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Nanowire grid polarizer for energy efficient and wide-view liquid crystal displays

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We report a liquid crystal display (LCD) using a nanowire grid polarizer (NWGP) to replace the bottom sheet linear polarizer (LP). The top LP and bottom NWGP configurations enable backlight recycling for enhancing optical efficiency while keeping a high contrast ratio and wide viewing angle. The electro-optic performance of this device configuration is studied based on the effective-medium theory and 4×4 matrix method. Results show that this configuration exhibits a 100:1 contrast ratio over 75° viewing cone in a film-compensated multidomain vertical alignment LCD and 10:1 over 65° viewing cone in a fringe-field switching LCD without any compensation film. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2988267]

Liquid crystal displays (LCDs) have been widely used in high definition televisions, computer monitors, and mobile devices. In a conventional LCD, the LC cell is sandwiched between two crossed absorption-type sheet linear polarizers (LPs) in order to obtain high contrast ratio (CR>2000:1). A LP is usually made of a stretched polyvinyl alcohol film with two protective triacetyl-cellulose films, whose total thickness is ~200 μm. Such a LP has strong absorption over the entire visible wavelengths along the stretched direction. When two such LPs are used together, the maximum transmittance is only ~40% for an unpolarized backlight, which means more than 60% of the backlight is absorbed. How to enhance LCD's optical efficiency for reducing its power consumption is an urgent issue.

To avoid the absorption loss from the bottom sheet polarizer, a reflective polarizer, e.g., 3M's dual brightness enhancement film[1,2] and subwavelength gratings such as nanowire grid polarizers (NWGPs)[3–7] have been considered. A reflective polarizer transmits one polarization (say, *p*-wave) of the incident light while reflecting the *s*-wave back for recycling. The recycling efficiency of 50%–70% has been achieved.[2] In the past, the transmission CR of a reflective polarizer is inadequate for display applications and thus a bottom sheet LP (sitting between LC layer and reflective polarizer) is still required in order to keep a high CR. This configuration has two shortcomings: (1) the bottom LP still absorbs light and reduces the optical efficiency, and (2) the display thickness is increased. As the nanoimprinting technology advances,[4–6] the transmission CR of NWGP-based reflective polarizers has been improved substantially. Therefore, replacing the conventional bottom sheet LP with a NWGP for backlight recycling and thickness reduction becomes feasible. These features are very important for achieving a brighter, thinner, and lighter LCD, especially for mobile displays. Meanwhile, the removal of a sheet LP helps to reduce the display cost.

In this letter, we report a high optical efficiency, high CR, and wide-view LCD using a top absorptive LP and a bottom reflective NWGP. Two commonly employed wide-view LC modes, multidomain vertical alignment[8] (MVA) and fringe-field switching (FFS),[9,10] are investigated based on the effective-medium theory[11,12] and 4×4 matrix method.[13,14] Results show that the LP-NWGP combination not only enables backlight recycling but also preserves the wide-view characteristics as the conventional LCD using two crossed sheet LPs.

Figure 1 shows the device configuration of the proposed LCD. The LC cell is sandwiched between a top sheet LP and a bottom NWGP with their optic axes crossed. A detailed structure of NWGP is shown in Fig. 2, where thin metal wires with a width *w* are periodically formed on a glass substrate with a pitch *p*. When the pitch *p* is far smaller than the incident wavelength λ, which is known as the quasistatic limit ($p/\lambda\to0$), WGP functions as a reflective polarizer.[7,11,12] As shown in Fig. 2, for an unpolarized incident light, those components with electric fields parallel to the metal wires (*s*-polarization) will stimulate the free movement of electrons along the wires, which then emit a reflected wave. For the light with electric fields perpendicular to the wires (*p*-polarization), the electron movement is confined by the gap, thus only a small amount of energy is lost and the light transmits through the metal wires.

