Polarization-independent modulation for projection displays using small-period LC polarization gratings

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Abstract — Progress in the use of liquid-crystal polarization grating (LCPG) to modulate unpolarized (and polarized) light with a grating period as small as 6.3 μm is reported. Similar to LCPGs formed at larger periods (11 μm) reported previously, polarization-independent switching, predominantly three diffraction orders, maximum contrast ratios of ~100:1 for unpolarized broadband light, very low scattering, and diffraction efficiencies ≥98% continue to be observed. The smaller period led to an expected lower threshold voltage, even though the thickness was greater. Because the smaller grating period enables a brighter result from a Schlieren projection scheme for a microdisplay using the LCPG light valve, the inherent tradeoffs involved with both material and design parameters are discussed, and prospects for a polarization-independent projection display are commented upon.

Keywords — *Liquid crystal, diffraction, polarization grating, projection display, polarization independent.*

1 Introduction

The development of a practical liquid-crystal display (LCD) element capable of modulating unpolarized light with high contrast, and to ultimately integrate it into a highly efficient portable projection display based on a light-emitting-diode (LED) light engine, is the goal of this work. Liquid-crystal polarization gratings (LCPGs) show great promise as modulators of unpolarized light, exhibiting high contrast and a diffraction efficiency of ~100% has been experimentally demonstrated[1] for monochromatic light and ~98% efficiency for broadband light[2,3] (in an étendue-limited arrangement). This type of modulator is particularly suited for mobile battery-powered "pocket" projectors that demand high contrast and brightness with minimal power consumption. A theoretical study of finite-difference time-domain predictions and elastic-continuum theory was also reported recently.[4] While many properties disclosed thus far are encouraging, one limitation has been that high-quality gratings were experimentally difficult to achieve below periods of about 10 μm when using commercial-grade photoalignment materials. Because the diffraction angle of this modulator in the Schlieren projection scheme[2,3,5] determines the required collimation on the light engine, it is best if the grating period is smaller, ideally between 4–6 μm. To quantify this within the context of projection displays, here we will estimate the relationship between the étendue of the microdisplay and the grating period and explore its impact on other display parameters.

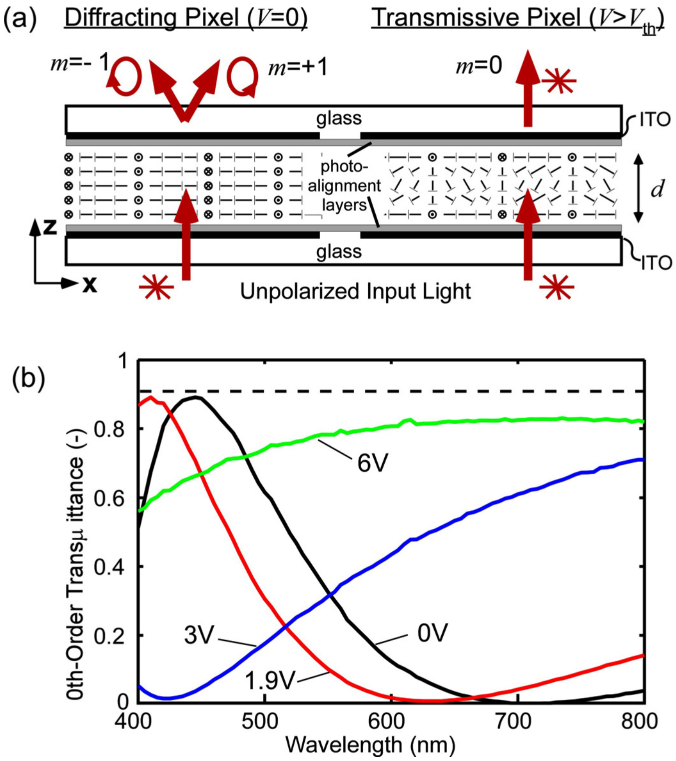

FIGURE 1 — LCPG properties. (a) Side view of the pixel structure in its diffracting and transmissive states and (b) raw transmittance of the zero order with input unpolarized light.

