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Four-domain twisted nematic liquid crystal display fabricated by reverse rubbed polyimide process

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In Appl. Phys. Lett. 67, 1990 (1995), we proposed a particularly simple four-domain (4-D) twisted nematic(TN) liquid crystal display(LCD) device, which is composed of two left-handed and two right-handed TN subpixels. The two members of each pair of same handedness subpixels are rotated 180° with respect to each other, resulting in four domains that spatially average one another optically to provide a wide angle of viewing with no gray scale inversion. The optical performance of the 4-D TN LCD was confirmed by studies of a test cell fabricated by a two-step SiO₂ oblique evaporation technique. In this article, we report the realization of our four-domain TN display by a reverse rubbing technique that should be suitable for mass production in the display industry. The optical simulation of our 4-D TN cell was performed and the effect of disclinations at subpixel boundaries on display contrast investigated. A simple model was developed to evaluate the stability of our 4-D structure. © 1996 American Institute of Physics. [S0021-8979(96)06216-0]

I. INTRODUCTION

It is well known that single-domain twisted nematic (TN) cells, which are now most commonly employed in flat panel liquid crystal displays (LCDs), have a narrow and non-uniform viewing angle characteristic.1 Furthermore, the electro-optic (EO) characteristics of conventional TN LCDs are strongly dependent on the viewing angle, a serious inconvenience for good gray-scale operation, which is a prerequisite to developing a full color display. These drawbacks originate from the fact that the optic axis in the midplane of the cell is uniformly tilted in one direction. Because the nematic liquid crystal is highly birefringent, different viewing directions give substantially different degrees of birefringence, resulting in optical transmission behavior depending strongly on the viewing direction. This effect is illustrated in Fig. 1.

To overcome this shortcoming of conventional TN LCDs, two major approaches have been proposed, namely, the use of negative retardation films2,3 and multidomain LCDs.4-12 The latter includes amorphous TN LCDs.13-15 The negative retardation film compensation technique can only improve the gray-scale characteristic in one viewing plane; namely, a plane containing the cell normal that is 45° from the polarizer directions. The gray-scale inversion problem still exists and sometimes becomes even worse in other viewing planes. The controlled multidomain technique was proposed in the late 80s. The main idea is to divide each pixel into subpixels in which the molecular configurations and optical responses are different. In this way, properly designed domains will spatially average in the contrast angular dependence to give a wide angle of viewing and improved gray-scale characteristics.

Many techniques have been developed to achieve multidomain TN(MDTN) structures. In both the Tanuma et al.4 and Otani5 patents, each pixel was divided into two domains where the rubbing directions are opposite to each other. Takano6 as well as Lien and John7 also developed a two-domain (2-D) TN device based on the effect of fringe field produced by the edges of the pixel electrode. Yang8 published a detailed multiple rubbing process to fabricate a 2-D TN cell in which the rubbing directions of one or both substrates of the different domains of a pixel are opposite to each other. Koike et al.9 used a multiple alignment layer method to develop a 2-D TN cell based on different pretilt angles induced by the different alignment layers. In the complementary 2-D TN device developed by Takatori et al.,10,11 the top substrate has a low pretilt angle while the bottom one has a high pretilt angle. This device has alternating reverse tilted stripes. Two-domain TN techniques have been reviewed in Ref. 12. On the other extreme, an amorphous TN LCDs with randomly varying domains has been developed by Kobayashi’s group.13 Although the amorphous multidomain TN LCD has its own merits, i.e., a wide viewing angle and no rubbing, the creation of disclinations at reverse tilt domain boundaries during the cell operation degrades its performance.15

Recent optical simulation of the EO performance of MDTN cells shows that optimum viewing characteristics are obtained in a four-domain (4-D) TN LCD structure.16 The first conceptualization of 4-D TN LCD, the so-called super multidomain(SMD) configuration, was reported by Kobayashi’s16 group and realized by patterning photopolymer alignment layers with linearly polarized UV light.17 However, the complicated process is a barrier to practical application. In our previous paper,18 we proposed a particularly simple 4-D TN LCD, which is composed of two left-handed and two right-handed subpixels. One member of each pair of same-handedness subpixels is rotated 180° with respect to the other, resulting in four domains that spatially average one another optically to provide a wide angle of viewing without the gray-scale inversion. The optical performance of this 4-D TN LCDs was confirmed by studies of a test cell fabricated by a two-step SiO₂ oblique evaporation technique.

