P-209: Evaluation of Projection Schemes for the Liquid Crystal Polarization Grating Operating on Unpolarized Light

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Abstract

We report on our first experimental comparison of polarization-independent projection schemes using the liquid crystal polarization grating (LCPG) modulator as the active element. This recently-demonstrated LC grating has unique diffraction properties, and we evaluate its performance using the bright- and dark-field Schlieren configurations and consider its use with a TIR-prism assembly. Each scheme shows promise for high-brightness and good-contrast projection for different applications.

1. Introduction

Liquid crystal polarization gratings (LCPGs) show great promise as projection display modulators of unpolarized light, exhibiting high contrast and experimentally-demonstrated 100% diffraction efficiency [1]. This type of modulator is particularly suited for mobile, battery-powered "pocket" projectors that demand high contrast and brightness with minimal power consumption. As with the other types of projection display systems using diffractive modulators, the contrast and brightness of our system depends on the projection scheme employed. Since the principle of operation in the LCPG is distinct from previous LC gratings, we anticipate comparably improved projected image properties (contrast and brightness). As only very limited experimental and theoretical investigations into LCPG switches have been carried out (and none utilizing a realistic projection scheme), here we report on the first examination of such. This information should strongly inform the design of any realistic projection system based on the LCPG modulator.

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

$$\eta_0 = \cos^2\left(\frac{\pi\Delta nd}{\lambda}\right) \quad \text{and} \quad \eta_{\Sigma\pm1} = \sin^2\left(\frac{\pi\Delta nd}{\lambda}\right), \tag{1}$$

where η_m is the diffraction efficiency of the m-order, Δn is the LC birefringence, d is the cell gap, and λ is the wavelength. In addition, the polarization state of these orders is controllable to create a 100%-efficient diffractive element [2,3]. The ±1 orders exhibit orthogonal circular polarization states while the zero 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)).

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The LCPG has several advantages when compared to previous polarization-independent LC diffractive modulators [5,6,7,8]: its fabrication is substantially less complex, larger diffraction angles can be achieved, and large defect-free areas are easily formed [1].

Any efficient projection display system will require a high contrast modulator, efficient light engine, and intelligent stray-light management approach. Since we are using a diffractive modulator, the projection optics design must also be capable of separating the grating's diffracted orders (2º-10º for visible light) with acceptable contrast for image display. Furthermore, a "pocket-sized" projection display must accomplish this in a relatively small amount of space. Because the ability of a LCPG projection display achieving the above is not obvious, we experimentally construct several projection schemes and evaluate their properties. To this end, we examine Schlieren projection optics and a total-internal-reflection (TIR) prism assembly with a light engine based on light-emitting-diodes (LEDs).

2. Diffractive Projection Schemes

Multiple methods exist for image projection from a diffractive modulator, including Schlieren optics and TIR-prism assemblies. The Schlieren method [9] has been applied with some experimental success to binary LC gratings [5,6,7]. Both the

