34.4L: *Late-News Paper:* Polarization Independent Projection Systems using Thin Film Polymer Polarization Gratings and Standard Liquid Crystal Microdisplays

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Abstract
We report on our progress in using polymer Polarization Gratings (PGs) to enhance the brightness of standard Liquid Crystal (LC) microdisplays. By replacing conventional polarizers with PGs, high transmittance (>85%) and contrast ratios (>300:1) can be achieved with common LC modes and unpolarized input light. Using this approach, we demonstrate a polymer-PG projection display prototype with double the brightness compared to a polarizer-based system using the same illumination (input acceptance angles ≥ ±15°).

1. Introduction
We report on a revolutionary new approach for polarization independent modulation using standard Liquid Crystal (LC) microdisplays and Polarization Gratings (PGs). In most LC display approaches, absorbing film polarizers transmit only the eigen-polarizations parallel to their transmission axes, and block ≥ 50% of the (unpolarized) input light. Our method [1] involves replacing polarizers with thin-film polymer-PGs that act on both orthogonal eigen-polarizations simultaneously, and thus improve the overall efficiency by a factor of two. As a result of this simple transformation, ~85-90% experimental throughput can be achieved, as opposed to 30-45% in polarizer-based systems.

Here, we report our success in using several common LC-modes along with enhanced polymer-PGs (1.8µm period) to achieve high optical throughput and contrast ratios above 300:1 (in one case), all with a source divergence angle of ±7.5° (larger than [1]). We also introduce a fractional *a*-plate in between the PGs, which improves the extinction-ratio by a factor of four. Finally, we report results from a polymer-PG-based prototype projector with a commercial transmissive LC microdisplay with nearly twice the brightness of the comparable polarizer-based LCD system.

In the past, several alternative schemes [2-5] for polarizer-free modulation have been pursued, but with limited success, owing to fabrication challenges that manifest as low contrast ratios, limited acceptance angles, or low optical throughput. Our initial attempts with electrically switchable PGs [6-11] were successful in developing a polarizer-free LCOS based projection display [12] with high optical throughput and reasonable contrast ratios. However all of these techniques fundamentally require significant internal modification to conventional LC microdisplays. We recently introduced the concept of a polymer-PG display system [1] that is twice as bright as conventional polarizer-based displays. This technique presents a "snap-on" approach requiring little alteration to the projection system, and can be implemented with virtually *any* commercial LC microdisplay. The basic procedure involves replacing the conventional polarizers of the microdisplay with polymer-PGs, and this allows for easy integration with any "off the shelf" commercial product.

2. Polymer-PG Display
The basic modulation scheme is illustrated in Fig. 1. Ideally, the first PG splits input unpolarized light into just two first orders with orthogonal circular polarizations. In the example shown, the LC microdisplay then modulates the polarization state of diffracted orders. Depending on the state of the LC pixel, these beams are either diffracted even more by the second PG or redirected back to the normal direction as shown in Fig. 1a and Fig. 1b, respectively. We limit our discussion to this particular design, where two PGs are aligned in the anti-parallel configuration, but note that other implementations are possible.

