Invited Paper

A High Throughput Liquid Crystal Light Shutter for Unpolarized Light using Polymer Polarization Gratings

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ABSTRACT

We report on a broadband, diffractive, light shutter with the ability to modulate unpolarized light. This polarizer-free approach employs a conventional liquid crystal (LC) switch, combined with broadband Polarization Gratings (PGs) formed with polymer LC materials. The thin-film PGs act as diffractive polarizing beam-splitters, while the LC switch operates on both orthogonal polarization states simultaneously. As an initial experimental proof-of-concept for unpolarized light with $\pm 7^{\circ}$ aperture, we utilize a commercial twisted-nematic LC switch and our own polymer PGs to achieve a peak transmittance of 80% and peak contrast ratio of 230:1. We characterize the optoelectronic performance, discuss the limitations, and evaluate its use in potential nonmechanical shutter applications (imaging and non-imaging).

Keywords: polarization grating, diffraction, modulator, variable optical attenuator, shutter, imaging, liquid crystal

1. INTRODUCTION

Liquid Crystal (LC) materials have enabled several modern day appliances including digital wrist watches, pocket calculators, cell phones, flat panel displays, etc. The concept of aligning LCs between absorbing thin film polarizers[1,2] is the most popular way to utilize the electro-optical properties of these materials. Although this method offers several advantageous features, it has one major disadvantage that we address here: high optical losses ($\geq 50\%$) in the transmissive-state when the light source is unpolarized. In some applications,[3,4] conversion of unpolarized light to partially polarized light polarization is possible, but in other applications unusable or still inefficient.

Several alternatives offer inherently polarization-independent optical switching by modulating the propagation direction of light instead of polarization, which therefore establishes the direction of the viewer, projection optics, or detector as crucial. Most widely studied are techniques with electrically-controlled scattering in polymer dispersions,[5–10] where one extreme optical state is transparent while the other extreme is highly scattering, sending light into approximately all angles of the hemisphere (forward, rear, or both). But such devices suffer from one or more issues: high operating voltages, long switching times, complex processing, or only modest maximum transmittance. Diffractive LC switches formed as binary patterns of bulk LCs[11,12] or holographic LC/polymer dispersions[13–16] instead scatter light into well-controlled directions. However, these have had limited success due to difficulty in commercial-scale fabrication, low contrast ratios, low spectral bandwidth, and in some cases, high operating voltages.

Recently, several researchers have studied a novel diffractive optical element called a Polarization Grating (PG),[17–20] formed with polarization holography and LC materials. These have several compelling properties in both theory and experiment including a periodic continuous profile which is fairly easily recorded using photo-alignment materials over large areas, that leads to high diffraction efficiencies ($> 95\%$) into just two diffracted orders, large polarization sensitivity ($> 3000:1$ polarization contrast), and broadband[21] functionality (demonstrated bandwidths ≈200 nm in the visible range), among others. As a result, PG technology is being developed for diverse applications, including beam steering,[22] tunable optical filters,[23] variable optical attenuators,[24] orbital-angular-momentum elements,[25] and polarimetric imaging,[26] among others. Additionally switchable PGs were demonstrated as diffractive switches using conventional nematic LCs. These were originally

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envisioned to modulate unpolarized light, in both transmissive[27,28] or reflective configurations.[19,29] However, these were limited by their narrowband spectrum (suitable for a single LED color or laser), and relative difficulty in achieving large diffraction angles due to materials constraints.[30]

In 2008, we described how[31,32] to use broadband polymer PGs[21] in combination with conventional LC modes to modulate unpolarized light in display applications. The polymer PGs selectively direct the diffracted orders whose polarization states are modulated by the active LC switch. This technique combines the diffractive properties of PGs, and polarization manipulation capabilities of ordinary LC modes to modulate both orthogonal polarizations simultaneously thus achieving high throughput and contrast ratios. While the PGs can be designed to be extremely efficient polarizing beam splitters for the desired wavelength range, the LC mode can be optimized for polarization handling, and switching properties. This distinction between diffractive and switching functions offers additional degrees of freedom in design which can be used to overcome many limitations of prior approaches. With substantial improvements in both PG fabrication and polarization management, we report here on a diffractive shutter that provides both high throughput and contrast ratio for unpolarized input light, that has strong potential for various applications.