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In this article, we report the realization of our 4-D TN device by a reverse rubbing technique that should be suitable for mass production in the display industry. Optical simulations as well as the stability of this structure and the effect of disclinations at subpixel boundaries on display contrast are reported.

II. EXPERIMENT

The structure of our 4-D TN cell is shown in Fig. 2. The arrows and dashed arrows in each subpixel indicates the pretilt directions for the top and bottom plates, respectively. The letters R (right) and L (left) indicate the handedness of TN subpixels. The handedness of a subpixel is totally determined by the pretilt angle as no chiral additive LC was used in this method. This structure can be realized by a reverse rubbing technique whose flow charts are shown in Fig. 3. A cleaned indium tin oxide coated glass substrate was spin coated with Nissan PI7311 polyimide. The plate was then soft baked at 100 °C for 1 min to evaporate solvent and then hard baked at 275 °C for 2 h for curing. After unidirectional buffing was carried out on the PI coated substrate, a photolithography step was used to form a mask of equal width stripes. The photoresist we used is Shipley S1400-31. After the photolithography step, reverse buffing was performed 180° relative to the first buffing direction. Finally, the photoresist used as a mask was removed by acetone. The 4-D TN cell was assembled just as a conventional TN cell is assembled using two identical plates fabricated by the method described above. For electro-optical performance measurement, test cells of thickness 5 μm filled with Merck’s NLC(Zli4792) and 6 μm filled with Merck’s NLC(E7), were prepared. They satisfy the first and second minimum conditions given by the Gooch and Tarry equation, respectively. The pixel size varies from 1200 to 48 μm.

III. RESULTS AND DISCUSSION

We did an optical numerical simulation using “Twist Cell Optics,” a software package developed at the Liquid Crystal Institute of Kent State University. The model is based on an adaptation of Berreman’s 4 × 4 matrix method, which provides an exact solution to Maxwell’s equations in stratified media. The LC director orientation in a TN cell is found from a minimization of Oseen–Frank free energy under the assumption of strong surface anchoring. The optical simulation gives the viewing angle characteristic of an assumed perfect 4-D TN cell. The geometric structure and the relevant parameters used in the simulation are summarized in Table I. The cell thickness is 5 μm, which satisfied the first minimum condition of Gooch and Tarry’s equation if LC material Zli4792 was used. The effect of disclination

<table>
<thead>
<tr>
<th>Elastic constant (pN)</th>
<th>$K_1$</th>
<th>13.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_2$</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>$K_3$</td>
<td>18.3</td>
</tr>
<tr>
<td>Relative dielectric const</td>
<td>$\varepsilon_1$</td>
<td>7.10</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_2$</td>
<td>3.0</td>
</tr>
<tr>
<td>Refractive index at 550 nm</td>
<td>$n_e$</td>
<td>1.573</td>
</tr>
<tr>
<td></td>
<td>$n_0$</td>
<td>1.479</td>
</tr>
<tr>
<td>Pretilt angle</td>
<td>$\theta_p$</td>
<td>5°</td>
</tr>
<tr>
<td>Twist angle</td>
<td>$\phi_{TN}$</td>
<td>90°</td>
</tr>
<tr>
<td>Cell thickness</td>
<td>$d$</td>
<td>5 μm</td>
</tr>
<tr>
<td>Chiral pitch</td>
<td>$P$</td>
<td>N/A</td>
</tr>
<tr>
<td>On-state voltage (V)</td>
<td>$V$</td>
<td>5</td>
</tr>
</tbody>
</table>

FIG. 1. Cross sectional view for LC cell with field on state. The different viewing directions give substantial differences of birefringence.

FIG. 2. Structure of our four-domain TN cell. Dashed and solid arrows indicate the LC molecular tilt directions at the top and bottom plates, respectively. R and L indicate the left and right handedness of TN subpixels, respectively.
lines on EO performance is neglected in this calculation. The optical modeling of our four-domain TN cell can be done as follows: (1) Input, according to the definition in the “Twist cell Optics” software package, one right-handed (RH) and one left-handed (LH) TN subpixel with a positive pretilt angle and one RH and LH TN subpixel with a negative pretilt angle. (2) Calculate the optical characteristic of each subpixel separately. (3) The final optical modeling data for our 4-D TN cell is obtained by averaging the optical characteristics of the four subpixels.