The key feature of our polarization-independent modulator is the diffractive LCPG, whose operation and structure are outlined in Fig. 1. This grating is unique compared to conventional gratings in that only three orders m = {±1, 0} are present, and its diffraction efficiency for unpolarized light follows[1] as

$$\eta_0 = \cos^2\left(\frac{\pi \Delta n d}{\lambda}\right), \tag{1a}$$

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$$\sum \eta_{\pm 1} = \sin^2\left(\frac{\pi \Delta n d}{\lambda}\right), \tag{1b}$$

where η_m is the diffraction efficiency of the mth-order, Δn is the LC birefringence, d is the cell gap, and λ is the wavelength. The ±1 orders exhibit orthogonal circular polarization states while the zero-order presents the same polarization as the incident beam.

LCPGs are fabricated[1–3] by exposing a photoalignment layer[5] to two interfering ultraviolet beams with orthogonal circular polarizations such that a periodic alignment of the LC is created that follows $\mathbf{n}(x) = [\sin(\pi x/\Lambda), \cos(\pi x/\Lambda), 0]$ [as is shown in Fig. 1(a) and Ref. 1]. An applied voltage reduces the effective birefringence and tunes the transmission spectrum [Fig. 1(b)].

A family of theoretically polarization-independent binary LC gratings was previously studied[6–8] but was plagued by the presence of domain boundary lines and random disclinations, were limited to very large grating periods, and did not achieve theoretical diffraction efficiencies (limiting contrast and brightness). Even the more-recent improvements[9,10] with polymer-wall LC gratings still manifest less-than-ideal efficiencies, diffract noticeably up to the 5th diffraction order and are challenging to fabricate at periods on the order of tens of microns. The central limitation in all of these approaches is the binary nature of the gratings.

Several research groups[11,12] recognized that a continuous LC diffractive grating will have improved diffraction properties (over binary LC gratings) and that holography can be used to greatly simplify fabrication[13] and achieve smaller grating periods. Further theoretical studies by Zeldovich and co-workers[14] identified compelling characteristics, including the potential to modulate unpolarized light with high contrast. Initial experimental results by Crawford and co-workers[13,15] were promising, but were plagued by pervasive defects degrading their optical properties. Consequently, the maximum diffraction efficiency and switching contrast ratio was poor and strong incoherent scattering outside of the diffraction orders was present. While more recent experimental studies by Zeldovich and co-workers[16] have improved to 18% maximum diffraction efficiency, scattering continues to dominate its properties. We have overcome these deficiencies[1–3] by carefully balancing the choice of LC and commercially available photoalignment materials (from ROLIC Technologies) with cell geometry and were the first to experimentally realize and report ideal polarization gratings. High-efficiency LCPGs were subsequently obtained by other research groups[17] using azo-dye-doped polyimide as the alignment material. However, for these materials, long-term stability is fundamentally limited by thermally and optically induced degradation.

In this work, we report our progress in attaining smaller grating periods and larger diffraction angles in order to ultimately improve the overall throughput of the projection system incorporating the LCPG.

2 LC polarization-grating properties

The LCPG has several competing design parameters over which to optimize. The most important is that the cell thickness must be determined by the half-wave retardation thickness for the longest wavelength $\lambda_{\max}$ of interest in order to maximize diffraction properties in Eq. (1). This implies

$$d \geq \frac{\lambda_{\max}}{2\Delta n}. \tag{2}$$

It is also imperative to maintain a thickness that is below the critical thickness[13,14] in order to prevent spontaneous out-of-plane orientation without applied fields. This condition can be predicted with reasonable accuracy using a two-constant approximation and strong anchoring assumptions[4]:

$$d < d_C = \frac{\Lambda}{\sqrt{2 - K_2/K_1}}, \tag{3}$$

where d_C is the critical thickness and K_1 and K_2 are the coefficients of the splay and twist deformations. Combining Eqs. (2) and (3), we can predict the smallest grating period possible for a given material in order to potentially achieve a half-wave retardation:

$$\Lambda > \frac{\lambda_{\max}}{2\Delta n}\sqrt{2 - \frac{K_2}{K_1}}. \tag{4}$$

From this prediction, a red LED with a center wavelength of 620 nm and the parameters of MLC-6080,[1] a grating period as low as ~2 μm should be possible. While Eq. (4) may be a useful minimum bound, we have found experimentally that this is too optimistic (even if it is more accurate than previously published estimates[14]), as we will see from data below. We suspect this is due to the not-always-attainable assumptions of strong anchoring and a zero pretilt used in the derivation of Eq. (3).