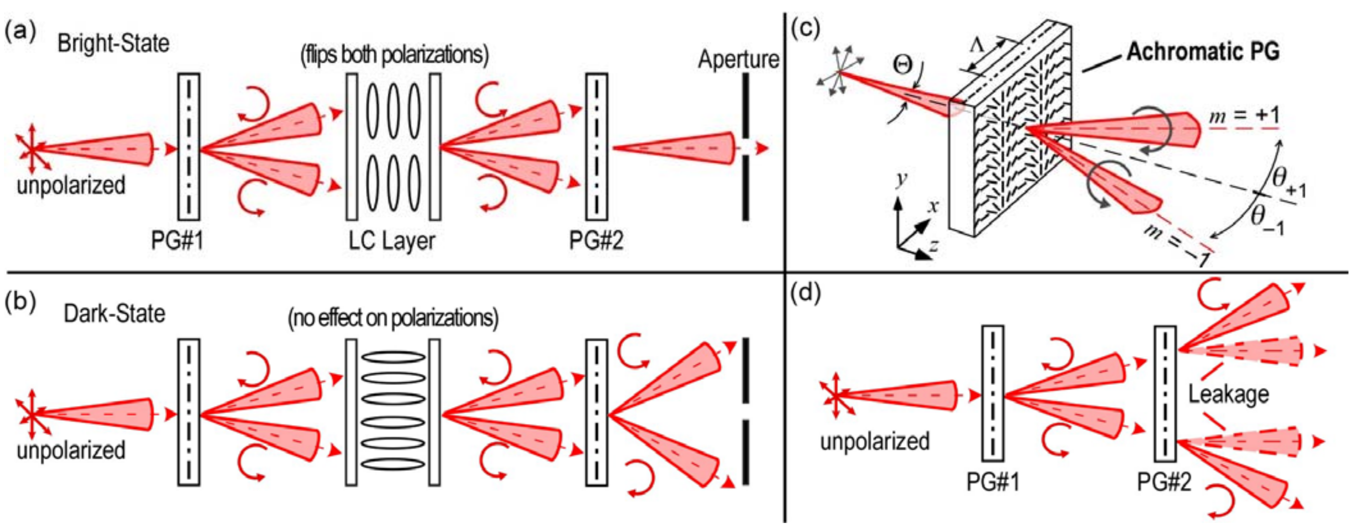

Figure 1 –Polymer-PG LC projector operation: (a) zero applied voltage, and (b) high voltage. (c) Small period achromatic PGs resolving the diverging light source. (d) Leakage into the redirected beam from anti-parallel PGs.

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In order to operate the polymer-PG display with standard étendue limited light sources the diffraction angle $\theta_{\pm 1}$ of PGs has to be at least as large as the divergence angle Θ of the light source ($\theta_{\pm 1}$>Θ, shown in Fig. 1c), which requires small period PGs followed by the grating equation ($\sin\theta_{\pm 1}=\lambda/\Lambda$, Λ is the grating period). By carefully understanding the relationships between material parameters [10, 11, 14, 15] and by optimizing fabrication processes, we have achieved high quality (efficient and low scattering) polymer-PGs with the grating period as small as 1.7 µm, that allow for divergence angles as large as ±15°.

To achieve modulation over the entire visible range for display applications, achromatic diffraction from polymer-PGs is required. Conventional PGs can diffract ~100% into the two (±) first orders near the center wavelength with a modest bandwidth [14, 16, 17]. We have identified an achromatic PG [13] that can diffract broadband light (i.e., most of the visible wavelengths) mainly into the two first-orders with orthogonal circular polarizations. Note that when input light is circularly polarized, it is diffracted into just one of the first-orders.

For anti-parallel PGs with small grating periods, however, there is leakage into the normal direction (Fig. 1d). In this work, we discuss a simple approach to reduce this leakage, leading to a dramatic improvement in the extinction-ratio of these polymer-PGs. As a result, higher contrasts are achieved with certain LC modes, which will be discussed in the next section.

3. Results

First we discuss our most recent results on achieving small period achromatic PGs (1.7 µm period). We fabricated defect-free achromatic PGs formed as a reactive mesogen (RM) film by polarization holography and photo-alignment techniques. We utilized a linear- photopolymerizable polymer [18] (LPP) LIA-01 (DIC, Japan) as the photo-alignment material. The PG pattern was recorded in the LPP layer by using orthogonal circular polarized beams from a HeCd laser (325 nm). Then two chiral RM layers with opposite twist senses were spin-coated on the LPP-coated substrate. The first layer was composed of RMS08-075 (Merck, Δn = 0.2 at 589 nm) with 0.54%-wt of chiral dopant CB15 (Merck, right-handed), chosen to achieve a twist of 70° for half-wave thickness ($\Delta nd = \lambda_0/2$, λ_0 = 530 nm). The second layer was deposited directly on top of the first, and consisted a small amount (0.34%-wt) of a different chiral agent ZLI-811 (Merck, left-handed), subject to the same thickness and −70° twist angle. A description of the fabrication process is described elsewhere [13, 19].