Figure 4 shows the simulation results of viewing angle characteristics of our 4-D TN cell. A symmetric viewing zone is obtained as expected. The polar angle dependence of the transmission in eight gray-scales at three azimuthal angles is illustrated in Fig. 5, which indicates the contrast inversion free region is $\geq 50^\circ$ in all directions. We note that, although the structure of our 4-D TN cell is different from the SMD structure proposed by Kobayashi’s group, the nearly identical molecular configurations at the midplane in both structures make our simulation results quite similar to theirs.16

Either from the optical modeling or experimental measurements, viewing our 4-D TN cell 45° to the polarizer axis shows the lowest contrast. This drawback can be alleviated by using negative birefringent compensation films. Figure 6 shows an optical simulation of a 4-D TN cell with a half of cell negative birefringent retardation film at the front of the cell. Obviously, a more homogeneous viewing angle characteristic is obtained. We also note that this viewing angle feature is much more uniform in comparison to that of the film compensated super multidomain TN display.22 The operating modes in all subpixels of our 4-D TN display can be either e mode or o mode. However, there is always a mixture of two e and o modes in super multidomain TN display. The symmetry difference between two structures results in their different behaviors under the birefringent film compensation.

The reverse rubbing technique should be more suitable for mass production. Two key factors should be considered in selecting proper PI materials. These are the LC pretilt angle and the compatibility with the photolithography process. Many PI materials have been tried. Our best results thus far, were obtained using Nissan PI7311. Figure 7 shows photomicrographs of our test cells with two different pixel sizes (800 and 100 $\mu$m) and 2.0 V voltage was applied. The polarizers are purposely not crossed to show that same-handedness pixels along diagonal directions have the same...
shade of gray. The sharp boundaries indicate the high quality of the LC alignment layer. The twisted states in our 4-D TN cell are fully determined by the pretilt angle. This means we need a high pretilt angle to offset the energy cost of the generation of twist disclinations. Whether our 4-D structure is stable at zero field or not is simply determined by the competition between the free energy costs of forming disclination lines and the wrong-handedness subpixels that cost splay energy. Our experimental results suggest that a 7° pretilt angle is not large enough to hold the structure. Figure 8 shows a photomicrograph of a typical cell fabricated by the reverse rubbing technique. The reverse disclination lines are stable if the cell voltage is larger than 1 V. However, disclination lines disappear when the cell voltage is less than 1 V; thus, the 4-D TN display finally becomes a 2-D TN reverse tilt cell.

We developed a simple and crude model to evaluate how the stability of this 4-D TN display depends on geometry (tilt angle, $t$, and subpixel dimensions $L \times L \times d$) from the known elastic (Frank free energy) and defect (twist disclination) properties of the nematic. In the absence of disclinations, the entire LC film has either a right- or left-handed 90° twist. Thus, half of the subpixels have the “wrong” handedness, which introduces a splay distortion given approximately by $2t/d$; the corresponding splay energy of two subpixels is

$$F_S = K\left(\frac{2t}{d}\right)^2 L^2 d,$$  \hspace{1cm} (1)

where $K$ is a Frank elastic constant. This can be a stable configuration if $F_S < F_d$, where $F_d$ is the twist disclination energy given by

$$F_d = 8E_cL,$$  \hspace{1cm} (2)

where $E_c$ is the disclination core energy per unit length. Although the nature of the core still remains an interesting unsolved problem, since the tension increases on approaching the center of the disclination, below a certain critical radius, people believe it should be large enough to transform the material from nematic to the isotropic phase. We also take this assumption. The core energy is approximately given by

$$E_c \equiv \frac{1}{\alpha}aS^2(\pi\xi^2),$$  \hspace{1cm} (3)

where $\alpha S^2/2$ is the first term of the nematic Landau free energy, $\alpha = \alpha_0(T - T^*)$ and $S$ is the nematic order parameter. $\xi$ is some nematic correlation length (we take $2\xi$ to be the core diameter) and is given by $\xi^2 - K/\alpha S^2$. As the stability condition of the 4-D TN display, we have