Since the LCPG is a diffraction grating, it follows the diffraction equation (where the "optical" period Λ is half the "nematic" period, as is shown in Fig. 1(a) and Ref. 1):

$$\sin\theta_{out} = \frac{\lambda}{\Lambda} + \sin\theta_{in}, \tag{5}$$

where θ_{in} and $\theta_{out} = \theta_{m=\pm 1}$ are the incident and first-order diffraction angles, respectively.

An LCPG cell that meets these criteria should have[4] the following voltage-threshold and dynamic-response-time constants, assuming strong anchoring:

$$V_{th} = \pi\sqrt{\frac{K_1}{\varepsilon_0 \Delta\varepsilon}\left[1 - \left(\frac{d}{d_C}\right)^2\right]}, \tag{6}$$

$$\tau_{on} = \frac{\gamma_1 d^2}{\varepsilon_0 \Delta\varepsilon\left(V^2 - V_{th}^2\right)} \text{ and } \tau_{off} = \frac{\gamma_1 d^2}{\varepsilon_0 \Delta\varepsilon V_{th}^2}. \tag{7}$$

In a more recent study,[18] we derived analytical expressions for these parameters in a more-general situation with arbitrary elastic constants. Moreover, the effect of weak surface anchoring on the critical parameters was studied. We found that both the threshold voltage and critical thickness can degrade considerably (even to zero!) even for modest anchoring strengths and that these effects become more pronounced at smaller grating periods. The choice of alignment materials and processing conditions therefore becomes crucial. Earlier, we have used LCPG as a polarization-independent light modulator[2,3] and demonstrated its applicability using various projection schemes with good contrast and increased brightness over the entire visible range. As we will later see, the efficiency of such a projection system can be enhanced by working with smaller grating periods and the above analysis becomes all the more important.

3 Experiment

The LCPG is fabricated as follows: first, ITO-coated substrates must be coated with a UV-sensitive photoalignment layer[19] and the LC cell with a fixed spacing d must be assembled. Second, the cell is exposed to a UV polarization hologram (with superimposed, orthogonal circularly polarized beams leading to a linearly polarized standing optical wave). Third, this cell is filled with a nematic LC (preferably within its isotropic state). The holographic setup is explicitly illustrated in Refs. 13 and 20.

Previous experimental work with LCPGs[13,15] led to less-than-ideal LC alignment rife with defects. We have overcome[1] this through two primary avenues: designing cell geometry in view of the critical thickness,[4,13,14] and by extensive materials optimization (of both the LC and photoalignment layers).

The following process was used for the results reported here. Standard ITO glass was assembled to achieve a uniform cell thickness. We used the photoalignment layer[19] ROP201 (ROLIC, with standard recommended coating processing). A He–Cd laser (325 nm) delivering a dose of ~300 mJ/cm^2 with orthogonal circularly polarized beams was used to expose a surface periodic alignment pattern. Filling of the LC was done on a hotplate at 115°C and annealed on another hotplate at 90°C for 2 min. In this work, we compare two samples with contrasting parameters:

Sample A: Λ = 11 µm, d = 2 µm, liquid crystal MLC-6080 (MERCK, Δn = 0.202, T_{NI} = 95°C, K_1 = 14.4 pN, K_2 = 7.1 pN, K_3 = 19.9 pN, $\Delta\varepsilon$ = 7.2, γ_1 = 157 mPa-sec).

