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Normally black reflective twisted-nematic cell for microdisplay application

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A normally black reflective twisted-nematic mode is proposed for microdisplay application. This mode is based on the polarization rotation effect of a twisted-nematic liquid crystal. In the dark state, the cell exhibits a large gap tolerance and weak color dispersion. For twist angle ranging from 45° to 65° , the maximum normalized reflectance can achieve 100% through d/p (cell gap over pitch) ratio optimization. Particularly, when the twist angle equals to 52° , the normalized reflectance can reach 100% without any chiral dopant. The twist angle and polarizer angle also make important contributions to the bright state optical efficiency and dark state spectral bandwidth. © 2004 American Institute of Physics. [DOI: 10.1063/1.1751234]

I. INTRODUCTION

Liquid crystal on silicon (LCoS)^{1,2} is an emerging rear-projection microdisplay developed for high definition televisions (HDTVs). Due to the high electron mobility, the pixel size of the LCoS can be made as small as $5\text{--}10\text{ }\mu\text{m}$. Therefore, for a HDTV resolution (1920×1080 pixels), the panel diagonal size is less than 2.2 cm. For such a microdisplay, liquid crystal functions as a light valve. LCoS has been used extensively in front projection, rear projection, and near-the-eye virtual projection displays.

Several LC modes have been proposed for LCoS microdisplay applications, such as vertical alignment (VA) mode,³ mixed-mode twisted nematic (MTN),⁴ self-compensated twisted nematic mode,⁵ and 45° reflective twisted-nematic (RTN) mode.⁶ The VA mode exhibits an unprecedented contrast ratio, but it suffers from a serious fringing field effect from adjacent pixels.^{7–9} As a result, each bright pixel is split into two unequal parts separated by a dark line. This split pixel decreases the optical efficiency to $\sim 70\%$. The 90° MTN cell is a normally white display using both polarization rotation and birefringence effects, therefore exhibiting a high contrast ratio and weak color dispersion. Moreover, its fringing field effect is the weakest among all of the available LC modes developed for microdisplay applications.⁹ A drawback is that its maximum normalized reflectance is limited to $\sim 88\%$. On the other hand, the 45° RTN cell is a normally black display.⁶ Its cell gap is in the $4\text{--}5\text{ }\mu\text{m}$ range, depending on the LC birefringence employed. Large cell gap helps to enhance manufacturing yield. Moreover, the on-state voltage for the 45° RTN cell is relatively low. Without chiral additive, its normalized reflectance is limited to $\sim 95\%$. The major shortcoming of the 45° cell is that its fringing field effect is quite severe which degrades the device contrast ratio and optical efficiency. A simple method to suppress the fringing field effect is to use a thinner cell gap. If the cell gap is below $3\text{ }\mu\text{m}$, the fringing field effect is reduced substantially.

In this article, we present a normally black 52° RTN mode for microdisplay applications. This mode provides a better overall performance over the 45° RTN mode. Detailed simulation results are presented in Sec. II.

II. LC MODE

In a TN reflective display, the cell gap and birefringence product ($d\Delta n$) is large so that the polarization rotation effect is the major light modulation mechanism.¹⁰ In the voltage-off state, the LC directors are uniformly twisted from the bottom to the top substrate. The incident linearly polarized light basically follows the rotation of the TN LC, provided that $d\Delta n \gg \lambda$ is satisfied. If such a TN LC is used in reflective display, the reflected beam preserves the same polarization as the incident linearly polarized light due to the pure polarization rotation effect. Therefore, in a microdisplay system incorporating a polarizing beam splitter (PBS), the reflected light from the LCoS panel is blocked by the PBS resulting in a dark state. Such a RTN-based microdisplay is usually operated in the normally black mode.

Figure 1 shows the structure of a RTN based microdisplay. It consists of a reflective TN cell and a PBS. If the incident polarization axis of the PBS makes an angle β with respect to the top substrate LC alignment direction, then the normalized reflectance ($R_\perp$) can be expressed as¹¹

$$R_\perp = \left(\Gamma \frac{\sin X}{X} \right)^2 \left(\sin 2\beta \cos X - \frac{\phi}{X} \cos 2\beta \sin X \right)^2, \quad (1)$$

where $\Gamma = 2\pi d\Delta n/\lambda$ and $X = \sqrt{\phi^2 + (\Gamma/2)^2}$. Here d is the cell gap, Δn is the LC birefringence, λ is the incident wavelength, and ϕ is the twist angle of the TN LC. We define the left-handed twist angle as positive while the right-handed twist as negative.

From Eq. (1), if $\sin X = 0$, then $R_\perp = 0$; independent of β angle. Apparently, this will lead to the Gooch–Tarry minimum conditions¹²

$$\sqrt{\phi^2 + (\Gamma/2)^2} = m\pi \quad (m = 1, 2, 3, \dots). \quad (2)$$

Figure 2 plots the $d\Delta n/\lambda$ dependent $R_\perp$ at different twist angles with $\beta = 0^\circ$. As expected, there exists a series of

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FIG. 1. Schematic view of a RTN mode microdisplay.