2. POLYMER PG SHUTTER CONCEPT AND OPERATION

The polymer PG shutter utilizes the polarization-sensitive diffractive properties of PGs to direct two orthogonal polarizations through a conventional polarization modulator, along with angular discrimination of the output. It operates on unpolarized light equally well as polarized, which results in roughly twice the brightness for unpolarized light compared to a polarizer-based shutter. The PG shutter depends on both the broadband nature of the thin-film PGs for the polarizing/analyzing function, and the broadband opto-electronic function of the polarization modulator (which may be entirely off-the-shelf LC cells, among other technologies).

2.1 Polarizing and Analyzing With Polymer PGs

The essence of this modulation scheme is illustrated in Fig. 1, for a ray that is normally incident. This may be most directly understood from two extreme configurations. The shutter manifests a maximum transmittance, analogous to parallel polarizers, when two identical PGs are arranged in parallel configuration (Fig. 1(a), with their periodic birefringence profile oriented in exactly the same way). Light input close to the normal direction is polarized by PG_1 into two orthogonal circularly polarized beams which deviate from the input direction by an angle $\pm\theta_1$, according to the classic grating equation

$$\sin\theta_1 = \lambda/\Lambda + \sin\theta_{in} \tag{1}$$

where λ is the wavelength, Λ is the grating period, and θ_{in} is the incident angle. These two beams are returned by PG_2 to the original input angle (θ_{in}), and can be transmitted through the rest of the optical system or toward the viewer. Conversely, the shutter manifests a minimum transmittance, analogous to crossed polarizers, when PG_2 is arranged in an antiparallel configuration (Fig. 1(b), where PG_2 is rotated by 180° compared to PG_1). In this situation, the beams from PG_1 are redirected by PG_2 into larger angles that are more off-axis (ie, $\pm\sin^{-1}(2\lambda/\Lambda + \sin\theta_{in})$), and blocked by angle-discriminating optics after this shutter.

Before discussing the use of the LC switch, it is important to note an artifact in the transmissive-state just described (Fig. 1(a)). While both orthogonal polarizations are transmitted at identical output angles, the rays of each are spatially offset by a significant amount (easily several mm). Any scene viewed through this arrangement would be seen with a "double image", as previously documented,[18] which also manifests significant chromatic dispersion, as utilized in a prior imaging spectropolarimeter.[26] In most imaging applications, this would be catastrophic.

However, a simple and effective solution is possible: add a third grating (PG_3), and reduce the grating period of PG_2 slightly, so that the following relation is maintained:

$$\frac{1}{\Lambda_1} = \frac{1}{\Lambda_2} - \frac{1}{\Lambda_3}. \tag{2}$$

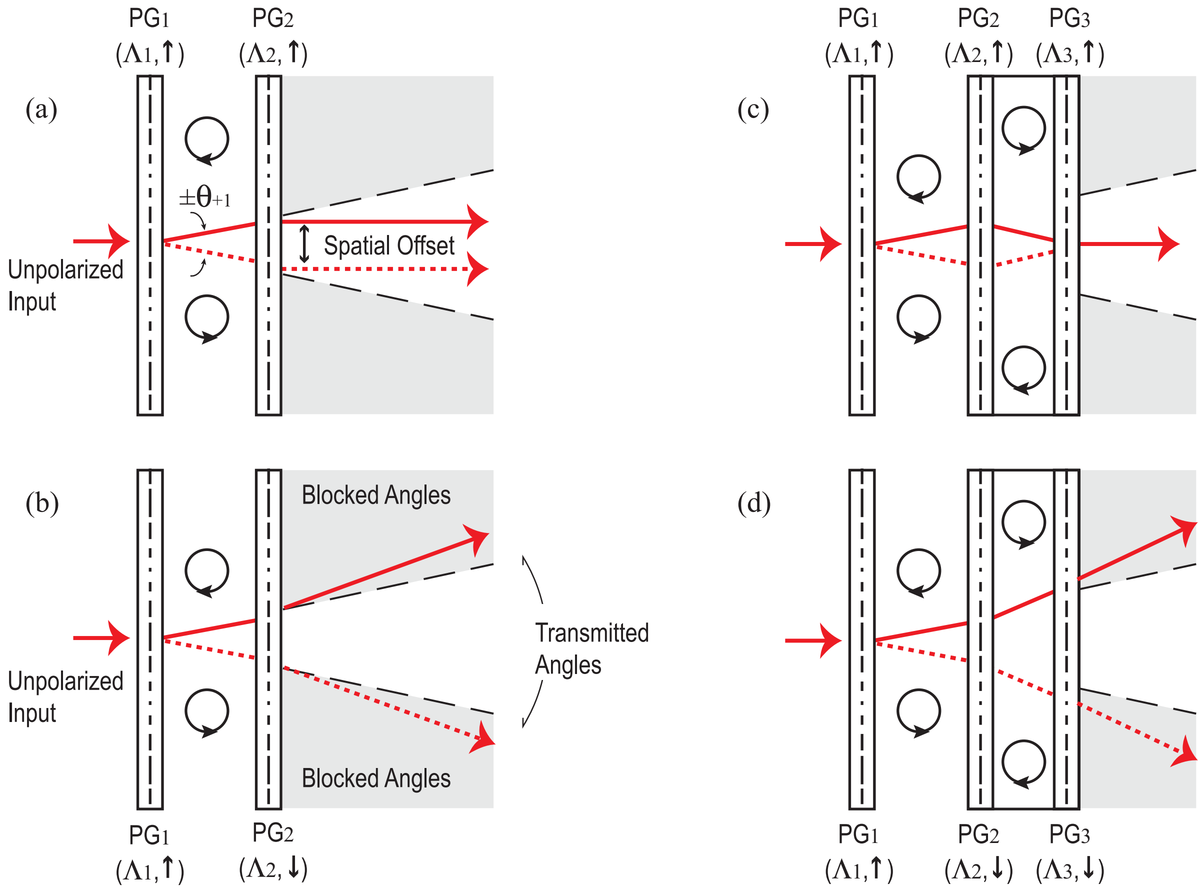

Figure 1. Illustration of light propagating through two ((a) and (b)) and three ((c) and (d)) polarization gratings (PGs). Arrangement (a) shows parallel PGs with correct output angles but with unwanted spatial offset; (c) shows this corrected by the addition of a third PG, manifesting an image-preserving transmissive-state. Both (b) and (d) show antiparallel PGs where light is directed significantly off axis, the blocking-state.

Illustrated in Fig. 1(c), the spatial offset is eliminated because PG_2 over-deflects both beams, and PG_3 is positioned at exactly the position where the two images coincide in order to return both beams to the original incident angle. In this way, both the position and angle of every ray entering this shutter is maintained in the transmissive-state.

2.2 Opto-electronic Modulation With Polymer PGs and LC Switch

Note that PG_2 (or the combination PG_2 and PG_3) essentially acts as an analyzer that selectively redirects the light from PG_1. While the discussion above described rotating the later gratings with respect to the first, this same analyzing function can occur when the polarization is modified by an element in between PG_1 and PG_2. That is, in either configuration (parallel or antiparallel), the amount of light output in the on-axis or off-axis directions can be controlled by affecting the polarization states coming out of PG_1. This is, of course, similar to the classic shutter based on polarizers, where a polarization-modifying element (eg, LC cell) placed between either parallel or crossed polarizers achieves continuous opto-electronic modulation. But the crucial difference and advantage, however, is that in the PG shutter *all* polarizations are directed through the entire device, and acted upon *simultaneously* by the same polarization-modifying element.