Sample B: Λ = 6.3 µm, d = 2.9 µm, liquid crystal MLC-12100-000 (MERCK, Δn = 0.113, T_{NI} = 92°C, K_1 = 11.4 pN, K_3 = 13.8 pN, $\Delta\varepsilon$ = 8.5, γ_1 = 183 mPa-sec).

We determine the *transmittance* as $T = I_{MOD}/I_{REF}$, where I_{MOD} is the modulated intensity of the LCPG and I_{REF} is reference intensity with the LCPG removed. This measure includes the effect of the cell reflections and any absorption. The *diffraction efficiency* of the LCPG itself is $\eta_m = I_m/I_{REF}$, where I_m is the measured intensity of the mth transmitted diffraction order and where I_{REF} is a reference intensity for an ITO-glass cell filled with a solvent. All electro-optic measurements were done with a 4-kHz square wave.

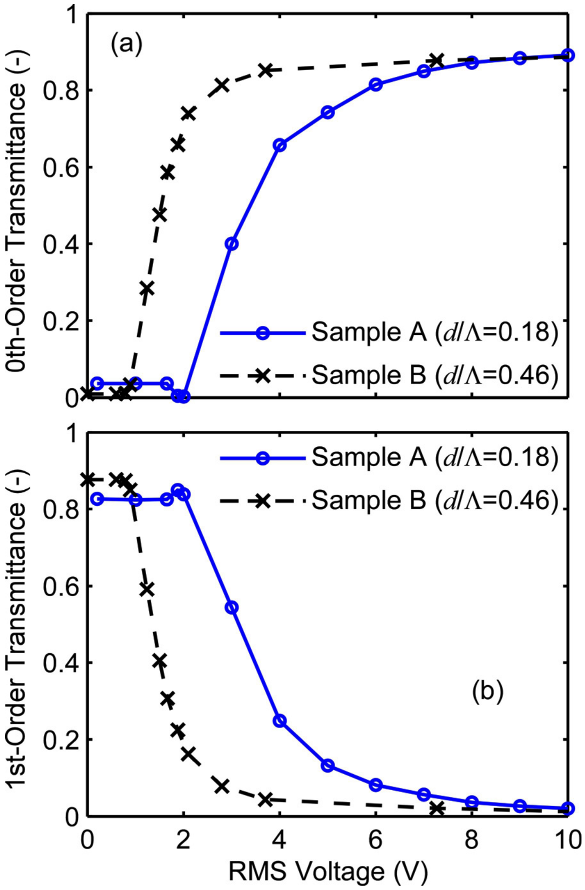

FIGURE 2 — LCPG transmission *vs.* voltage characteristics (633-nm laser): (a) zero order and (b) sum of ±1-orders response. Note that both η_0 and $\Sigma\eta_{\pm 1}$ were experimentally polarization-independent.

4 Results

We generally find excellent agreement between our experimental results and the predictions of Eq. (1). Most remarkably, the diffraction of a He–Ne (633 nm) laser was maintained almost completely within the 0th and ±1 orders regardless of voltage, and very little incoherent scattering (<0.3% for red light) was routinely observed. Note that for Fig. 2(b), we plot the sum of the first-order diffraction efficiencies, a quantity that in both theory and experiment is independent of the incident polarization state (whether unpolarized, or polarized). Experimental measurements with unpolarized light-emitting-diodes (LEDs) (red, green, and blue LEDs) supporting this conjecture have been previously reported.[2,3]

Basic switching behavior is shown in Fig. 2 for He–Ne (633 nm) laser light. The maximum zero-order contrast ratio was 380:1 and 95:1 for Samples A and B, respectively. The maximum ±1-order contrast ratio was 600:1 and 400:1 for Samples A and B, respectively. We consider these to be sub-

