1. Introduction

Electronic holography is a prospective 3D display technology. Displays using holographic technology reconstruct the wavefronts of object images by displaying the interference pattern (hologram) on a spatial light modulator (SLM). This means that they can control the position at which the light converges, so that they show 3D images without visual fatigue effects such as vergence-accommodation conflicts. Many types of holographic displays have previously been suggested, but they share the common problem that their field of view is too narrow for practical use. This problem is attributed to insufficient SLM definition. Electronic holographic displays reconstruct wavefront of object light by the diffraction of light. Therefore, the field of view is restricted by the maximum diffraction angle. For example, when the pixel pitch of the SLM is 3.74 µm, which represents the minimum pixel pitch of the liquid crystal SLM (LC-SLM), the field of view is only 8.4° (for a wavelength of 550 nm). To achieve a field of view of 30°, which is the effective field of a human being's visual range, it is necessary for the SLM to have 1-µm-pitch pixels.

To minimize the pixel pitch of the SLM, magneto-optical SLM (MO-SLM) has been suggested. MO-SLM has achieved binary modulation of light intensity with 0.5-µm-pitch-pixels. However, MO-SLM can rotate the polarization direction of light only by 2–3°. This means that the light use efficiency is extremely low and very dark reconstructed images are obtained. On the other hand, LC-SLM can modulate the phase of light into multiple values, and can enable phase-type holograms; this can achieve high light use efficiency and reproduce bright reconstructed images. For this reason, we investigated LC-SLMs with 1-µm-pitch pixels.

We previously reported that individual pixel driving is difficult when the pixel pitch of the LC-SLM is 1 µm because of the leakage of the electric field and the penetration of the elastic force of the LC between pixels. To overcome this problem, we suggested a dielectric shield wall structure, which adds dielectric walls between pixels as shown in Fig. 1. We have already clarified the optimum width of dielectric walls and the anchoring strength on the walls for uniform light modulation. We have also investigated the influence of the nonuniformity of LC alignment in a pixel on the reconstructed images, and found that the nonuniform phase distribution in a pixel increases zero-order diffraction light on the reconstructed images.
The dielectric shield wall structure has a lattice-shaped wall to reduce the influence of adjacent pixels. Because of this, it is difficult to inject liquid material, such as LCs and solution containing an alignment material for forming alignment film in the dielectric walls. Therefore, to establish a fabrication process for LC-SLMs having the dielectric shield wall structure, optimization of the wall shape is required. In this paper, we investigated the dielectric shield wall structure with added slits for liquid material and evaluated its shield effects.

2. Dielectric shield wall structure with slits

2.1 Investigation of slit position

There are many possible slit position patterns, but all of them can be categorized into two major types; one where the slit is at the center of the walls, and the other where the slit is at the intersections. Therefore, we simply compared phase distributions between these two patterns. For clarifying the LC alignment distribution in the dielectric shield wall structure with slits, we conducted numerical simulations based on the elastic continuum theory of LC using an LC device simulator, LCD Master 3D (Sintech Inc.). This device simulates the directions of the LC directors by minimizing global elastic free energy in the LC cell using the finite element method (FEM). The following equation is the free energy density in LC bulk considering electric field.

\[ f = \frac{1}{2} k_{ii} (\text{div } \mathbf{n})^2 + \frac{1}{2} k_{22} (\mathbf{n} \cdot \text{rot } \mathbf{n})^2 + \frac{1}{2} k_{33} |\mathbf{n} \times \text{rot } \mathbf{n}|^2 - \frac{1}{2} \epsilon E \cdot E, \]  

(1)

where \( k_{ii} \) are the elastic constants, \( \mathbf{n} \) are the directors of the LC, \( \epsilon \) is the dielectric constant tensor of the LC, and \( E \) is the electric field.

Figure 2 shows the geometry of the dielectric shield wall structure with slits used for the simulations. The wall width was 200 nm and the relative dielectric constant of the walls was 3.0 representing the relative dielectric constant of general acrylic resin. For qualitative comparison between the two slit patterns, the width of the slits was 500 nm at the centers and the injections of the walls. The thickness of the LC layer was 1 µm. The LC material was a high birefringence LC material, No. 1760-2 in Ref. 11), allowing a large amount of light modulation. Table 1 shows the parameters of 1760-2. In this simulation, we assume parallel alignment along the X-axis with a pretilt of 10° for uniform LC alignment; we also assume that the LC molecules are fixed on the surface of the substrates and the walls (strong anchoring) to provide an ideal LC alignment. This means that LC directors have a pretilt angle of 10° from the X-axis in the X-Z plane.

