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# P.36: Polarization-Independent Modulation for Projection Displays Using Small-Period LC Polarization Gratings

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**Abstract:** We report our progress in using a liquid crystal polarization grating (LCPG) to modulate unpolarized (and polarized) light with a grating period as small as 6.3  $\mu\text{m}$ . Similar to LCPGs formed at larger periods (11  $\mu\text{m}$ ) reported previously, we continue to observe polarization independent switching, predominantly three diffraction orders, maximum contrast ratios of  $\sim 100:1$  for unpolarized broadband light, very low scattering, and diffraction efficiency of  $\geq 98\%$ . However, the smaller period led to an expected lower threshold voltage of  $\sim 0.72$  V, and longer fall-times of  $\sim 9$  ms. Since the smaller grating period enables a brighter result from the Schlieren projection scheme for a microdisplay using the LCPG light-valve, we discuss the inherent tradeoffs involved and the prospects for a polarization-independent projection display.

**Keywords:** liquid crystal; diffraction; polarization grating; projection display; polarization-independent.

## Introduction

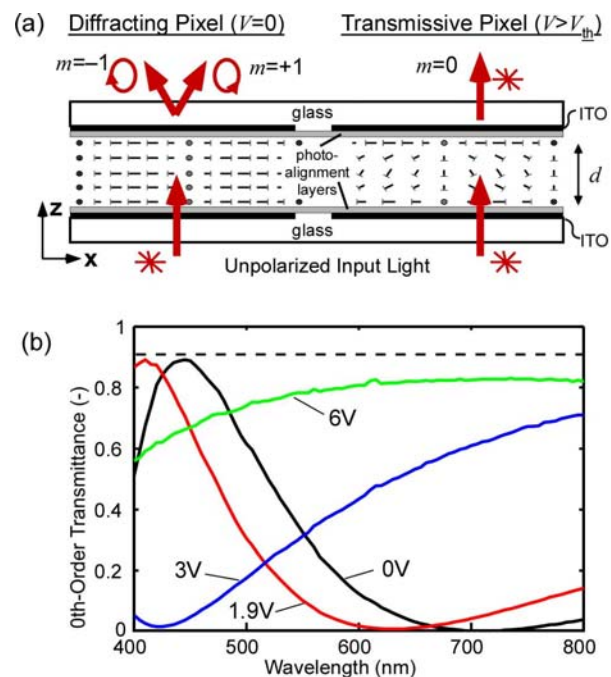
Our objective is to develop a liquid crystal (LC) display element capable of modulating unpolarized light with high contrast, and to ultimately integrate it into a highly efficient portable projection display based on a light-emitting-diode (LED) light engine. Liquid crystal polarization gratings (LCPGs) show great promise as projection display modulators of unpolarized light, exhibiting high contrast and experimentally-demonstrated  $\sim 100\%$  diffraction efficiency [1] for monochromatic light and  $\sim 98\%$  efficiency for broadband light [2] (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 [3]. While many properties disclosed so far are encouraging, one limitation facing our group has until now been the fact that high quality gratings were only possible at periods of 10  $\mu\text{m}$  or higher. Since the diffraction angle of this modulator in the Schlieren projection scheme [2, 4] determines the required collimation on the light-engine, it is best if the grating period is smaller, ideally between 4-6  $\mu\text{m}$ . To quantify this dependency, here we will estimate the relationship between the étendue of the microdisplay and the grating period, and explore its impact on other display parameters.

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 from conventional gratings in that only three orders ( $m=\pm 1, 0$ ) are present, and its diffraction efficiency for unpolarized light follows [1]:

$$\eta_0 = \cos^2\left(\frac{\pi\Delta nd}{\lambda}\right) \quad \text{and} \quad \Sigma\eta_{\pm 1} = \sin^2\left(\frac{\pi\Delta nd}{\lambda}\right), \quad (1)$$

where  $\eta_m$  is the diffraction efficiency of the  $m$ -order,  $\Delta n$  is the LC birefringence,  $d$  is the cell gap, and  $\lambda$  is the wavelength. The  $\pm 1$ -orders exhibit orthogonal circular polarization states while the 0-order presents the same polarization as the incident beam.

LCPGs are fabricated [1] by exposing a photo-alignment layer [4] 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 (see Fig. 1(b)).