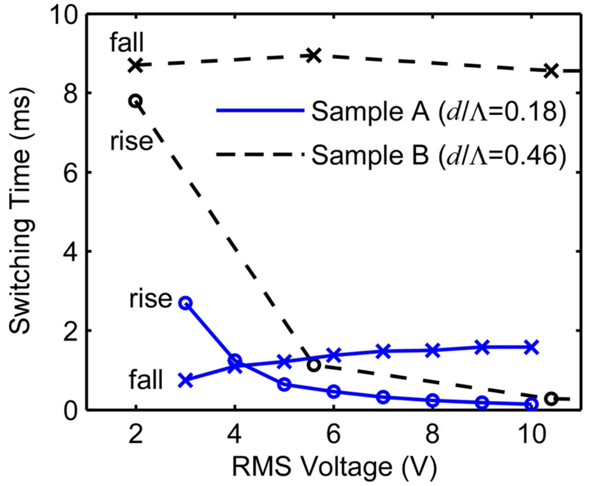

FIGURE 3 — LCPG dynamic response.

stantially similar and the difference is most likely due to slight fabrication variations from sample to sample more than anything inherent. Maximum diffraction efficiencies were nearly identical at ~99%.

As expected, a voltage threshold exists for our samples and was V_{TH} = 1.65 and = 0.72 V for Samples A and B, respectively. Sample B also has a much more non-linear transmittance characteristic. The major difference between these two samples is their d/Λ ratio – a parameter that plays a key role in Eq. (6) through the influence of Eq. (3).

The full-contrast switching times of the zero-order intensity were measured with the He–Ne laser and a modulated drive signal. Figure 3 shows the 10–90% rise and fall times of both samples. While Sample A has a fall-time of ~1.5 msec, Sample B exhibits a longer time of ~9 msec. Note that the fall times predicted by Eq. (7) for Sample A and B are 10 and 42 msec, clearly several times longer. We suspect the "fortunate" discrepancy is related to the prominent flow effects in the bend-splay LC profile of the LCPG that were neglected in the analytical reasoning.

5 Discussion

We have achieved good diffraction and contrast in an LCPG switch at a 6.3-μm period (Sample B), and thereby have increased the diffraction angle of red light to ~6° (compared to only 3° in the 11 μm, Sample A). While these numbers are encouraging, the projection-display application also places strong demands on switching time and aperture.

In order to illuminate the general dependence of the switching time on the grating period, we have used Eq. (7) to calculate the fall time [Fig. 4(a)] for the material parameters of Sample A (and d = 2 μm). Recall that the critical thickness for any LCPG is related to the grating period [Eq. (3)]. Two important points are in order: (i) the fall time is roughly constant as Λ is decreased until a certain point (in this case ~4 μm); and (ii) as the actual thickness approaches the critical thickness, the fall time increases dramatically. In light of these trends, it is interesting to note that the fall-time becomes infinite when $d = d_C$, which means the "thresholdless" grating[13] will not relax to its OFF-state.

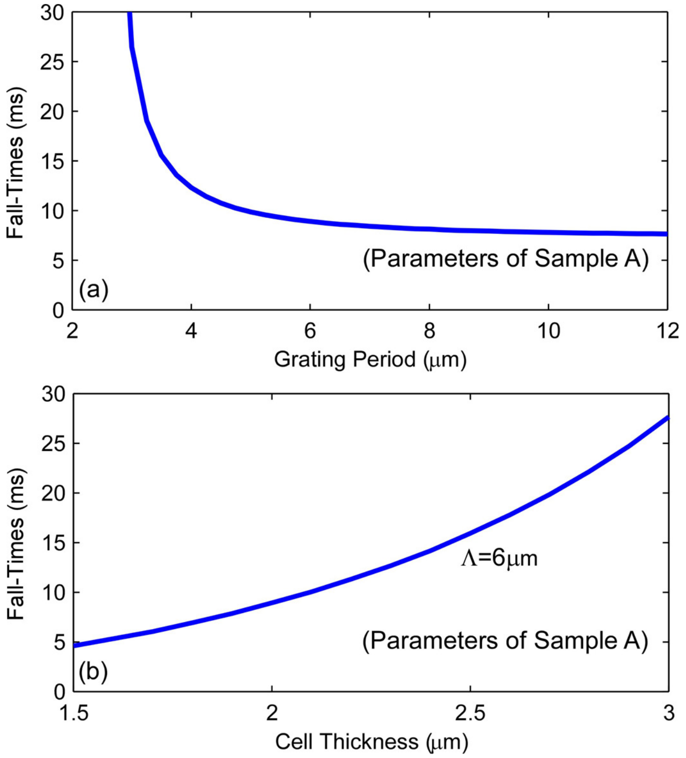

FIGURE 4 — Fall times as a function of (a) grating period and (b) cell thickness.