3.1 Extinction-Ratio Enhancement

The parallel and anti-parallel configurations of two achromatic PGs illustrated in Fig. 2a are directly analogous to parallel and crossed polarizers. Most importantly, note that the transmittance of parallel PGs is approximately double that of parallel polarizers (Fig. 2b). However, the raw extinction-ratio from anti-parallel PGs (at this small period) are significantly lower than expected and are limited to ≤ 100:1, as shown in Fig. 2c, mainly related to leakage illustrated in Fig. 1d. We have discovered that a fractional +*a*-plate placed immediately after the first PG can dramatically improve the extinction-ratio of anti-parallel PGs. The relative orientation of this Extinction-ratio Enhancement Film (EEF) is shown in Fig. 2a. We found that the best matched EEF has a retardation ~0.04λ, and it improves the peak extinction-ratio by nearly a factor of four (up to 400:1 versus 100:1, Fig. 2c). The EEF adjusts the polarization of the diffracted orders from the first PG to match the eigen-polarizations of the second grating, thus reducing the leakage into the redirected beam at the output, even at large diffraction angles. Although the retardation of this film may vary with the grating period, we find in general that such thin retardation films nearly always offer a significant enhancement.

3.2 Single Pixel Polymer-PG LCD Results

We demonstrate the polymer-PG displays for three common LC modes: Vertically Aligned (VA), d = 3.1 µm, MLC-6610 (Δn=0.1); Twisted Nematic (TN), d = 1.6 µm, MLC-6080 (Δn=0.2); and Electrically Compensated Birefringence (ECB), d = 2.7 µm, MDA-06-177 (Δn=0.15). In Fig. 3a, we show that the bright state transmittance of these single pixel displays is roughly double that of the conventional polarizer approach. The enhancement in extinction-ratio of the polymer-PGs directly impacts the electrical contrast ratios of the polymer-PG display system. Fig. 3b shows spectrum of the contrast ratios for the above samples measured at 5V. As expected, the best values are achieved with the VA-mode with a peak contrast of nearly 400:1 (limited by the extinction-ratio of these particular PGs). The TN and ECB modes manifest relatively poor contrast due to the absence of retardation compensation (RC) films. Note also that for

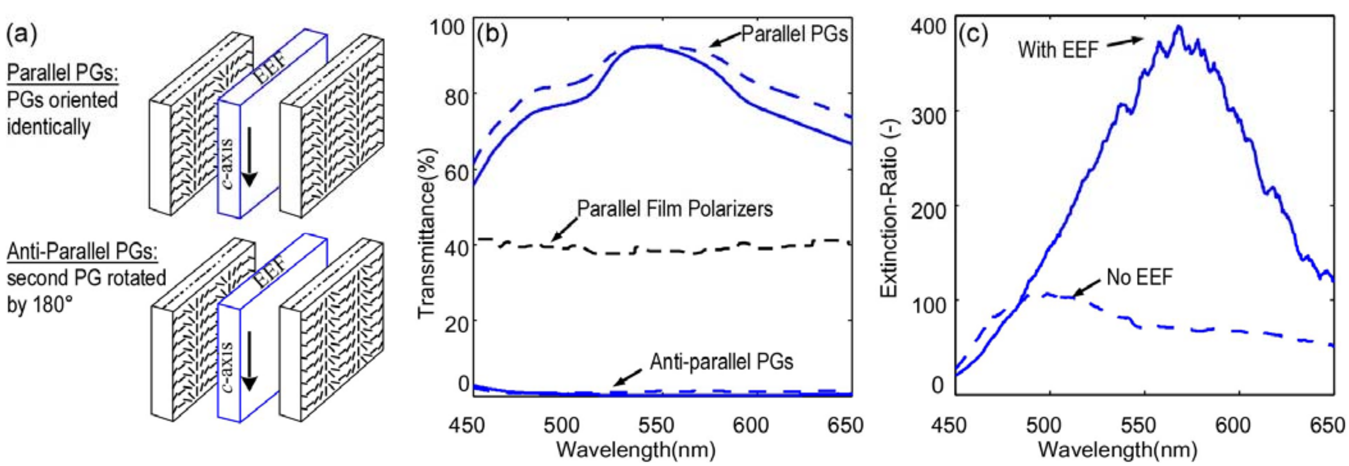

Figure 2 –(a) Anti-Parallel and parallel polymer-PG configurations. (b) Transmittance of anti-parallel and parallel PGs with and without EEF. and (c) Extinction-Ratio enhancement using the EEF.