The fabrication of a NWGP typically involves imprint, demolding, and pattern transfer using reactive ion etching technology.[5,6] More specifically, first, a thin layer of alumi-

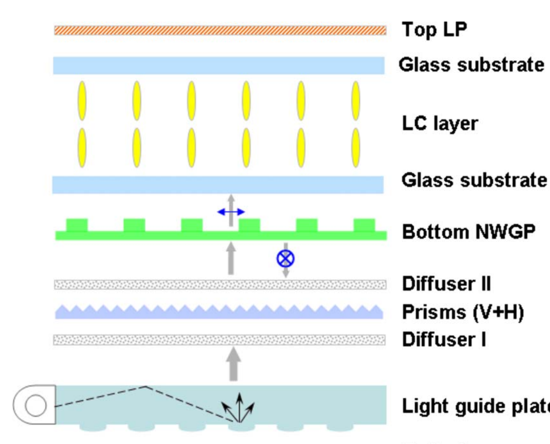

FIG. 1. (Color online) Device structure of the LCD using a top sheet LP and a bottom NWGP for light recycling.

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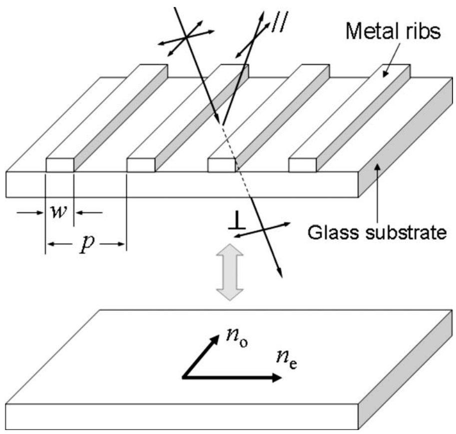

FIG. 2. Device structure of a NWGP and its equivalent optical model.

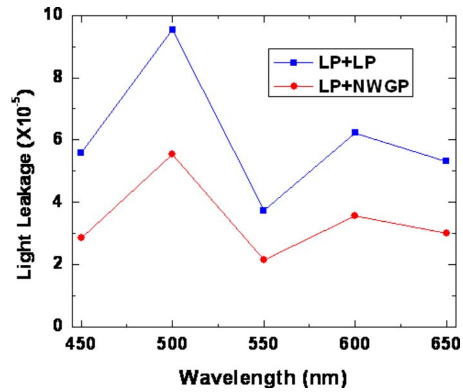

FIG. 3. (Color online) Wavelength dependent light leakages from two crossed sheet LPs, and from a top LP plus a bottom NWGP at normal incidence.

num is coated on a glass substrate, followed by coating of a thin SiO_2 layer on its surface to function as a hard mask for aluminum etching later on. Then an imprint resist layer is spin coated on the SiO_2 surface and a nanoimprint silica stamp with a predesigned wire grid pattern is used to replicate the pattern onto the imprint resist. After demolding the stamp, a series of reactive ion etchings are applied to remove the residual layers (such as the patterned imprint resist and the SiO_2 layers) on the aluminum surface and finally the aluminum layers in the replicated pattern. Thus the wire grid pattern from the stamp is transferred to the aluminum layer.

In Fig. 1, the light from the source such as a cold cathode fluorescent lamp or light emitting diodes is coupled out toward the viewer by the light guide plate (LGP). The light after passing diffuser II is basically unpolarized and only the *p*-wave can penetrate the NWGP. The *s*-wave is reflected back to the LGP, becomes sufficiently depolarized after passing through the diffusers, and then bounces back to the NWGP again. This light recycling process repeats internally for several times before the light is absorbed or scattered away.

To validate the device concept, we calculated the electro-optic performance of the LCD configuration using finite-element method[15] for the LC director distribution and the 4×4 matrix method for the optical characterization thereafter. The 4×4 matrix method solves the exact solution of Maxwell's equations for light propagation in birefringent media such as a LC cell. To include the NWGP into the optics modeling based on 4×4 matrix method, we take the effective-medium theory to model the NWGP. Under the effective-medium theory,[11,12] the NWGP shown in Fig. 2 could be equivalently modeled as a uniaxial birefringent layer with its ordinary and extraordinary refractive indices n_o and n_e as

$$n_o^2 = n_1^2\frac{w}{p} + n_2^2\left(1-\frac{w}{p}\right), \tag{1}$$

$$\frac{1}{n_e^2} = \frac{1}{n_1^2}\frac{w}{p} + \frac{1}{n_2^2}\left(1-\frac{w}{p}\right). \tag{2}$$