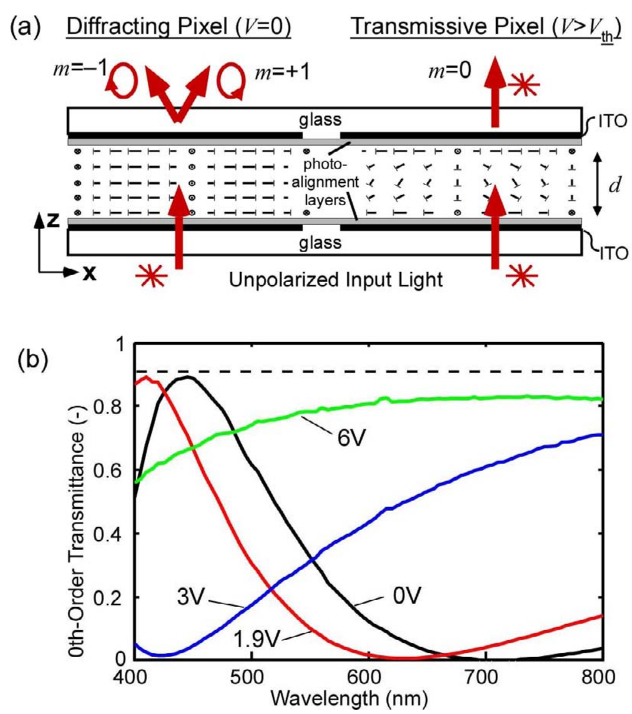

Figure 1: LCPG properties - (a) Side-view of the pixel structure in its diffracting and transmissive states; and (b) raw transmittance of the 0th order with input unpolarized light. Note the blue-shift of the spectra as voltage is applied.

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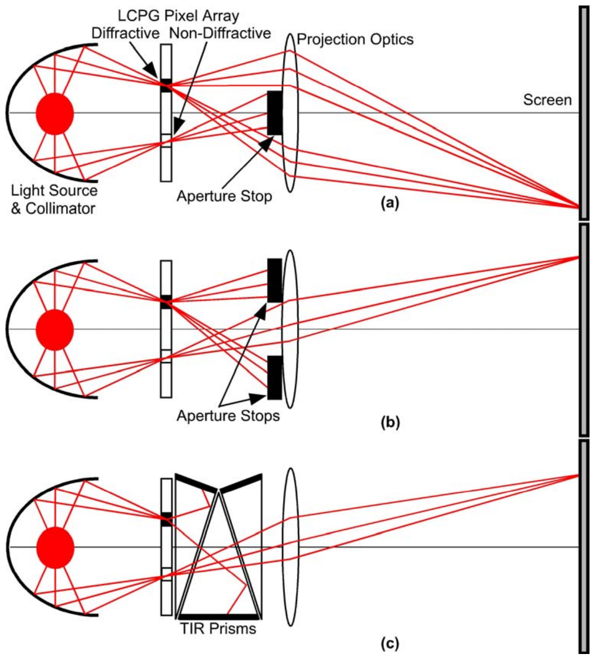

Figure 2: Diffractive Projection Schemes – (a) Dark-field Schlieren, (b) Bright-field Schlieren, (c) TIR assembly.

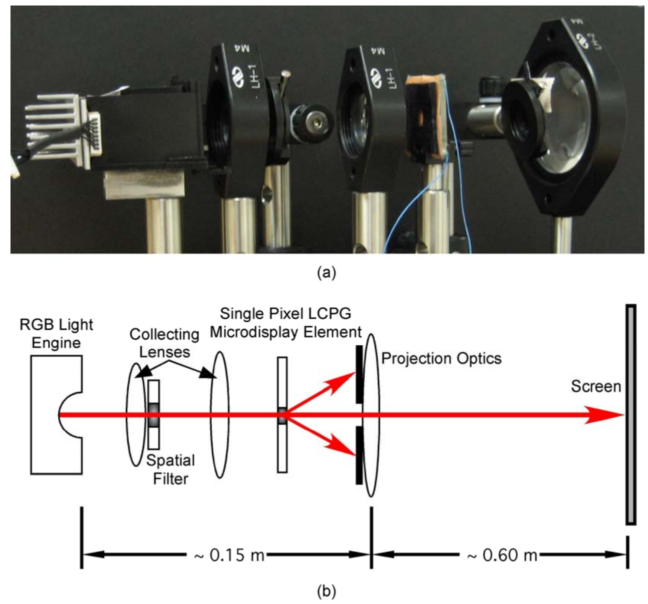

Figure 3: Custom-built projection system – (a) Photo of system with RGB light engine (at left) to projection optic (far right); and (b) illustration of complete set-up utilizing the bright-field Schlieren projection scheme.

bright-field and dark-field Schlieren configurations are illustrated in Fig. 2. Since the LCPG only diffracts into the zero and first diffraction orders, the Schlieren system is relatively simple. In the bright-field configuration (Fig. 2(b)), an aperture stop is placed in such a way as to block all diffracted orders except the zero order, similar to a conventional spatial-filter. In the dark-field configuration (Fig. 2(a)), the complementary situation occurs: the zero order is blocked and the first orders are projected. The modulator achieves bright-dark contrast at any given pixel in either Schlieren configuration as it directs incident light into or out of the zero and first diffraction orders.