**Figure 1.** LCPG properties - (a) Side-view of the pixel structure in its diffracting and transmissive states; and (b) raw transmittance of the 0-order with input unpolarized light.

A family of theoretically polarization-independent, binary, LC gratings was previously studied [5-7] 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 [8, 9] with polymer-wall LC gratings still manifest less than ideal efficiencies, diffract noticeably up to the 5<sup>th</sup> diffraction order, and are challenging to fabricate at periods on the order of 10s of  $\mu\text{m}$ . The central limitation in all of these approaches is the binary nature of the gratings.

Several research groups [10, 11] 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 [12] and achieve smaller grating periods. Further theoretical studies by Zeldovich and coworkers [13] identified compelling characteristics, including the potential to modulate unpolarized light with high contrast. Initial experimental results by Crawford and coworkers [12, 14] 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 coworkers [15] have improved to 18% maximum diffraction efficiency, scattering continues to dominate its properties.

We have overcome these deficiencies [1, 2] by carefully balancing the choice of LC and photo-alignment materials with cell geometry to experimentally realize ideal polarization gratings. 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.

### 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  $\lambda_{\text{max}}$  of interest in order to maximize diffraction properties in Equation (1). This implies:

$$d \geq \frac{\lambda_{\text{max}}}{2\Delta n}. \quad (2)$$

It is also imperative to maintain a thickness that is below the critical thickness [12, 13] 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 [3]:

$$d < d_c = \frac{\Lambda}{\sqrt{2 - K_2/K_1}}, \quad (3)$$

where  $d_c$  is the critical thickness, and  $K_1$  and  $K_2$  are the coefficients of the splay and twist deformations. Combining

Eqns. (2) and (3), we can predict the smallest grating period possible for a given material in order to potentially achieve a halfwave retardation:

$$\Lambda > \frac{\lambda_{\text{max}}}{2\Delta n} \sqrt{2 - \frac{K_2}{K_1}}, \quad (4)$$

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  $\sim 2 \mu\text{m}$  should be possible. While Eq. (4) may be a useful minimum bound, we have found experimentally that this is too optimistic, as we will see from data below (even if it is more accurate than previously published estimates [13]). We suspect the discrepancy is due to the unrealistic assumptions of strong anchoring and the neglect of other influences not modeled (e.g. flexo-electric effect).

Since the LCPG is a diffraction grating, it follows the diffraction equation (where the ‘‘optical’’ period  $\Lambda$  is half the ‘‘nematic’’ period, as is shown in Fig. 1(a) and Ref. [1]):

$$\frac{\lambda}{\Lambda} = \sin \theta_m + \sin \theta_{out}, \quad (5)$$

An LCPG cell that meets these criteria should have the following voltage threshold and dynamic response time constants [3], assuming strong anchoring:

$$V_{TH} = \pi \sqrt{\frac{K_1}{\epsilon_0 \Delta \epsilon} \left( 1 - \left( \frac{d}{d_c} \right)^2 \right)}, \quad (6)$$

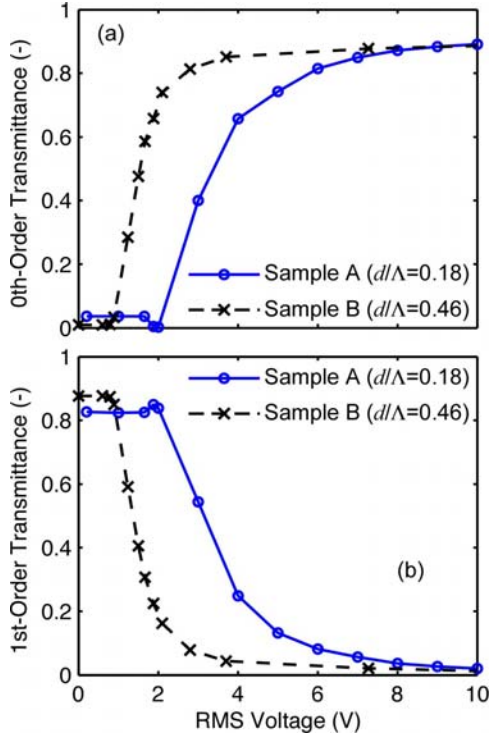
$$\tau_{on} = \frac{\gamma_1 d^2}{\epsilon_0 \Delta \epsilon (V^2 - V_{th}^2)}, \quad \text{and} \quad \tau_{off} = \frac{\gamma_1 d^2}{\epsilon_0 \Delta \epsilon V_{th}^2}. \quad (7)$$

### Experiment

The LCPG is fabricated as follows: first, ITO-coated substrates must be coated with a UV-sensitive photo-alignment layer [16] 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. [12, 17].