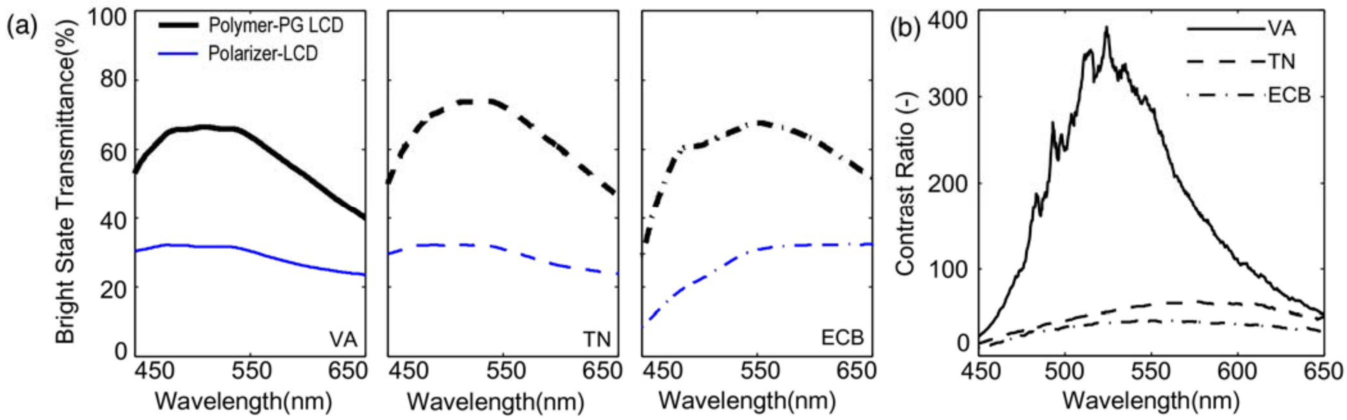

Figure 3 – (a) Bright State Transmittance comparison between polarizer-based and polymer-PG LCDs for different configurations. (b) Contrast ratio comparison for different LCD modes with polymer-PGs

the TN mode, two achromatic quarter-waveplates were added to generate linear polarization modes from the PGs.

3.3 Prototype Projector

To confirm the imaging properties of the polymer-PG display, we have built a prototype projector (Fig. 4a and 4b) using a commercial LC microdisplay panel (transmissive, 0.41" VGA, ECB mode) with our achromatic PG films. Fig. 4a illustrates a projection system that employs the polymer-PG LCD and a LED light source for color-sequential operation and Fig. 4b shows the actual picture of our prototype projector. The front assembly consists of the first PG and the EEF. As part of the rear assembly, we included a RC film (+*a*-plate) along with the second PG, which is aligned anti-parallel to the first PG. We also employ an Offset-Compensator (OC), composed of two additional parallel PGs, to remove the spatial offset due to the gap between the imaging plane and the second PG. To implement this system, we used a Golden-eye LED light source (supporting color-sequential operation) with a ±7° divergence angle at the microdisplay as shown in Fig. 4b. Angle filtering (lens and aperture) is used to block the higher orders. A simple projection lens is used to achieve a magnification of ~20, with a throw of ~2 ft.

A comparison (Fig. 4c) of images from the original polarizer-based display and the polymer-PG display shows nearly identical color saturation and excellent image focus, and more importantly the obvious brightness enhancement offered by our technology. The full-on transmittance values of the polymer-PG LCD (R: 28.4%, G: 34.3%, B: 30.3%) are about double the values of the unmodified polarizer-based LCD (R: 16.8%, G: 20.1%, B: 16.5%) for unpolarized LED input. This includes in both cases all losses within the display itself (e.g. electrode absorption, fill-factor blocking, interfaces), PGs, and polarizers. The contrast ratios of polymer-PG LCD (around 25:1 for all colors) are admittedly not nearly as high as the polarizer-based LCD (around 100:1 for all colors), which we feel is predominantly related to the sub-optimal retardation compensation film we fabricated for the polymer-PG Display. We continue pursuing schemes to compensate for the viewing angle response of microdisplays at large viewing angles