Gooch–Tarry minima. From the response time viewpoint, a small cell gap is preferred. Thus, the first minimum condition ($m=1$) is commonly chosen for RTN mode. From Fig. 2, the 90° RTN does not lead to a high reflectance bright state when the effective $d\Delta n/\lambda$ is reduced (i.e., voltage is increased). The normalized reflectance $R_\perp$ reaches 100% when the twist angle is around 60° . However, this is under the assumption that LC directors are uniformly twisted throughout the cell. When the applied voltage exceeds a threshold, the LC directors are tilted up so that the assumption of uniform twist does not hold anymore. To determine the optimal twist angle, the voltage-on state needs to be calculated.

A. LC parameters

In order to calculate the electro-optic properties of a RTN mode with applied voltage, we first use the continuum elastic theory¹³ to obtain the LC director distributions and then use the extended Jones matrix method¹⁴ to calculate the optical reflectance. In this article, we use Merck MLC-6694-100 LC mixture for the numerical simulations. The relevant LC parameters are listed as follows: $K_{11}=13.9$ pN, $K_{22}=9.0$ pN, $K_{33}=21.5$ pN, $\epsilon_{||}=10.9$, $\epsilon_{\perp}=3.5$, $n_e=1.5925$, and $n_o=1.4865$ at $\lambda=589$ nm and $T=20^\circ\text{C}$. During simulations, the LC birefringence dispersion¹⁵ for the red-green-blue (RGB) colors has also been taken into consideration.

B. Effect of d/p ratio

For a TN cell, a small amount of chiral dopant is added in order to control the twist sense. By changing the concentration of chiral dopant the pitch length (p) can be adjusted. To study the LC pitch length effect on the bright state reflectance, we scan the d/p ratio for a given twist angle. The cell gap is predetermined by Eq. (2) for the first minimum condition ($m=1$). For every d/p ratio, the voltage dependent normalized reflectance is calculated and the maximum value selected. We then choose the d/p value which corresponds to $R_\perp=1$ for each twist angle.

FIG. 2. Dependence of $R_\perp$ on $d\Delta n/\lambda$ at different twist angles for $\beta=0^\circ$. FIG. 3. The d/p ratio required to achieving $R_\perp=1$ at different twist angles for $\beta=0^\circ$ and $\lambda=550$ nm.

tance, we scan the d/p ratio for a given twist angle. The cell gap is predetermined by Eq. (2) for the first minimum condition ($m=1$). For every d/p ratio, the voltage dependent normalized reflectance is calculated and the maximum value selected. We then choose the d/p value which corresponds to $R_\perp=1$ for each twist angle.

Figure 3 depicts the d/p ratio required for achieving $R_\perp=1$ for the RTN cells at $\beta=0^\circ$. As the twist angle increases from $\phi=40^\circ$ to 65° , the required d/p ratio also increases gradually from negative to positive. A negative d/p ratio means the sense of chiral dopant is opposite to the twist sense of the RTN cell. When $\phi=52^\circ$, $d/p=0$, which means no chiral dopant is necessary to obtain $R_\perp=1$. This result is consistent with that reported by Yu¹⁶ and Beynon,¹⁷ except that we used crossed polarizers (PBS) instead of parallel polarizers used therein. For $\phi>52^\circ$, a left-handed chiral dopant is necessary to boost $R_\perp$ to 100%, while a right-handedness chiral dopant is needed for $\phi<52^\circ$. In our simulations, we assume the LC layer has a left-handed twist angle.

Figure 4 shows the effect of different d/p ratios on the maximum $R_\perp$. Apparently, when $d/p=0$ or $d/p=\phi/2\pi$ there exists only one twist angle whose maximum $R_\perp$ is 100%. Nevertheless, if the d/p ratio is optimized as shown in Fig. 3, $R_\perp=1$ can always be achieved for any twist angle between 40° and 65° . Of course, an overdosed chiral dopant is unfavorable because it will increase the LC response time.

FIG. 4. Effect of d/p ratio on the maximum $R_\perp$ for $\beta=0^\circ$ and $\lambda=550$ nm.

FIG. 5. Dependence of $R_{\perp}$ on $d\Delta n/\lambda$ for different β at $\phi=52^{\circ}$.

On the other hand, a negative chiral dopant (i.e., opposite to the LC twist sense) will cause instability to the LC twist structure.

C. β angle effect

To achieve high contrast ratio, a good dark state is critically important. Since the RTN mode is normally black, its dark state is affected by the twist angle (ϕ), the $d\Delta n$ value of the LC layer, the β angle, and the spectral bandwidth. Figure 5 depicts the β angle effect on the dark state reflectance of the $\phi=52^{\circ}$ RTN cell. As long as $\beta \neq 0^{\circ}$, the curves exhibit a “W” shape, which contributes to widen the $d\Delta n/\lambda$ tolerance. On the other hand, the twist angle ϕ also affects the dark state $d\Delta n/\lambda$ tolerance when $\beta \neq 0^{\circ}$, as shown in Figs. 6(a) and 6(b). A larger twist angle has a lower light leakage on the central peak of the W curves, which means a larger twist angle has a larger β angle tolerance.