A TIR-prism assembly may also be used as a means of angularly separating diffracted orders [10]. Figure 2(c) illustrates the principle of operation: light from the OFF pixel experiences TIR at the two prism-prism interfaces and is directed into absorbing layers (for clarity, only one ray of each diffracted order is drawn). Conversely, light from the ON pixel avoids TIR and is projected onto the screen. A challenging aspect in this approach is the design of the optimum TIR layers and angles.

Other angularly selective modulators exist including the Grating-Light-Valve (GLV) [11], Holographic-Polymer Dispersed Liquid Crystal (H-PDLC) gratings [12,13], and the Digital-Micromirror-Device (DMD) [14]. Despite some similarities to our LCPG display, these do not operate with both 100% efficiency and high contrast. The most notable exception to this is the DMD approach, but it is arguably more complex and costly to fabricate.

3. Experiment

LCPGs were fabricated for operation over the entire visible wavelength range using liquid crystal MLC-6080 (Merck, Δn = 0.2, $\Delta\varepsilon$ = 7.2, T_{NI} = 95°C) and photo-alignment material ROP-103/2CP (Rolic), resulting in an 11 μm pitch and 2 μm cell gap [1]. Glass substrates coated with indium-tin-oxide (ITO) were used, and the polarization hologram was formed using a HeCd laser (325 nm) with a dose of ~0.3 J/cm^2.

This single-pixel LCPG microdisplay element was placed in a custom-built projection system shown in Figure 3. The light engine consisted of individual red, green, and blue LEDs (Lumileds). Several lenses were used for efficient light collection from the LEDs, and an iris was placed at an intermediate focal point to control the collimation (acting as a spatial filter). For the bright-field Schlieren configuration, an additional iris was used as an aperture stop. In the dark-field configuration, a narrow strip of metal blocking the zero order was used instead. A single biconvex lens was used as the final projection optic, resulting in an overall image magnification of ~15 with a throw of 0.6 m. A simple housing was constructed to block stray light during contrast measurements.

4. Results

We measured the projected intensity for a range of applied voltages (4 kHz square wave) using both Schlieren approaches. A calibrated photo-detector was placed at the screen to record the radiometric power. We normalized our measured modulated intensity (I_{MOD}) to the projected intensity (I_{REF}) at the same spot when the LCPG and the Schlieren aperture stops were removed (without changing the light engine): $T = I_{MOD} / I_{REF}$. The intention was to measure a realistic transmittance (T) that would be comparable for any microdisplay element.

As reported elsewhere [1], the maximum experimental contrast ratio of our LCPGs using monochromatic light (633 nm) was 380:1 in the zero order and 600:1 in the first orders. This indicates that the minimum transmittance was nearly 0%, as predicted by Eq. (1). In the case of LEDs, the full-width at half-maximum (FWHM) spectral width is approximately ±25 nm for all colors. Because of light leakage in the dark state, we therefore anticipate a maximum contrast ratio with LEDs that is

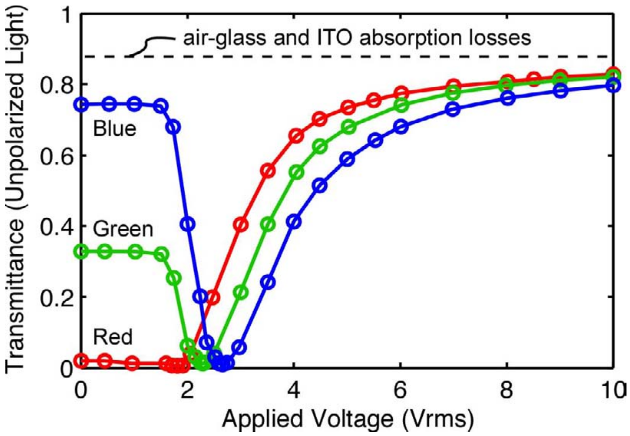

Figure 4: Bright-field Schlieren projected transmittance for red, green, and blue LEDs.