$$\frac{F_S}{F_d} = \frac{Kt^2L}{2dE_c} = \frac{t^2L}{d \pi} \geq 1.$$  \hspace{1cm} (4)
None of the 4-D TN cells prepared by reverse buffing as long as the instability voltage is less than the Fréedericksz threshold. We have achieved an instability voltage less than 1 V. As an alternative, a polymer network can be used to stabilize our 4-D TN structure. However, if NLC E7 instead of Zli4792 is used, the LC pretilt angle increases to 6.5° and the instability voltage is reduced to 1 V. In order to verify the geometry factor on the 4-D instability, we made wedge cells whose substracts were fabricated using two-step SiOx evaporated surfaces. The wedge cell gap varied from zero to 50 μm. After LC was injected into the cell, there was a clear boundary that separates the stable and unstable 4-D structure region. It was found that the critical cell thickness is round 12 μm for our 4-D structure having subpixel size 75 μm, while the critical cell gap increased up to 25 μm if the subpixel size changed to 200 μm. In spite of the ratio of the critical cell gap to pixel size not exactly equal in two cases, the tendency matches with the expectation of Eq. (4). Furthermore, from Eq. (4), we can also estimate the critical stable subpixel size is about 1200 μm for 6.5° pretilt alignment surface with a cell gap of 6 μm. A 4-D TN test cell made using PI7311 alignment layer and E7 nematic LC with subpixel size 1200 μm did show 95% of area is stable. The disclination was only broken at the pixel center. The pattern shown in the Fig. 8(b) can be held at the zero voltage for good. Although our model does give us the important information on how to get our stable 4-D TN display and seems to work very well, we admit that our model is very crude. The validity of assumptions can still be arguable. It seems that there is a very well-defined instability threshold voltage for this 4-D TN structure. We are now extending our free energy model to include an external electric field.

We, of course, hope there are available PI materials that can generate a large enough LC pretilt angle to stabilize this 4-D TN structure at zero field. However, although our 4-D TN display is not stable at zero field, if a low pretilt angle PI is used, it can still be used in practical applications. A process we call “initialization” can be used; that is a high voltage (~5 V) is applied to the display as it is turned on. When the 4-D TN structure is completely formed, the display can be driven by bilevel voltages in which the full off-state voltage is not zero and is larger than the instability threshold voltage. This approach can totally freeze boundary wall motion. We have achieved an instability voltage less than 1 V. As long as the instability voltage is less than the Fréedericksz threshold of the TN cell, the contrast of the display will also not be affected. As an alternative, a polymer network can be used to stabilize our 4-D TN structure. Figure 9 shows a microscope picture of our polymer stabilized 4-D TN cell. NLC Zli4792 doped with two percent of monomer (desolite 2002-33) was used. The monomer was polymerized under UV exposure with 10 V applied to the cell. The results sensitively depend on curing voltage and the percentage of monomer used. The switching time at different conditions has not yet been measured. The detailed results of this work will be published elsewhere.

IV. CONCLUSIONS

The 4-D TN display proposed by us is realized by a reverse rubbed polyimide fabrication process. Optical simulations indicate that the viewing angle characteristic of our 4-D TN display is almost identical to that of the SMD display. It is also found that our 4-D TN structure is not stable at zero field if the LC pretilt angle of the alignment layer is too small. However, our 4-D TN display is stable if a voltage is applied to the cell. There is a well-defined stability threshold voltage for this 4-D TN display. A simple model is developed to evaluate the stability of our 4-D TN display, which is based on the energy competition between the disclination lines and the splay energy cost for “wrongly

![Image of transmission curves of 4-D TN cells with different resolutions.](image-url)

**FIG. 10.** Transmission curves of 4-D TN cells with different resolutions. The numbers shown at the right corner of the figure are the size of subpixels L.
twisted’’ subpixels. The predications of the model qualita-
tively match our experimental facts. For display applications,
a bilevel drive scheme combined with an initialization pro-
cess can be used to avoid the instability problem. The poly-
mer network can also be used to stabilize our 4-D structure at
zero field. Reverse disclination lines reduce display contrast.

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