High-Efficiency, Liquid-Crystal-Based, Controllable Diffraction Grating

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We propose a new reflective liquid-crystal diffraction grating design attained by combining the use of a polymer wall to reduce the detrimental effect of the fringing electric field in a high-resolution grating and a quarter-wave plate to make the device polarization independent. This design could offer significant performance advantages in a projection display system. Results of calculations are compared with experimental data. © 2005 Optical Society of America

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1. INTRODUCTION

A simple liquid-crystal (LC) phase modulator is polarization dependent, making 50% of the incident light not diffracted. Improved LC configurations, such as a 180°-twist cell and a cell structure enhanced by incorporating a quarter-wave plate with a reflective LC element, have been proposed to make the LC phase modulator polarization independent. Although a polarization-independent design is realized, the actual operation of a LC diffraction grating is complicated by the effects of the fringing electric fields in high-resolution devices. To address this problem, the use of polymer walls has been investigated. In this paper, we propose a new reflective LC phase modulator design that combines the advantages of polymer walls to reduce the fringe field with a QWP to make the device polarization independent. A detailed analysis of the diffraction efficiency is provided.

The new design has a promising application in a projection display system, since the resolution and brightness of current LC-on-silicon (LCoS) projectors are limited by the fringe field and diffraction effects, while this new design utilizes the diffraction effect and is immune to the fringing field problem. In this paper, first the device design idea is introduced; then the design method is illustrated through an example. The wavelength dependency of the design is also discussed. Furthermore, we show data acquired from a test device that verifies the design concept. Finally, we consider the application of this device to a projection display.

2. DEVICE DESIGN CONSIDERATIONS

In our design, an untwisted nematic LC configuration is applied, with a planar, homeotropic, or hybrid alignment. Regions of LC material are separated by polymer walls that have optical properties similar to those of the LC material when no voltage is applied.

To construct the cell, two plates are coated with a transparent conductor and an alignment layer that aligns the LC surface layer at a defined angle with respect to the surface (which may be different on the two surfaces). The plates are then assembled with spacers between them to define the cell gap (see Fig. 1). A mixture of reactive LC monomers and normal LC materials is then introduced into the cell. The polymer wall is formed using a photo mask and UV light. In regions where the UV light is exposed, the reactive LC monomers will polymerize to form the desired walls. The monomer materials will phase-separate from the normal LC material and diffuse to the wall region, so after a sufficient exposure time the regions exposed by the UV light are primarily a polymer material, and the regions not exposed are primarily LCs. The grating is designed to include a reflector and a QWP with its optic axis aligned in the plane of the cell and at 45° to the LC alignment direction. A side view of the grating is shown in Fig. 1. In our design example, we will consider that the LC directors are aligned parallel to the cell surface and the long axis of the polymer walls.

Considering the operation of the grating, we can think of unpolarized light as the combination of s and p-polarized light. When the LC region is off (no voltage applied to the electrodes) as shown in Fig. 1, the input p light sees the $n_e$ (extraordinary refractive index) of the polymer wall and the LC region, while the s light sees the $n_o$ (ordinary refractive index) of the polymer wall and the LC region. If the polymer wall and LC materials have similar values of $n_e$ and $n_o$, then both input p light and s light are nondiffracted. When the LC region is on (voltage applied to the electrodes), as shown in Fig. 2, the incident p-polarized light experiences no phase difference because it sees the $n_e$ of both the polymer wall and the LC region; the s light, however, experiences a phase difference because it sees the $n_e$ of the polymer wall but the $n_o$ of the LC region. Because of the QWP, the input p light, after
reflecting from the mirror and passing twice through the QWP, is converted to s light, and the input p light is converted to p light. Therefore, after reflection, this phase modulator structure is polarization independent since the input p polarized light has experienced the same phase difference as the input s light.

Because of the presence of the polymer walls, the phase profile at the diffraction state is close to a rectangular waveform. For the ideal rectangular phase profile, the condition of having the maximum diffraction efficiency is to have a phase difference of \( m\pi \) between equally spaced polymer walls and the LC regions, where \( m \) is an odd number. Since a fast switching speed is also desired, the phase difference is set as \( \pi \), where \( m = 1 \), in order to have a thin cell gap. However, in the real system, the phase profile is not ideally rectangular because of the surface effect of the polymer walls. In this case, there are two means of optimization. One is to vary the width ratio of the polymer walls and the LC pixels, and another way is to make the phase profile as rectangular as possible. Next, we will demonstrate the design and optimization procedure through a two-dimensional example.