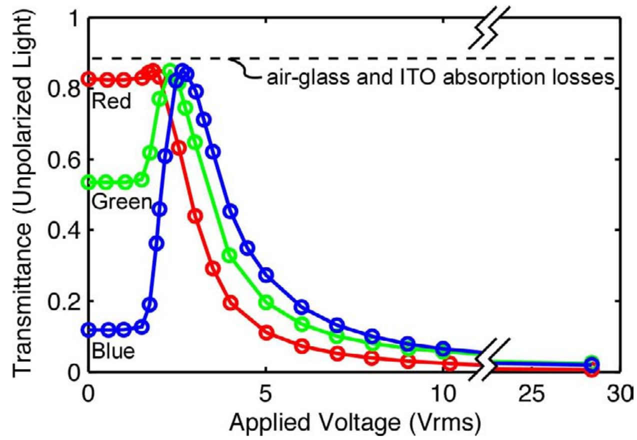

Figure 5: Dark-field Schlieren projected transmittance for red, green, and blue LEDs.

substantially reduced. Nonetheless, we will show below that the experimental contrast ratios with LEDs are promising.

4.1 Bright-Field Schlieren LCPG System

The measured transmittance characteristic using the bright-field Schlieren configuration is shown in Fig. 4, and the resulting contrast ratios are tabulated in Table 1. Somewhat surprisingly, the maximum contrast ratio obtained for the red LED was 144:1 even for applied voltages ≤ 10V. Note that the dark-state voltage is different for each color, an inherent feature of this display type (since an applied voltage varies the Δn). However, driver electronics can manage these voltages and provide maximum contrast for each color.

The threshold voltage can be clearly observed (V_{th}~1.65V for this sample). At high voltages, the maximum transmittance of all three colors is nearly identical, since the diffraction grating is effectively erased. At voltages below V_{th}, the transmittance varies greatly according to LED color since the parameter $\Delta nd/\lambda$ is different for each. The dark state in this configuration occurs when the retardation is halfwave ($\Delta nd = \lambda/2$), which was designed to be slightly above V_{th} for the red LED. Note that since Δn is dependent on the order parameter, we anticipate that the bright-field Schlieren projection scheme would be moderately sensitive (in contrast and color) to temperature changes.

The contrast-limiting aspect of this bright-field projection scheme is primarily the light-leakage in the dark state due to the wide source spectral width. Unless the spectral width of the source is narrowed (e.g. with interference filters), it will most likely be difficult to improve the contrast of this projection scheme further.

4.2 Dark-Field Schlieren LCPG System

The measured transmittance characteristic using the dark-field Schlieren configuration is shown in Fig. 5, and the resulting contrast ratios are tabulated in Table 1. The maximum contrast ratio obtained was 136:1 for the red LED. The bright state in this configuration occurs when the retardation is halfwave ($\Delta nd = \lambda/2$). Unlike the previous case, the dark state in this mode occurs at the high voltage state, as the grating is erased. Therefore, we anticipate that the dark-field Schlieren projection scheme will offer the maximum possible contrast ratios for the LCPG modulator. In our current data, it appears that 30V is not enough to demonstrate this, but it should be clear that even higher contrast ratios could be achieved with higher drive voltages and/or with a thinner cell gap.

The contrast-limiting aspect of the dark-field projection scheme is the higher drive voltage. The effect of light leakage and the temperature dependence of the dark state are both minimized in this configuration.