Any polarization-modifying element may be placed between the PGs to accomplish the opto-electronic modulation. For this discussion and our experiment discussed later, we will employ a twisted-nematic (TN) LC cell[1,2] as a representative case. This has the function that for one extreme state (0 V) it causes optical rotation of linearly polarized light by 90°, and for the other extreme state (10 V) it allows light to pass through without

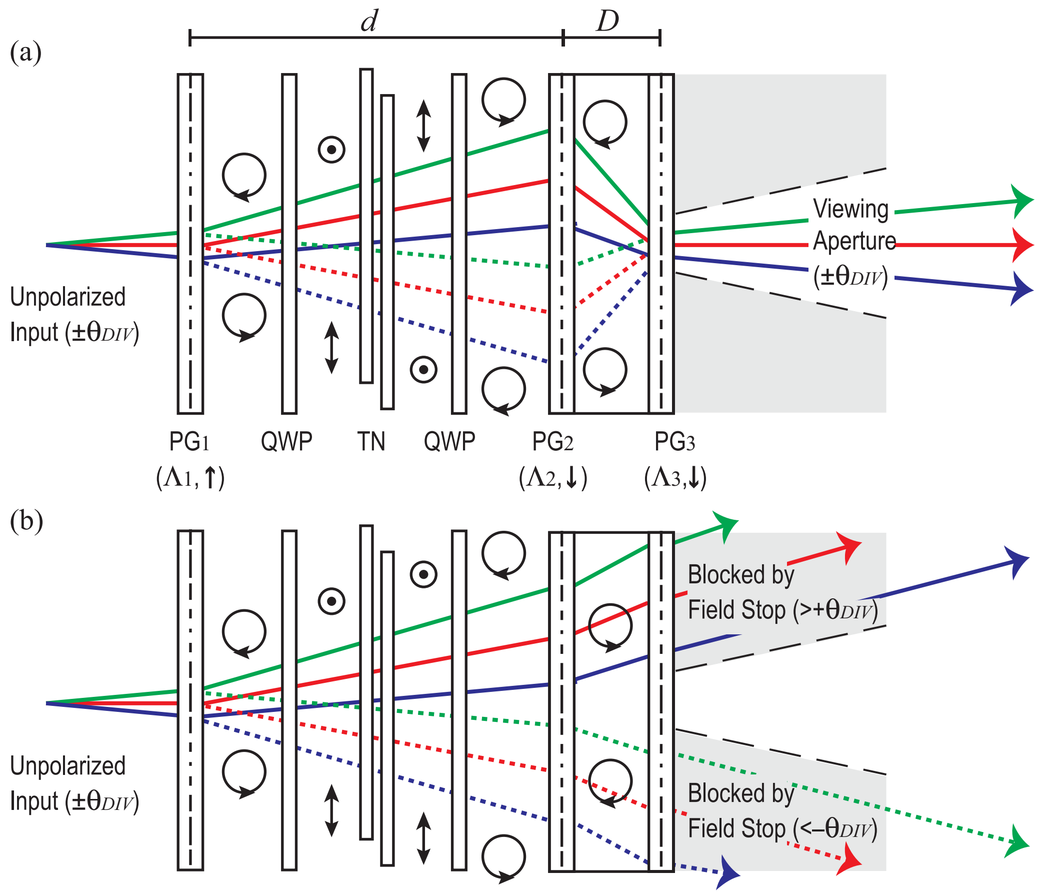

Figure 2. Illustration of light propagating through the PG shutter: (a) transmissive-state at zero applied voltage, and (b) blocking-state when sufficiently high voltage is applied.

changing its polarization. Since the TN operates best on horizontal and linear linear polarization states, we add achromatic Quarter-Wave Plates (QWP) on either side of the TN to convert from and to the circular polarization states of the PGs.

