vertical alignment of the LC by elastic alignment alone, it is necessary to clarify the relationship between the shape of the LC-filled space and the LC alignment by elastic alignment effect. For confirming the behavior of LC alignment in LC-filled spaces of different shapes, we fabricated LC cells with lattice-shaped wall structures of different pitches and observed them by polarization microscopy.

Fig. 2 shows the structure of the LC cell with lattice-shaped walls. The pitch of the lattice-shaped wall structure in the x-direction (x-pitch) was fixed at 0.5 μm, and the pitch in the y-direction (y-pitch) was set to 1 μm, 1.5 μm, 2 μm, 3 μm, 5 μm, and 10 μm to lengthen the shape of the LC-filled space in one direction. To make it easier to compare the LC alignment between different pitches, the wall height was set to 1 μm and the area ratio between the lattice-shaped wall and the LC-filled area was kept constant. In the LC-filled space, the x-direction is the lattice short side and the y-direction is the lattice long side.

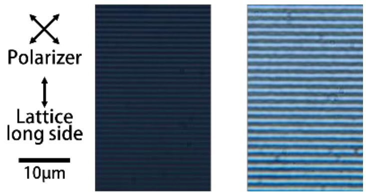
To investigate the effect of wall structure on elastic alignment, no alignment film was used. We used a flexible polycarbonate substrate as an upper substrate to improve the adhesion between the upper substrate and the wall structure. Since the purpose of this experiment was to observe the LC alignment, we used E7 (supplied by LCC Co.), a common LC material.



(a) (b)

Fig. 2 The structure of a 0.5 μm × 1~10 μm pitch lattice-shaped dielectric shield wall

Fig. 3 shows crossed-Nicol polarizing images of the LC cells. The angle between the polarizing direction of the incident light and the lattice long side direction is 45°. In Fig. 3 (a), the x- and y-pitches are 0.5 μm × 1 μm, and in Fig. 3 (b), 0.5 μm × 1.5 μm. In Fig. 3 (a), a dark image was observed. On the other hand, Fig. 3 (b) showed a bright state when the y-pitch is 1.5 μm or larger.



(a) (b)

Fig. 3 Crossed-Nicol polarizing microscope images of LC cells within lattice-shaped wall structure. A lattice structure of pitch 0.5 μm × 1 μm (a), 0.5 μm × 1.5 μm (b)

Fig. 4 shows the relationship between y-pitch and average transmittance values of multiple LC-filled spaces when the angle between the polarization direction and the lattice long side direction is 45°. From these results, we confirmed that the y-pitch of 1.5 μm and above showed higher average transmittance than that of 1 μm, and the average transmittance increased with increasing y-pitch.

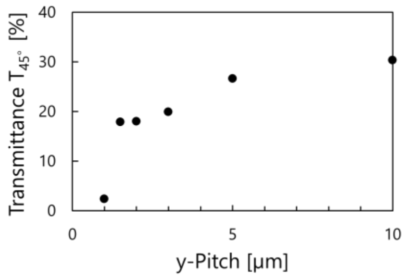


Fig. 4 Average transmittance values at a 45° angle between the direction of lattice long side and the polarization when only y-pitch is varied

3.2 Elastic Alignment Effect by Wall Structure

To investigate the effect of the elastic alignment on the wall structure with a pitch of less than 1 µm, we fabricated LC cells and observed them with a polarizing microscope. The lattice-shaped wall structure had an x-pitch of 0.5 µm, a y-pitch of 1 µm, and a wall height of 1 µm. Using this structure as a reference, we fabricated lattice-shaped wall structures with x- and y-pitches 0.8, 0.6, and 0.5 times finer, respectively, while keeping the area ratio of the lattice-shaped wall to the LC-filled area and the wall height constant. Fig. 5 shows a cross-sectional scanning electron microscope (SEM) image of the wall structure with an x-pitch of 0.4 µm and a y-pitch of 0.8 µm. The wall x-pitch was 0.4 µm and had a width of 250 nm.

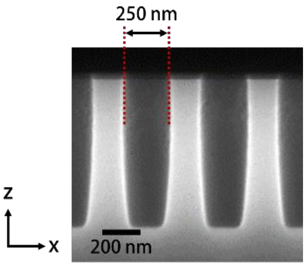


Fig. 5 Cross-sectional SEM image of the walls with an x-pitch of 0.4 µm and a y-pitch of 0.8 µm

Fig. 6 shows the results of observation of the LC cell using a polarizing microscope. Fig. 6 (a) has an x- and y-pitch of 0.5 µm × 1 µm, and Fig. 6 (b) has 0.25 µm × 0.5 µm. A dark image was observed for the structure with a smaller pitch compared to the structure with a large pitch at an angle of 45° between the direction of the lattice long side and the polarization.

(a) (b)

Fig. 6 Crossed-Nicol polarizing microscope images of LC cells within lattice-shaped wall structure. A lattice structure of pitch 0.5 µm × 1 µm (a), 0.25 µm × 0.5 µm (b)

Fig. 7 shows the relationship between y-pitch and average transmittance values when the angle between the polarization direction and the lattice long side direction is 45°. We confirmed that the average transmittance decreased with the narrower pitch of the wall structure. These results indicate that the finer the wall structure, the more the elastic alignment effect works to align the LC molecules in a direction vertically to the substrate. Besides, this result implies that a vertical alignment of the LC is useful for wall structures finer than 1 µm.