Previous experimental work with LCPGs [12, 14] 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 [3, 12, 13], and by extensive materials optimization (of both the LC and photo-alignment 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 photo-alignment layer [16] ROP201 (ROLIC, with standard recommend processing). A HeCd laser (325 nm) delivering a dose of  $\sim 300 \text{ mJ/cm}^2$  with orthogonal circularly polarized beams was used to expose a surface periodic alignment pattern. Filling of the LC was done on a hotplate at  $115^\circ\text{C}$  and



**Figure 2.** LCPG transmission vs. voltage characteristics (633 nm laser): (a) 0-order and (b) sum of  $\pm 1$ -orders response. Note that both  $\eta_0$  and  $\Sigma \eta_{\pm 1}$  were experimentally polarization-independent.

annealed on another hotplate at 90°C for 2 min. In this work we compare two samples with contrasting parameters:

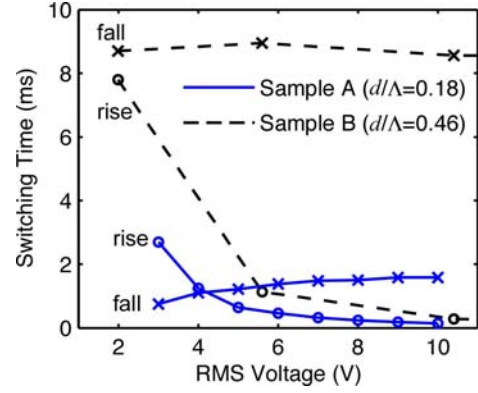
**Sample A:**  $\Lambda = 11 \mu\text{m}$ ,  $d = 2 \mu\text{m}$ , liquid crystal MLC-6080 (MERCK,  $\Delta n = 0.202$ ,  $T_{NI} = 95^\circ\text{C}$ ,  $K_1 = 14.4\text{pN}$ ,  $K_2 = 7.1\text{pN}$ ,  $K_3 = 19.9\text{pN}$ ,  $\Delta\epsilon = 7.2$ ,  $\gamma_1 = 157\text{mPa}\cdot\text{s}$ )

**Sample B:**  $\Lambda = 6.3 \mu\text{m}$ ,  $d = 2.9 \mu\text{m}$ , liquid crystal MLC-12100-000 (MERCK,  $\Delta n = 0.113$ ,  $T_{NI} = 92^\circ\text{C}$ ,  $K_1 = 11.4\text{pN}$ ,  $K_3 = 13.8\text{pN}$ ,  $\Delta\epsilon = 8.5$ ,  $\gamma_1 = 183\text{mPa}\cdot\text{s}$ )

We determine the *transmittance* as  $T = I_{\text{MOD}} / I_{\text{REF}}$ , where  $I_{\text{MOD}}$  is the modulated intensity of the LCPG and  $I_{\text{REF}}$  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  $\eta_m = I_m / I_{\text{REF}}$ , where  $I_m$  is the measured intensity of the  $m^{\text{th}}$  transmitted diffraction order, and where  $I_{\text{REF}}$  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.

## Results

We generally find excellent agreement between our experimental results and the predictions of the Eq. (1). Most remarkably, the diffraction of a HeNe (633 nm) laser was maintained almost completely within the 0<sup>th</sup>- and  $\pm 1$ -



**Figure 3.** LCPG dynamic response.

orders regardless of voltage, and very little incoherent scattering ( $<0.3\%$  for red light) was routinely observed.

Basic switching behavior is shown in Fig. 2 for HeNe (633 nm) laser light. The maximum 0-order contrast ratio was 380:1 and 95:1 for Samples A and B, respectively. The maximum  $\pm 1$ -order contrast ratio was 600:1 and 400:1 for Samples A and B, respectively. We consider these to be substantially similar and differences are most likely due to slight fabrication differences more than anything inherent. Maximum diffraction efficiencies were nearly identical at  $\sim 99\%$ .