The path and polarization of light in the transmissive and blocking-states of the shutter is illustrated in Fig.2. Consider three rays emitting within the angle cone $\pm\theta_{DIV}$ from the same location input into the shutter (shown with false colors in Fig. 2(a)). These rays are split by PG_1 into orthogonal circularly polarized beams as before. Because the combination of QWP-TN(0V)-QWP reverses the handedness of these beams, the combination of PG_2 and PG_3 return these rays back together to have the same location and direction as at the input. This is the transmissive-state, and the shutter would appear largely transparent when voltage is not applied.

Fig. 2(b) illustrates the opposite case. When a sufficiently high voltage is applied (eg, 10 V) to the LC switch, then the QWP-TN(10V)-QWP transmits the beams from PG_1 without affecting their polarization, and the combination of PG_2 and PG_3 deflect the beams to higher angles. This is the blocking-state, as long as the rest of the optical system ensures that rays with $> +\theta_{DIV}$ and $< -\theta_{DIV}$ are blocked. Note that all continuous gray levels in between these transmissive and blocking states are accessible when intermediate voltages are applied to the TN, as some light gets directed on-axis and some off-axis.

2.3 Additional Design Constraints

We have identified the use of three PGs to preserve the transmitted image through this shutter, but we have not yet addressed their required relative positions in the stack. Two distances are important in this regard (both defined in Fig. 2(a)): the distance d between the film surfaces of PG_1 and PG_2, and the distance D between the film surfaces of PG_2 and PG_3. If we assume that the glass, LC, and QWP all have the same refractive index n (which is approximately true), then the following relation must be true in order to avoid a double image:

$$d \tan\left(n^{-1} \sin^{-1} \frac{\lambda}{\Lambda_1}\right) = D \tan\left(n^{-1} \sin^{-1} \frac{\lambda}{\Lambda_3}\right) \tag{3}$$

Note also that Eq. (2) also implies that $\Lambda_2 < \Lambda_1 < \Lambda_3$.

Finally, we must comment on the design choice of Λ_1, which has a direct impact on the contrast ratio. If the input and output angular apertures of the shutter are $\pm\theta_{DIV}$, then it should be self-evident that the only way for the blocking-state of Fig. 2(b) to manifest is if the output rays are larger in magnitude than θ_{DIV}. This only occurs when the diffraction of the smallest wavelength of interest (λ_{min}) obeys $(\sin\theta_{DIV})/2 \leq \lambda_{min}/\Lambda_1$, which serves as an upper bound on Λ_1. In addition, a lower bound exists on Λ_1 that arises because of the zero-order leakage of each PG (light transmitted directly through the film without being diffracted into the first orders). In the above discussion we neglected this, but in reality there is always some (often small) non-zero leakage which depends non-linearly on λ, Λ, PG birefringence Δn, and incidence angle.[33] For all grating periods such that $\sin\theta_{DIV} \leq \lambda_{min}/\Lambda_1$, this leakage is completely prevented from entering into the output aperture. Note that there is no additional benefit to be obtained by exceeding this condition, and indeed several drawbacks to choosing the grating period too small, so we set the equal sign on this boundary as the lower bound. By combining these two conditions, we can express the choice of Λ_1 as follows:

$$\frac{\lambda_{min}}{\sin\theta_{DIV}} \leq \Lambda_1 \leq \frac{2\lambda_{min}}{\sin\theta_{DIV}} \tag{4}$$

where the lower limit enables higher contrast (with smaller aperture) with smaller grating periods, and the upper limit enables a larger aperture (with modest contrast) facilitated by larger grating periods. In the experiment below, we choose Λ_1 to be roughly in the middle of these two extremes.

Eqs. (2) through (4) therefore allow for the design of the polymer PG shutter. In most circumstances, several given parameters (eg, θ_{DIV}, λ_{min}, d) would be used to choose the remaining parameters (eg, Λ_1, Λ_2, Λ_3, D).