D. Spectral sensitivity

For projection display, each primary spectral band has about 50–60 nm bandwidth. To evaluate the spectral sensitivity of the 52° RTN cell, we plot the voltage-dependent reflectance at red (620–680 nm), green (530–570 nm), and blue (420–480 nm) bands. Results are shown in Fig. 7. In each band, we calculated the reflectance in every 10 nm step and then took the spectrum average. For these calculations, β angle is set at 0° , cell gap $d=4.9 \mu\text{m}$, and $d/p=0$. The dark states of these three colors do not overlap due to the different $d\Delta n/\lambda$ requirement. For instance, a red band needs a larger $d\Delta n$ value in order to obtain a good dark state. Therefore, the three-panel configuration projection system needs to be used in order to achieve high contrast ratio. To obtain a different $d\Delta n$ value for compensating the RGB wavelength difference, Merck has developed the so-called two-bottle LC mixtures. These two LC bottles have nearly the same physical properties (e.g., phase transition temperatures, dielectric constants, and elastic constants) except for different Δn . By properly mixing the two bottles, three mixtures with different Δn values for the RGB channels can be obtained fairly easily.

FIG. 6. Dependence of $R_{\perp}$ on $d\Delta n/\lambda$ for different ϕ at: (a) $\beta=3^{\circ}$ and (b) $\beta=-3^{\circ}$.

E. Cell gap tolerance

Cell gap tolerance is particularly important for the normally black display. Figure 8 shows the cell gap tolerance of the 52° RTN mode for the green band. Within $\pm 5\%$ cell gap error, a good dark state is preserved and the contrast ratio maintains larger than 1400:1 ($V_{\text{on}}=2.7 V_{\text{rms}}$ and $V_{\text{off}}=1.2 V_{\text{rms}}$). Large cell gap tolerance also implies to small

FIG. 7. Voltage dependent reflectance of the 52° RTN cell at $\beta=0^{\circ}$: $R=620\text{--}680\text{ nm}$, $G=530\text{--}570\text{ nm}$, and $B=420\text{--}480\text{ nm}$.

FIG. 8. Cell gap tolerance on the voltage-dependent reflectance of the 52° RTN cell at $\beta=0^\circ$. The simulated contrast ratio for $G=530\text{--}570\text{ nm}$ is 28 000:1 for the optimized cell gap, drops to 5300:1 for +5% cell gap error, and 1400:1 for -5% cell gap error, respectively. Here, $V_{\text{on}}=2.7 V_{\text{rms}}$ and $V_{\text{off}}=1.2 V_{\text{rms}}$ are assumed.

color dispersion. From Figs. 7 and 8, the on-state voltage is less than $3 V_{\text{rms}}$, which is lower than that of VA and MTN modes. For the purpose of comparison, Fig. 9 plots the voltage-dependent reflectance curves of the 52° RTN cell and the widely used 45° RTN cell with and without chiral dopant. Obviously, the on-state reflectance of the 45° RTN without chiral dopant does not reach 100%. With a suitable dopant ($d/p=-0.27$), the reflectance can be boosted to 100%. In the mean time, the on-state voltage is slightly decreased due to the pitch length effect. Although the doped chiral agent improves the optical efficiency of the 45° RTN cell from $\sim 95\%$ to 100%, it narrows the device viewing cone slightly. Viewing angle of the LCoS based microdisplay is an important issue for LCoS based microdisplay. If the LC panel has a wider viewing cone, then a smaller F -number projection lens can be used. As a result, the display brightness is greatly improved.¹⁸ Thus, the tradeoff for improving 5% optical efficiency by adding chiral dopant which, in turn, leads to a narrower viewing cone is not worth taking.

FIG. 9. Voltage dependent reflectance of the 45° and 52° RTN cells at $\beta=0^\circ$. Incident light is green band $\lambda=530\text{--}570\text{ nm}$.

FIG. 10. Iso-contrast contour of the 52° RTN cell with $V_{\text{on}}=2.7 V_{\text{rms}}$, $V_{\text{off}}=1.2 V_{\text{rms}}$, and $\lambda=530\text{--}570\text{ nm}$.

F. View angle

A wide viewing cone allows a smaller F -number projection lens to be used for enhancing display brightness. Figure 10 shows the simulated iso-contrast contours of the 52° RTN cell. During simulations, the on-state voltage is assumed at $2.7 V_{\text{rms}}$, dark state voltage at $1.2 V_{\text{rms}}$, and the incident green light has a bandwidth covering $\lambda=530\text{--}570\text{ nm}$. From Fig. 10, the 1000:1 contrast ratio is achieved within the central 10° viewing cone. A typical F -number for the projection lens is about 2.5–3.0.

III. CONCLUSION

A normally black 52° RTN mode exhibits a high contrast ratio, high light efficiency, low driving voltage, and large cell gap tolerance. By properly optimizing the d/p ratio, the normalized reflectance can reach 100% for any twist angle from 40° to 65°. A higher twist angle has better polarizer angle tolerance and a lower twist angle has lower color dispersion at the dark state. The 52° RTN mode will find potential application in LCoS based microdisplay.

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