4.3 TIR Prism LCPG System

While we were unable to assemble and experimentally examine the TIR-prism assembly as illustrated in Fig. 2(c), we expect its contrast ratio and brightness will be nearly identical to the bright-field Schlieren configuration since in both cases the zero-order is projected to the screen. Perhaps its primary advantage for separation of the diffraction orders is its potential for a compact size, due to the close proximity of the prism assembly to the LCPG panel (avoiding the need for longer distances to allow the diffraction orders to spatially separate). This characteristic is extremely important when building small, "pocket-size" projectors, or any system in which space is a premium.

5. Discussion

The projection scheme used in combination with a LCPG modulator will depend on the particular limitations required for the application context. Drive voltage, overall device size, maximum brightness, and contrast ratio all must be balanced. Table 1 summarizes the results reported here and highlights the advantages and disadvantages of the three classical projection schemes.

Our studies show that tradeoffs exist between contrast ratio, drive voltage, and anticipated system size in the three projection schemes. For low-voltage, moderate-sized projectors with adequate contrasts, the bright-field Schlieren method should be sufficient. If large drive voltages are not a limitation for the display, the dark-field Schlieren system should provide improved contrast (useful for TV and home theater applications). When a compact, low-voltage display assembly is required, a TIR prism will likely provide the best solution for adequate contrast.

Like all other projection displays, collecting light from the source emitter(s) is an extremely important factor in the overall brightness of an LCPG projection display. Since light from an LED is inherently divergent, it is important to collimate the light for its passage through the optical elements of the display system.

Table 1: Comparison of projection scheme properties.

	Bright-Field	Dark-Field	TIR-Prism
Red LED Max Contrast	144:1	136:1 (potentially as high as 600:1 given higher voltages)	similar to BF
Green LED Max Contrast	73:1	35:1 (potentially as high as 600:1 given higher voltages)	similar to BF
Blue LED Max Contrast	82:1	43:1 (potentially as high as 600:1 given higher voltages)	similar to BF
Drive Voltage	≤ 10 V	≥ 30 V	similar to BF
Max IntraPixel Efficiency	≥ 90%	≥ 95%	similar to BF
Temperature Response	moderately sensitive	most robust	similar to BF
Overall Size	--	--	smallest size?
Suggested Application Area	personal projector devices	TV and home theater projection	integrated into other devices (e.g. laptop)

In the LCPG system, the requirement for collimated light is stronger than in other displays, since it achieves modulation based on shifting energy between angularly-separated orders. In this respect, it is similar to a DMD-based modulator. Since we expect that the angular difference between the zero and first diffraction orders can be made as high as ±10° with further materials and fabrication development, we anticipate that the collimation requirements are comparable to DMD-based systems.

Note that the total switching times of these pixels have been experimentally shown to be ~2 ms [1] for the same LCPG sample examined here. With further materials optimization, we fully expect that this can be reduced even further and that a color-sequential microdisplay can be built using nematic LCPGs.

We have performed initial simulation and experiment on achieving an LCPG on a reflective substrate, and have generally observed all of the same optical properties (Eq. (1)) as with the transmissive mode. The primary complication is that the reflective substrate makes holographic fabrication very challenging. We anticipate that with novel fabrication techniques we will be able to achieve high contrast modulation suitable for use with a standard liquid-crystal-on-silicon (LCOS) backplane.

6. Conclusions

Microdisplays that modulate unpolarized light offer the best path toward mobile data projectors possessing high brightness and low-voltage demands. Our newly-developed LCPG modulates unpolarized light in a unique fashion and offers one of the best opportunities to produce a high contrast, portable projector for minimal cost using conventional transmissive and reflective backplanes. We have shown here that contrast ratios around 100:1 are possible using the bright-field Schlieren approach with an LED light engine and modest drive voltages (≤ 10V). Higher contrast ratios are most likely possible with the dark-field Schlieren scheme, but higher drive voltages are required (≥ 30V). The analysis of projection schemes described herein makes clear that the overall system design will strongly impact the contrast ratio of the projected image. We hope our results will support the design of the first prototype projection systems based on LCPGs and serve as a realistic comparison to previously published work.

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