This concept utilizes the polarization modulation properties of ordinary LC modes in combination with polymer PGs to create an efficient diffractive switch. This operates on all polarizations simultaneously, and therefore performs similarly for unpolarized and polarized inputs - quite unlike polarizer-based approaches. In Section 3, we describe the construction of the prototype polymer PG shutter, and in Section 4 we report its behavior as a broadband shutter within visible wavelengths.

3. EXPERIMENT

For the experimental prototype described here, we choose the input and output aperture as $\pm 7°$ (ie, $f/4$), substrates of 1 inch sq, and active area of roughly 2 cm diameter. In order to design the shutter for a broadband wavelength range, the constraint imposed by Eq. (4) was applied. For the visible wavelength range of 450 - 650 nm, we choose $\Lambda_1 = 2.58$ μm. We employed a commercial TN switch (ColorLink Japan, Ltd), with a twist angle of 90°, voltage threshold of ∼0.8 V, and total (rise+off) switching time of 28 ms (10 V). For the achromatic QWP, we used commercial films (ColorLink Japan, Ltd) which were laminated on glass substrates using optical adhesive (Norland).

The substrates of TN, the QWP films, and any additional substrates in between the first two PGs contribute to the distance d, which in this case resulted in $d = 2.22$ mm. Since we had little constraint on the total thickness of our prototype, we choose a relatively large value of ≤ 2 cm, which led to $\Lambda_2 = 2.2$ μm and $\Lambda_3 = 17.5$ μm. Note that even when a smaller device thickness (eg, 5 mm total) is used, our analysis suggests that the results would be largely similar to those reported here.

The reactive mesogen prepolymer mixture RMS09-025 was used to form the two smaller PGs (Λ_1 and Λ_2), with $\Delta n \sim 0.33$ at 589 nm. For Λ_3, we employed a different material RMS10-025 with $\Delta n \sim 0.16$. In addition, chiral materials CB-15 (right-handed) and MLC-6247 (left-handed) were mixed in appropriate quantities with

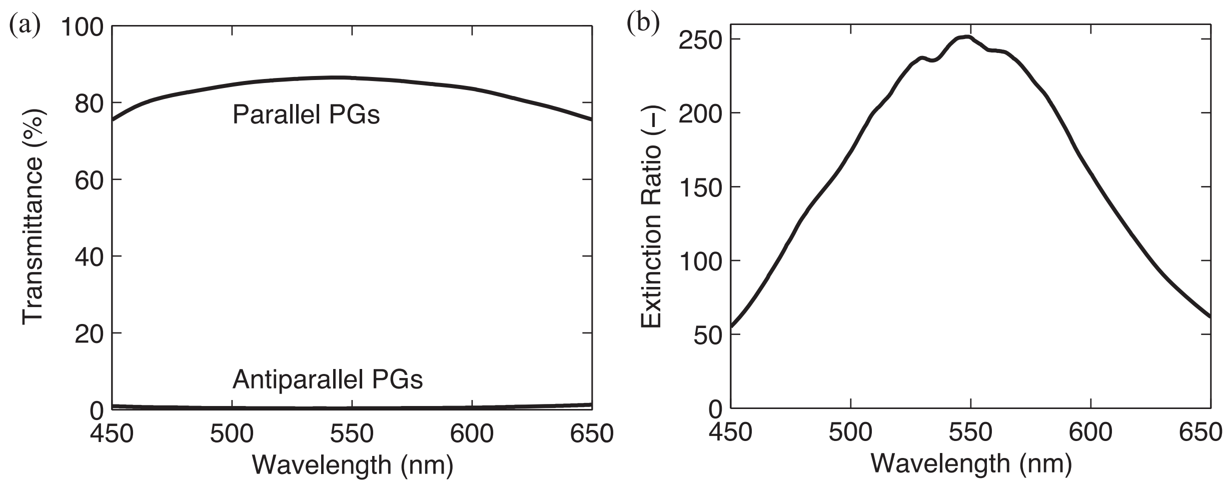

Figure 3. Measured transmittance from parallel and antiparallel PGs, with two QWP but no TN: (a) raw transmittance of the two configurations, and (b) extinction ratio (defined as the ratio of the transmittances in part (a)). Input light was unpolarized and within ±7°.