It is also important to study the effect of cell thickness on the fall times [see Fig. 4(b)] through Eq. (7). The general trend is that the fall times increase non-linearly with d. Here we identify the significance of implementing LCPGs with LCs having Δn as high as available, and on the benefits of an LCPG in reflection mode. The higher Δn materials achieve a $\lambda/2$ retardation with smaller d, enabling faster fall times, as seen in our two materials reported here. On the other hand, because the optical path length is doubled in reflective LC devices, it is likely that the thickness in reflective LCPGs could be reduced by a factor of ~2. This causes the fall times to decrease by a factor of ~4 once again, resulting in a faster display mode. Note also that the reflective-mode LCPG will have a smaller pixel size since a minimum number of grating periods (our estimate is ≥4) are required within each pixel for obtaining ideal diffraction efficiencies.[4]

The étendue of a rectangular display element can be expressed[5] as $E = 4A \sin \Omega \sin \Phi$, where A is the area if the microdisplay and Ω and Φ are half-angles of the divergence of light in the horizontal and vertical directions. If the grating diffracts in the horizontal direction, we can identify the condition [using Eq. (5)] needed in the Schlieren projection scheme to obtain good contrast: $\sin^{-1} (\lambda_{\min}/\Lambda) \geq 2\Omega$, where $\lambda_{\min}$ is the minimum wavelength of interest (typically blue at ~470 nm). In Fig. 5, we use these rough estimates to

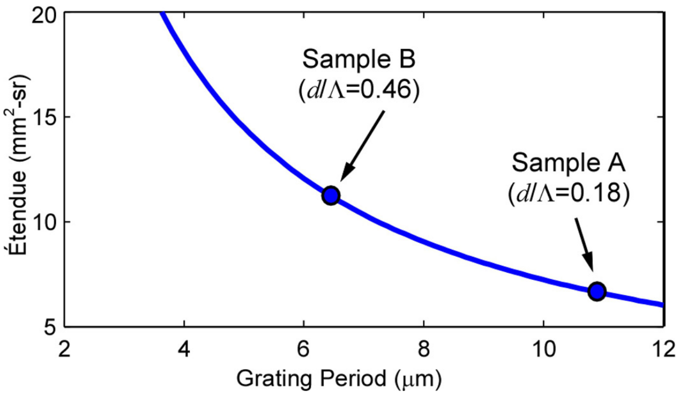

FIGURE 5 — Étendue for different grating periods.

calculate the étendue for the LCPG of various grating periods for a display area of 15 × 15 mm^2 and $\Phi = 20°$. Clearly, smaller grating periods lead to a larger aperture, as expected, and Λ of ≤ 5 μm will be needed to achieve étendue values similar to current microdisplay systems.

We continue to search for higher birefringence materials (ideally $\Delta n \geq 0.2$), which have a high anchoring energy with photoalignment materials and a high K_2/K_1 ratio, in order to reduce the grating period.

Several advantages of the LCPG are apparent as compared to the most extensively studied type of LC diffraction gratings: Holographic polymer-dispersed liquid crystals (H-PDLCs).[21–23] Approximately equivalent high-diffraction efficiencies can be achieved, but the LCPG offers substantially lower drive voltages and scattering.

6 Conclusion

We have experimentally demonstrated electro-optical switching with high contrast at modest drive voltages using the LCPG at grating periods as low as 6.3 μm. Very low scattering is observed, and almost all diffracted light (~99%) appears in the 0 and ±1 orders. While smaller periods are desired in order to achieve high projection-system performance, a trade-off currently exists where processing parameters and alignment materials have to be optimized for realizing high-quality LCPGs.

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