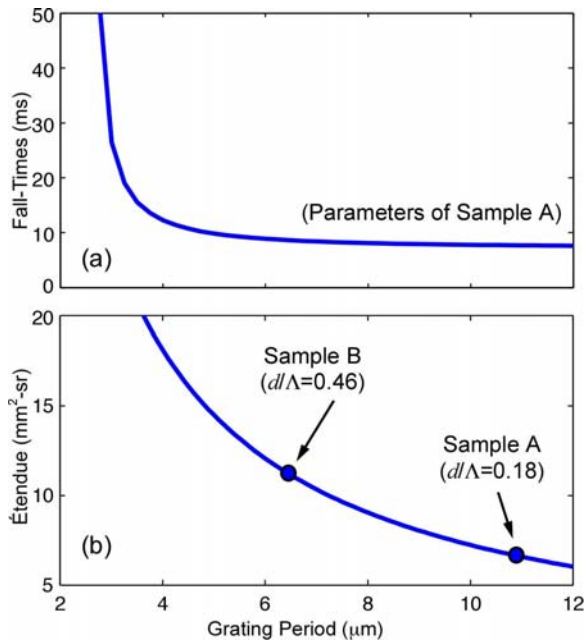
As expected, a voltage threshold exists, and was  $V_{TH} = 1.65 \text{ V}$  and  $= 0.72 \text{ V}$  for Samples A and B, respectively. Sample B also has a much more non-linear transmittance characteristic. The major difference between these two samples is their  $d/\Lambda$  ratio – a parameter that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

The full-contrast switching times of the 0<sup>th</sup>-order intensity were measured with the HeNe laser and a modulated drive signal. Fig. 3 shows the 10%-90% rise and fall times of both samples. While Sample A has a fall-time  $\sim 1.5 \text{ ms}$ , Sample B exhibits a longer time of  $\sim 9 \text{ ms}$ . Note that the fall-times predicted by Eq. (7) for Sample A and B are 10 ms and 42 ms, clearly several times longer. We suspect the “fortunate” discrepancy is related to a prominent flexo-electric effect in the bend-splay LC profile of the LCPG.

## Discussion

We have achieved good diffraction and contrast in an LCPG switch at 6.3  $\mu\text{m}$  period (Sample B), and thereby have increased the diffraction angle of red light to  $\sim 6^\circ$  (compared to only  $3^\circ$  in the 11  $\mu\text{m}$ , 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 grating period on switching time, we have used Eq. (7) to calculate the fall-time (Fig. 4(a)) for the material parameters of Sample A (and  $d=2\mu\text{m}$ ). Recall that the critical thickness for any LCPG is related to the grating period (Eq. (3)).



**Figure 4.** Impacts of smaller grating periods: both the (a) fall-time and (b) étendue increase.

Two important points are in order: (i) the fall-time increases only slightly as  $\Lambda$  is decreased until a certain point (in this case  $\sim 4 \mu\text{m}$ ); and (ii) as the critical thickness approaches the actual 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 [12] will not relax to its OFF state, an effect that may enable a bistable LC mode!

The étendue of a rectangular display element can be expressed [4] as:  $E = 4A \sin\Omega \sin\Phi$ , where  $A$  is the area of the microdisplay, and  $\Omega$  and  $\Phi$  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 get good contrast:  $\sin^{-1}(\lambda_{\min}/\Lambda) \geq 2\Omega$ , where  $\lambda_{\min}$  is the minimum wavelength of interest (typically blue at  $\sim 470 \text{ nm}$ ). In Fig. 4(b) we use these rough estimates to calculate the étendue for the LCPG of various grating periods for a display area of  $15 \times 15 \text{ mm}^2$ , and  $\Phi = 20^\circ$ . Clearly, smaller grating periods lead to a larger aperture, as expected, and  $\Lambda$  of  $\leq 5 \mu\text{m}$  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 photo-alignment 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) [18-20]. Approximately equivalent high

diffraction efficiencies can be achieved, but the LCPG offers substantially lower drive voltages and scattering.

## Conclusions

We have experimentally demonstrated polarization-independent switching with high contrast at modest drive voltages using the LCPG at grating periods as low as  $6.3 \mu\text{m}$ . Very low scattering is observed, and almost all diffracted light ( $\sim 99\%$ ) appears in the 0- and  $\pm 1$ -orders. While smaller periods are desired in order to achieve high projection system performance, a trade-off currently exists with regard to the increased switching times.

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