both of these LC materials to achieve broadband operation over the visible range.[21] All RMS, CB and MLC aforementioned materials were obtained from Merck Chemicals Ltd (ie, EMD Chemicals). The PG profiles were recorded using a He-Cd laser (325 nm, 5 J/cm^2) in the photo-alignment material LIA-CO01 (DIC Japan, Ltd) using polarization holography. More fabrication details can be found elsewhere.[20,21]

4. RESULTS

4.1 Extinction Ratio and Maximum Throughput

We measured the parallel and antiparallel transmittance of the three polymer PGs with the two QWP for ±7° input and output apertures, with a custom spectrophotometer. For this measurement, we added anti-reflection (BBAR) substrates on the outer faces, and used index matching fluid in between the elements. The result is shown in Fig. 3, where the peak transmittance was 87% and peak extinction ratio reached 250:1 near 550 nm. This represents the best that the shutter can achieve when the TN is added, and is analogous to parallel and crossed polarizers, respectively. Note that the brightness is limited mainly because the peak diffraction efficiency of each PG was 96-98% in the green with a lower value in the red and blue, and the extinction was limited for the converse reason (the non-zero zero-order leakage of each PG). Absorption of the polymer PG layers, QWP, glue layers, and substrates is negligible at these wavelengths. Further improvements in the PGs themselves will be required to improve these values.

4.2 Contrast Ratio and Brightness

When the TN switch is added to the three PGs and two QWPs, along with anti-reflection glass on the outer faces and optical adhesive in between the elements, the full PG shutter illustrated in Fig. 2 was completed. Again for an aperture of ±7°, we measured the transmittance of the transmissive (0 V) and blocking (10 V) states. The result is shown in Fig. 4, where the peak transmittance was 80% and peak contrast ratio was 230:1 near 550 nm. The contrast ratio was above 100:1 from roughly 460-615 nm. Both the peak contrast and the range of moderately high contrast are notably higher than any LC scattering based approaches.[5–9]

While these numbers clearly prove the function of this type of shutter, it is notable that the peak transmittance is only 80%. To examine the losses in our prototype, we also measured the raw transmittance of the TN switch alone (with anti-reflection glass index-coupled to on both faces). This is shown in Fig. 4(a), and reveals that roughly 5% of the loss comes from this. The remaining 15-20% seems to be largely related to the aforementioned 96% first-order efficiency of the PGs. However, we should note that a third cause is also possible, which may account for a few percent loss: the slightly imperfect polarization conversion of the TN in the 0 V state combined