Here n_1 and n_2 are the refractive indices of the metal and the material filled in the gap. Effective-medium theory provides sufficient accuracy and a good prediction of the performance of NWGP when $p \ll \lambda$. To obtain a better accuracy, more rigorous simulation methods such as rigorous coupled-wave theory[7,12] should be used. Nevertheless, NWGPs with a fine pitch length of ~100 nm were demonstrated by several groups.[4–6] As the nanolithography technology progresses, we believe a finer pitch resolution could be obtained to further satisfy the quasistatic limit ($p/\lambda \to 0$), making the effective-medium theory a better fit to the realistic situation.

For the NWGP discussed here, the fill-in factor w/p is set at 0.5. The metal for wire grids is aluminum with refractive index $n_1=0.895+i6.67$ at $\lambda=550$ nm,[16] and the gap is filled with air with refractive index $n_2=1$. Accordingly, the effective ordinary and extraordinary refractive indices of NWGP are $n_o=0.6400+i4.6641$ and $n_e=1.4295+i0.0043$, and n_o is along the wire grid direction. The thickness of the NWGP is taken as 200 nm which is within present lithography capability. Based on these values, NWGP functions as a metallic reflector for the incident light polarized along the n_o axis, and as a dielectric media for the light polarized along the n_e axis. Because the thickness of the NWGP is only 200 nm, light transmitting along the n_e axis will only experience a small amount of absorption. More importantly, for an unpolarized light, the transmitted light leakage polarized along the n_o axis is tiny based on the above values, thus a high transmission CR can be obtained.

Figure 3 plots the wavelength dependent light leakage at normal incidence from the crossed top sheet LP and bottom NWGP. For a reference, the light leakages from merely two crossed sheet LP are also depicted. The sheet LP has a thickness of 210 μm with $n_o=1.50+i3.26\times 10^{-5}$ and $n_e=1.50+i2.0753\times 10^{-3}$ at $\lambda=550$ nm. Material dispersions for other wavelengths are also considered in Fig. 3. For a single LP employed here, the transmission for the wave polarized along the n_o axis is ~78.8% and is $\sim 4.366\times 10^{-5}$ for the wave polarized along the n_e axis. For two crossed LP, the light leakage for an unpolarized light is estimated to be $\sim 3.733\times 10^{-5}$ (roughly equal to $2\times 1/2\times 4.366\times 10^{-5}\times 78.8\%$). For the NWGP here, the transmission for the *p*-wave (polarized along the n_e axis) is about 90% and the leakage for the *s*-wave (polarized along the n_o axis) is several orders below 10^{-5}. Thus for an unpolarized light passing through the bottom NWGP and the top sheet LP, the *p*-wave has a larger leakage out of the top LP (roughly $\sim 1/2\times 4.366\times 10^{-5}\times 90\%$) than that from two crossed LP ($\sim 1/2\times 4.366\times 10^{-5}\times 78.8\%$). However the output from *s*-wave is much more suppressed. Overall, the combination of a NWGP and a sheet LP produces a lower light leakage