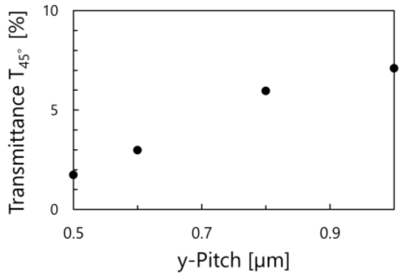


Fig. 7 Average transmittance values at a 45° angle between the direction of lattice long side and the polarization for a lattice structure with a fine pitch of 1 µm or less

In this section, we discuss the relationship between the elastic alignment effect and the alignment of the LC due to the shape of the LC-filled space. The LC-filled space in this structure is a rectangle surrounded by lattice-shaped walls and substrates, and the three sides are represented as l_x, l_y, and l_z, respectively. At this time, the LC is aligned along a direction of the longest of the three sides due to the elastic alignment effect. Furthermore, the longer the longest side is compared to the other two sides, the greater the alignment in the long side direction. In fact, in an experiment in which the shape of the LC-filled space was varied when the y-pitch was 1.5 µm or more, l_y was the longest of the three sides, and the LC was aligned in the y-direction. For a y-pitch of 1 µm, the longest side is l_z when the wall thickness is taken into account, but there is no significant difference between l_y and l_z, suggesting that the alignment is tilted toward the substrate. In the lattice-shaped structure with a very fine pitch of 0.25 µm × 0.5 µm, l_z is longer than l_x and l_y, which is considered to be vertically aligned.

For the above, we show that the shape of the fine LC-filled space enabled the control of parallel and vertical alignments. For LC-SLM with fine pixels of less than 1 µm × 1 µm, vertical alignment by elastic alignment effect is considered to be useful for sufficient phase modulation. Although we confirmed that the LC is vertically aligned only by the elastic alignment effect, the alignment can be further enhanced by forming a vertical alignment film on the upper substrate.

3.3 Directional Control of Rotation of LC Molecules by Pixel Structure

To apply a fine pixel structure with lattice-shaped walls to a SLM, there must be no difference in behavior when voltage is applied in each pixel. In particular, LCOS-SLMs, which are reflective devices, generally have an oblique incidence of light from the viewpoint of light utilization efficiency. Therefore, the tilt direction of the LC molecules when voltage is applied must be uniform in each pixel. In the case of a vertically aligned LC-filled space, it is seemingly possible to control the molecular tilt in the y-direction when voltage is applied by setting $l_z > l_y > l_x$ for the three sides. However, there are two directions of rotation of the LC molecules: +y and -y directions. Therefore, if only the elastic alignment effect aligns the LC, a structure is needed to unify the direction of rotation of the molecules in one direction.

Nanoimprinting technology has the advantage that various microstructures can be formed at once. To solve the problem, we devised a method to regulate the direction of rotation of LC molecules by adding a stepped structure to the lower substrate to create a shape anisotropy in the LC-filled space.

Fig. 8 shows the proposed structure. Nanoimprinting technology can form stepped structures at the same time as lattice-shaped wall structures.

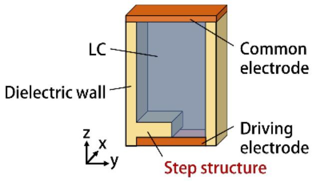


Fig. 8 Dielectric shield wall structure with a step

To confirm the usefulness of the stepped structure, we investigated the LC director and electric field distribution by using simulations based on the elastic continuum theory of LCs. The thickness of the LC layer was 1.6 μm, the y-pitch was 1 μm, and the common and driving electrodes were placed on the upper and lower substrates, respectively. The initial alignment of the LC was vertical, and we used the LC material with a negative dielectric anisotropy ($\Delta\varepsilon$=-3.3). The dielectric constant of the dielectric wall was set to 4.

Fig. 9 shows the simulation result. We confirmed that the LC molecules rotated toward the stepped structure when voltage was applied. This is thought to be caused by a change in the distribution of the electric field due to the stepped structure. A large oblique electric field is applied to the LC molecules near the drive electrode, but the oblique electric field applied to the LC above the step is small. As a result, the alignment of the LC in the space is dominated by the former, which is thought to have determined the direction of rotation. For the above discussion, the simulated result exhibited that the stepped structure is useful for controlling the direction of rotation of LC molecules in pixel structures with lattice-shaped walls.

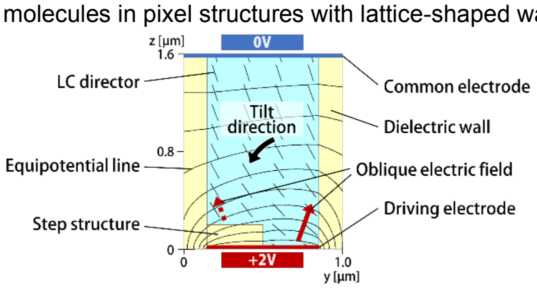


Fig. 9 Simulation result of LC director and electric field distribution for dielectric shield wall structure with a step

4 Conclusions

In this study, we proposed the new LC alignment control technique based on the elastic alignment effect using a fine dielectric shield wall structure for electronic holography with a wide field of view. We confirmed that the fine LC-filled space, which has a long shape along a uniaxial direction, can control the vertical LC alignment using only the elastic alignment effect without conventional alignment films. Simulation results showed that the direction of rotation of the LC molecules can be controlled by adding a stepped structure to the pixels. These results will contribute to realizing electronic holography with a field of view angle of 30° or more.

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