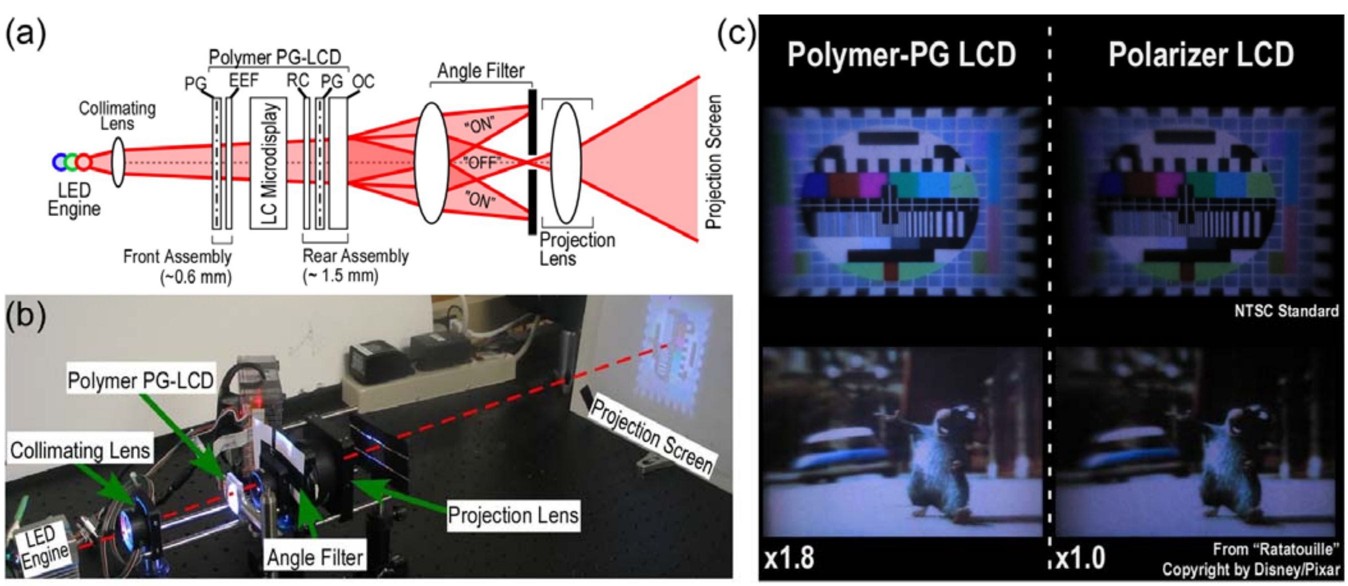

Figure 4 –Projection System geometry: (a) Illustration, and (b) Photo of constructed prototype. (c) Comparison of projected images from polymer-PG LCD and polarizer-based LCD, clearly showing brightness enhancement.

in order to improve this aspect of our system. In the current prototype, we have incorporated achromatic PGs with 1.7 µm that allows for this projection system to have the large acceptance angle of ~15°. With this configuration, we get several lm at the screen.

Note that we add the OC in order to eliminate the parallax in projected images (two images with spatial offset of dozens of pixels), which arises due to the distance (glass thickness) between the LC layer of the microdisplay and the second PG. The OC is formed by two parallel PGs with the same gap thickness as the glass after the second PG, which perfectly compensates for the offset, as Fig. 4c shows.

4. Conclusion

The Polymer-PG LCD is one of the most viable ways to achieve polarization independent modulation using commercial microdisplays. Just by replacing polarizers with PGs, almost x2 brightness enhancement is achieved. By carefully studying these PGs, we have demonstrated simple compensation films that dramatically enhance contrast ratios, which can be further enhanced by viewing angle compensators. We continue to strive for smaller grating periods that will allow for use with standard light sources with even larger divergence angles. These results are significant in context of achieving practical energy efficient portable projection displays.

5. Acknowledgements

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