### 3. DESIGN EXAMPLE

To minimize the diffraction in the zero field state, we choose the normal LC to have the same \( n_e \) and \( n_o \) as the LC monomer. Given the available maximum voltage and the design wavelength, the cell gap is determined by the design goal of producing a half-wave phase shift between polymer walls and LC regions. To start the design, a one-dimensional director calculation program is used to obtain the director profile. The phase retardation is a function of cell gap and index profile, the latter of which is based on the director profile. Given the director profile, the cell gap is then determined.

For example, we can choose the LC monomer RM826 (\( n_e = 1.656, n_o = 1.532 \)) and a LC material with the same refractive indices as the LC monomer. The maximum available voltage is assumed as 5 V, and the central wavelength is 550 nm. The LC parameters used in this calculation then are \( K_1 = 13.3 \text{ pN}, K_2 = 5.5 \text{ pN}, K_3 = 18.6 \text{ pN}, \Delta \varepsilon = 6, n_e = 1.656, n_o = 1.532 \). Following the procedures described above, the cell gap is designed as 2.87 \( \mu \text{m} \).

After the cell gap is determined, we then define the grating pitch, which is the combination of one polymer wall and one LC region. We would like the grating pitch as small as possible in order to provide a large diffraction angle, and for the case of the projection display, this will allow for a smaller pixel size. A polymer wall about 3 \( \mu \text{m} \) in width has been reported, and we will use that value in this example. First, the width of the LC region is assumed the same as the polymer wall. A modified version of a previously described algorithm (LC3D) is used to calculate the two-dimensional director profile at 5 V, which is shown in Fig. 3. The directors at the boundaries, including the two substrate surfaces and the polymer wall interfaces, are assumed to have strong anchoring strength.
Based on the above two-dimensional director profile, the phase profile of one diffraction unit of the reflective grating with a QWP is obtained by extended Jones calculation and shown in Fig. 4. In the following discussion, 10 grating cycles are assumed, and the aperture of the light source is assumed to be same as the width of 10 grating cycles. The far-field diffraction pattern is obtained by Fourier transform of the near-field distribution, which is obtained from the extended Jones calculation. Figure 5 shows the nondiffracting state of the grating when all 10 grating cycles are off (no voltage applied). When all 10 grating cycles are turned on (voltage applied), the far-field diffraction pattern is shown in Fig. 6. The normalization factor is the total far-field diffraction intensity of the nondiffracting state as shown in Fig. 5.

From Fig. 6, we can see that the polymer wall has an obvious effect on the director profile. As a result, the width of the region where the director is aligned by the electric field is less than the width of the LC region. This leads to decreased diffraction efficiency as evidenced by the nonzero intensity of the zeroth-order peak in Fig. 6. One way to improve the diffraction efficiency is to vary the width ratio of the polymer wall and the LC region. For example, the zeroth order is minimized, thus the diffraction efficiency is improved by increasing the LC region width to 4 μm while maintaining the polymer wall width at 3 μm. The phase profile of this case is shown in Fig. 7.

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and the far-field diffraction profile is shown in Fig. 8. Another way to improve diffraction efficiency is to keep the width of the LC region the same as the polymer wall, but to make the phase shape of the LC region more rectangular. This can be achieved by increasing the dielectric anisotropy of the LC. If the dielectric anisotropy $\Delta \varepsilon$ is increased from the previous value of 6 to 10, the zeroth-order diffraction intensity is greatly reduced as indicated by the phase profile in Fig. 9 and the far-field diffraction pattern in Fig. 10.

4. CHROMATIC ANALYSIS

Because of the wavelength dependence of the diffraction effect, we studied the effect of a finite bandwidth on the grating operation. Equal LC region and polymer wall width with high dielectric anisotropy of LC are assumed for this analysis. A bandwidth of 100 nm with central wavelength of 550 nm is considered.

A. Achromatic Quarter-Wave Plate Case

First, we assume the QWP is of an achromatic design. In this case, the input $p$ light will still be completely converted to $s$ output light, and the $s$, to $p$. However, the phase difference between the polymer wall and the LC region will deviate from the desired value of $\pi$ at other wavelengths than the designed central wavelength of 550 nm. The further from the central wavelength, the higher the deviation will be. The brightness is calculated as the integration outside the $-2^\circ$ to $2^\circ$ regions of the far-field diffraction. This is 0.9534 at 550, 0.9522 at 500, and 0.9339 at 600 nm. This means the 50 nm deviation from the design wavelength decreases the brightness only slightly.

B. Chromatic Quarter-Wave Plate Case

Here we assume the QWP is not achromatic but designed for the central wavelength of 550 nm, so we will have incomplete polarization conversion from the QWP for other wavelengths. In this case, the brightness is 0.9229 at 500 and 0.9249 at 600 nm. Compared with the achromatic QWP case, the brightness decreases slightly more. However, the brightness is still high, which means the design has a small wavelength dependence even with the chromatic QWP.