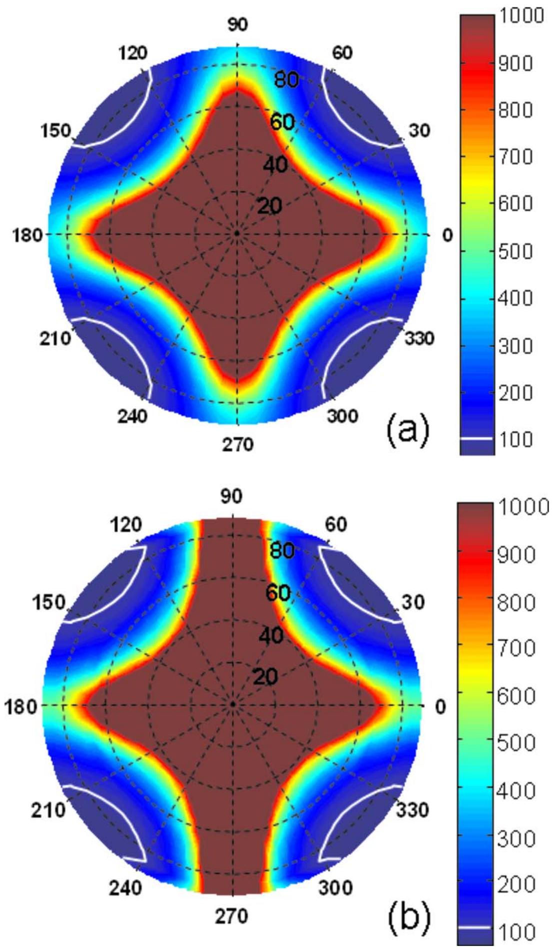

FIG. 4. (Color online) Isocontrast plots for a film-compensated MVA LCD under (a) two crossed sheet LPs and (b) a top sheet LP and a crossed bottom NWGP.

(2.14×10^{-5}, which is roughly equal to $1/2\times4.366\times10^{-5}\times90\%$) for an unpolarized incident light. Similar results are also obtained for other wavelengths, indicating that a high CR is attainable using this configuration.

We further investigate the viewing angle performance of this LP-NWPG configuration applied to the present mainstream wide-view LCD technologies: MVA and FFS LCDs. Similarly, we also plot the viewing angle of the same LCDs under merely two sheet LPs as a reference. For the MVA LCD, a negative dielectric anisotropy ($-\Delta\varepsilon$) LC mixture MLC-6608 is employed with its physical properties listed as follows: extraordinary and ordinary refractive indices $n_e=1.5625$, $n_o=1.4786$ (at $\lambda=550$ nm),[17] parallel and perpendicular dielectric constants $\varepsilon_{\parallel}=3.6$, $\varepsilon_{\perp}=7.8$, and elastic constants $K_{11}=16.7$ pN and $K_{33}=18.1$ pN. The cell gap is 4 μm and LC directors are initially aligned perpendicular to the substrates. Usually to suppress the off-axis light leakage from MVA cells, compensation films are required. Here we employ two positive *A*-films and negative *C*-films proposed by Hong *et al.* for the MVA LCD.[18] For such a compensation scheme, the retardation value of each film can be analytically solved as described by Zhu *et al.* in Ref. 19. Based on the calculation, each negative *C*-film with its refractive indices $n_e=1.4929$ and $n_o=1.5028$ at $\lambda=550$ nm is designed with a film thickness $d\sim8.29$ μm, and the thicknesses of each positive *A* film with $n_e=1.5110$ and $n_o=1.5095$ at $\lambda=550$ nm is designed at 61.38 μm.

Figure 4(a) shows the isocontrast plot of the MVA cell using a white light source. The viewing cone of the 100:1 CR (the white lines) extends to over 75°. However for the LP-NWGP configuration, we find the optimized parameters for the compensation films need to be slightly adjusted. The optimum thickness is 8.5 μm for the negative *C*-film and 69.5 μm for the positive *A*-film at $\lambda=550$ nm. Similarly as shown in Fig. 4(b), the 100:1 CR can also be obtained over 75°. Here as discussed before, stronger light leakage suppression along the n_o axis of the NWGP yields a wider viewing cone along the 90° azimuthal direction in the polar plot.

We also extend this LP-NWGP configuration to FFS LCD, which is another commonly used wide-view technology. In a FFS cell, all the electrodes are formed on the same bottom substrate and LCs are mainly reoriented in the horizontal plane by the fringe fields. A major advantage of FFS mode is its inherently wide viewing angle without any compensation film. For the isocontrast plots, we used the following parameters: LC material MLC-6608, cell gap $d=4$ μm, surface pretilt angle is 2°, and rubbing angle is 80° with respect to the stripe electrodes of the FFS cell.[9] Results (not shown here) for both polarizer configurations are very similar: for a white light source, the CR$>$10:1 is over 65° viewing cone without any compensation films.

In conclusion, the proposed LP-NWGP configuration not only provides a wide viewing angle comparable to the existing mainstream LCD technologies but also enables additional advantages such as high optical efficiency through backlight recycling and thin profile. Its potential applications for energy efficient and wide-view LCDs are foreseeable.

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