![Fig.1 Schematic image of the dielectric shield wall structure.](image1)

![Fig.2 Geometries of dielectric shield walls structure having slits.](image2)
whole of the LC cell, including the surface of the dielectric walls, as shown in Fig. 2. This alignment condition can be realized, for example, with dielectric walls composed of a liquid crystalline polymer that has anchoring power on the surface of the walls. We simulated an ON-state pixel (4 V) surrounded by 8 OFF-state pixels (0 V) and an OFF-state pixel surrounded by ON-state pixels for evaluating the individuality of the pixel driving at the center pixel. The dividing number of the FEM ($X \times Y \times Z$) was $60 \times 60 \times 50$, and a periodic boundary condition around the 9 pixels is assumed.

Figure 3(a) and 3(b) show the simulated phase distribution of the dielectric shield wall structure without a slit, as a reference. In these figures, only the phase in the ON-state pixel surrounded by eight OFF-state pixels advanced, and the phase shift in the OFF-state pixel surrounded by eight ON-state pixels was kept around 0. This means that individual pixel driving was achieved by the shield effect of the dielectric walls.

Figure 4 shows the phase distribution in the dielectric wall structure with slits at the centers of the walls. From Fig. 4(a), the phase at the edge of the surrounding OFF-state pixels advanced. In particular, as shown in Fig. 4(b), the phase advanced in the OFF-state pixel surrounded by ON-state pixels. This is because the LC molecules in the OFF pixel are rotated by the leakage of electric field and the penetration of the elastic force of the LC from adjacent ON-state pixels.

On the other hand, as shown in Fig. 5(a), the phase in the OFF-state pixels did not advance when the slits were at the intersections of the walls. The phase lead in the center OFF-state pixel surrounded by ON-state pixels was also suppressed in comparison with the case of the slits at the centers of the walls. This means that shielding the electric field and the elastic force of LCs between directly adjacent pixels is more important than shielding them from diagonally adjacent pixels. From these results, it can be seen that the dielectric shield wall structure having slits at the intersections of the walls can achieve better individual pixel driving than the design wherein the slits are at the center of the walls.

### 2.2 Effect of slit width on light modulation

To clarify the relation between the width of the slits and the light modulation, we also simulated the LC alignment and phase distribution in the dielectric shield wall structure with slits at the intersections of the walls, while varying the width of slits. We changed the slit width from 200 to 900 nm in steps of 100 nm and simulated the phase distribution in an ON-state pixel surrounded by eight OFF-state pixels, and in an OFF-state pixel surrounded by eight ON-state pixels. To evaluate the uniformity and individuality of the pixel driving, we calculated the modulable area ratio$^5$.

Modulable area is defined as the region wherein the phase shift is over 90% of the maximum phase shift in an ON-state pixel, and under 10% of the maximum phase shift in an OFF-state pixel. In this calculation, we excluded the wall region to evaluate only the uniformity and individuality of the phase modulation in the center pixel region.

Figure 4 shows the modulable area ratio of the dielectric shield wall structure, with slits where the width was 200 - 900 nm. The modulable area ratio of both ON- and OFF-state pixels decreased with an increase in slit width. The reason why the modulable
area ratio of the ON-state pixel was lower than that of the OFF-state pixel was that the anchoring force on the walls keep LC molecules parallel to the substrates. Therefore, the modulable area in the ON-state pixel can be increased by weakening the anchoring strength on the dielectric walls\(^7\).

Regarding the leakage of the electric field and the penetration of the elastic force of the LC, the simulation result of the OFF-state pixel surrounded by eight ON-state pixels when the slit was 700 nm is shown in Fig. 7. Figure 7(a) shows the phase distribution of the nine pixels. The phase in the center OFF-state pixel advanced due to the influences of adjacent pixels. Figure 7(b) shows the LC alignment and the electric field distributions at \(Y = 1.2\) \(\mu\)m, where there are slits. The equipotential line is at the 0.5 V step. In this figure, the leakage of the electric field from surrounding pixels rotated the LC directors in the OFF-state pixel. In the bulk of the LC layer, the leakage of the electric field was not strong, but the LC molecules rotated. This is because of the penetration of the elastic force of LCs. The elastic force penetrated along the thickness direction and from adjacent pixels through the slits, and rotated the LC directors in the bulk.

Focusing on the modulable area ratio of the OFF-state pixel, over 50% of the modulable area was achieved even when the width of slits was 400 nm. In the actual fabrication process, we can suppress the loss of modulable area by using liquid materials having a lower viscosity, or by improving the wettability of the substrates and walls because narrower slits are sufficient for injection. From these results, we conclude that individual pixel driving can be achieved with a dielectric shield wall structure with slits at the intersections of the walls.

3. Conclusion

We evaluated the shield effect of dielectric walls having slits for practical fabrication processes. The results of simulations based on the elastic continuum theory showed that the dielectric shield wall structure having slits at the intersections of the walls can achieve individual pixel driving in ON- and OFF-state pixels under the condition of strong anchoring on the surfaces of the substrates and the walls. These results will contribute to the realization of practical electronic holographic displays.

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