5. EXPERIMENT

The procedure for forming the polymer-wall-confined LC grating is shown in Fig. 11. Before UV exposure, LC ZLI 5049-100 (90% wt., $\Delta \varepsilon=6.9, n_e=1.7092, n_o=1.5065$), reactive LC monomer RM82 (9% wt.), and photoinitiator IRGACURE 651 (0.5% wt.) are homogeneously mixed and filled into an antiparallel-rubbed ($z$ direction) cell. Therefore, the LC and monomer directors are aligned along the rubbing direction. After exposure to a collimated UV light source with power of 1.2–1.3 mW/cm$^2$ for about 10 min through the photomask with a pitch of 100 $\mu$m, the periodic polymer walls of width 50 $\mu$m are formed by photo-polymerization. Microscopic images of the polymer walls with and without voltages are shown in Figs. 12(a) and 12(b). Since the directors of the normal LC monomers are locked in the polymer walls, they will not respond to the electrical field.

The experimental measurements of diffraction efficiency were performed at two orthogonal input polarization states in order to verify that the device is polarization independent. The measurement setup is shown in Fig. 13, and the result is shown in Fig. 14. The zeroth-order intensity in the OFF state is first measured, and then the grating is switched on and the voltage is adjusted until the minimum zeroth-order intensity is observed. At this voltage, the diffraction intensities at different orders are measured. The normalization is done based on the zeroth-order intensity of the nondiffractive state. An analyzer is used in the output path to eliminate the effect of surface reflections. The detector is located about 240 cm from the cell, and the distance between the two observed consecutive maximum spots is about 1.5 cm. From the experimental results shown in Fig. 14, we can clearly see that the zeroth order is minimized, and the diffraction is polarization independent. The diffraction efficiency is about 97%.

6. APPLICATION OF THE GRATING TO A PROJECTION DISPLAY

Diffractive devices for large-screen projection displays have been of interest for many years. The Swiss “Eidophor”$^{14}$ and General Electric “Talaria,”$^{15,16}$ which use an electrically deformable oil film as a phase modulator for image generation, have been successfully commercialized. As a phase modulator alternative to the oil film,
LC materials with an untwisted nematic layer have been investigated. In these types of devices, a LC material is contained in a cell that has picture elements (pixels) that consist of striped electrodes on one surface. By applying a voltage to the striped electrodes of a pixel, the degree of diffracted light passing through the pixel can be modulated. Advantages of the LC modulator include low voltage, inexpensive driving circuits, and compact size without the need of a vacuum chamber as is required for the deformable oil system.

A schlieren optical system, to convert the phase modulation to light intensity modulation, has been applied to

Fig. 12. Cell under polarized microscope: (a) OFF state, (b) ON state.

Fig. 13. Measurement setup: 1, red laser (632.8 nm); 2, polarizer; 3, grating; 4, QWP; 5, mirror; 6, analyzer; 7, detector.

Fig. 14. Measured result.
projects based on the diffraction effect since Eidophor. There are two types of configurations. One is dark-field, the other, bright-field projection. The setup of a dark-field projection system with a reflective light valve is shown in Fig. 15, where the nondiffracted light is blocked by the stop at the focal point of the schlieren lens, while the diffracted light passes it. In this configuration, the screen is dark if the reflective light valve is in the nondiffractive state. Bright-field projection works in the opposite way in that the diffracted light is blocked while nondiffracted light passes through.

The light transmission is calculated as the integration of the far-field diffraction pattern outside the area blocked by the stop. The angular extent of the stop is defined by the angular extent of the nondiffracted beam of light. In our example the angular extent of the nondiffracted beam is controlled by the single-slit diffraction pattern of the overall aperture (the width of 10 grating cycles), and is shown in Fig. 5. If we choose the stop size to cover a 2° diffraction angle, we will satisfy this condition and allow for a high-contrast display. For this stop size, when all ten grating cycles of our example device are activated, the brightness is calculated as 0.9445 from the far-field diffraction pattern shown in Fig. 8, and 0.9764 from Fig. 10. It should be noted that this is a very high efficiency for a LC-based display device.

We can consider the chromatic effects of this type of device using the results of the previous sections. It is seen that over the width of a color channel—typically 100 nm of the visible spectrum—the chromatic effects are negligible.

7. CONCLUSION

We propose a new design of a polarization-independent, reflective, LC diffraction grating with polymer walls. The design and optimization method is illustrated through an example. The wavelength dependency in a real projection system is discussed. This new design can have promising applications, such as the light modulator for a projection display device.

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