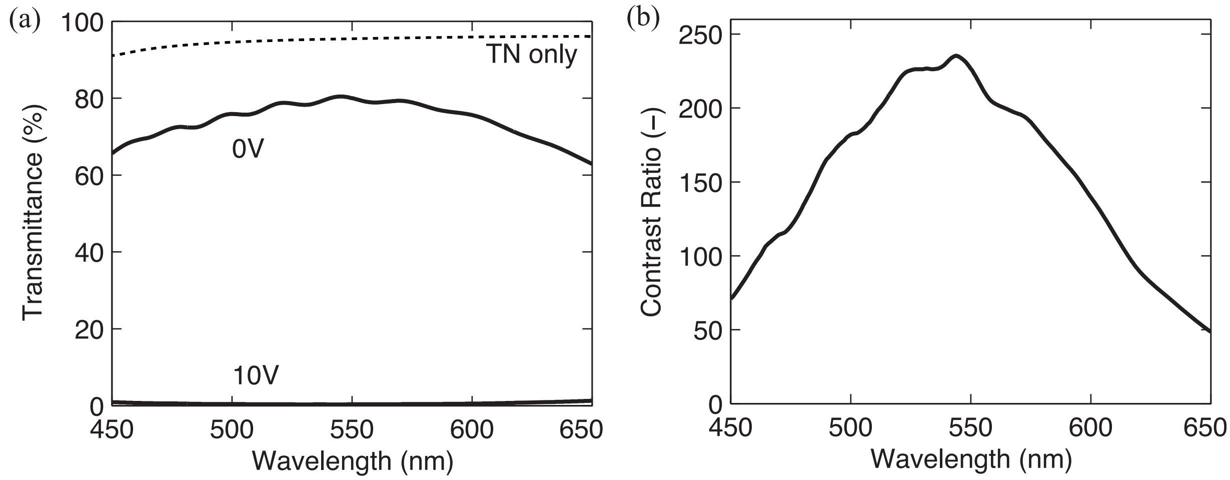

Figure 4. Measured transmittance of the full PG shutter (Fig. 2), with the TN switch added: (a) raw transmittance of the transmissive (0 V) and blocking (10 V) states, and (b) contrast ratio (defined as the ratio of the transmittances in part (a)). Input light was unpolarized and within ±7°.

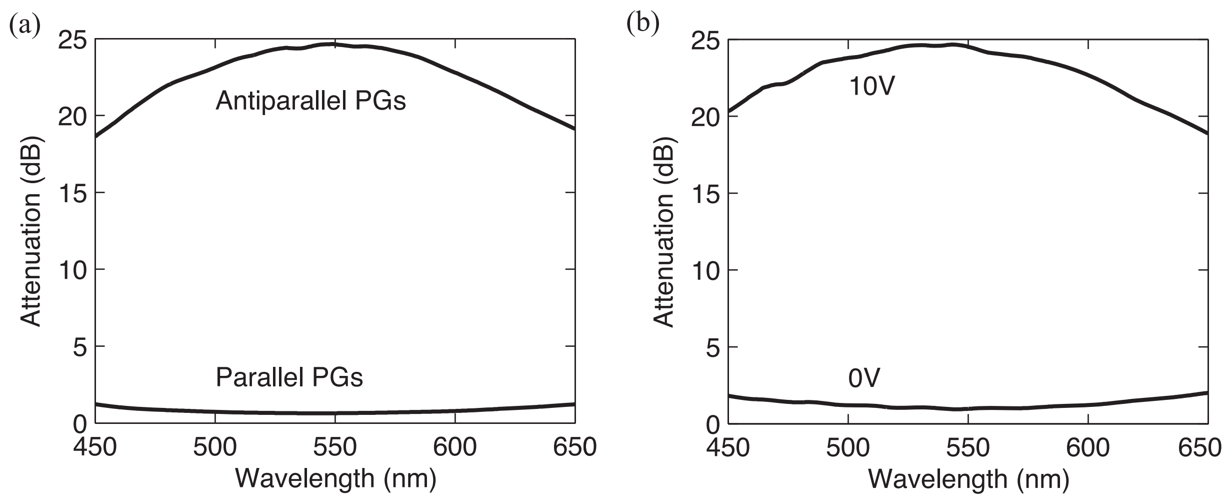

Figure 5. Measured attenuation of the (a) PGs and QWPs, and (b) full PG shutter. Data is the same as that in Fig. 3(a) and 4(a) but graphed in dB.

with slight misalignments in the QWPs. All of these losses can be improved, but would be the focus of later work.

Another way to examine the performance of the shutter is from the point of view of attenuation. In Fig. 4.2, we show the attenuation for the PGs (without the TN) and for the full PG shutter (with the TN). The maximum attenuation was nearly 25 dB, with an insertion loss as low as 1 dB. Of course, values in between these two extremes are also accessible by applying voltages to the TN less than 10 V.

4.3 Imaging

To demonstrate the image-preserving capability of the light shutter, we devised a simple experimental setup shown in Fig. 6(a) and 6(b). A cathode-ray-tube (CRT) monitor producing unpolarized images was used as the light source. The distance between the monitor and the light shutter was adjusted such that the acceptance angle within its active area was close to ±7° along the grating direction. A digital camera was placed behind the shutter in a similar way to accept the same set of angles.

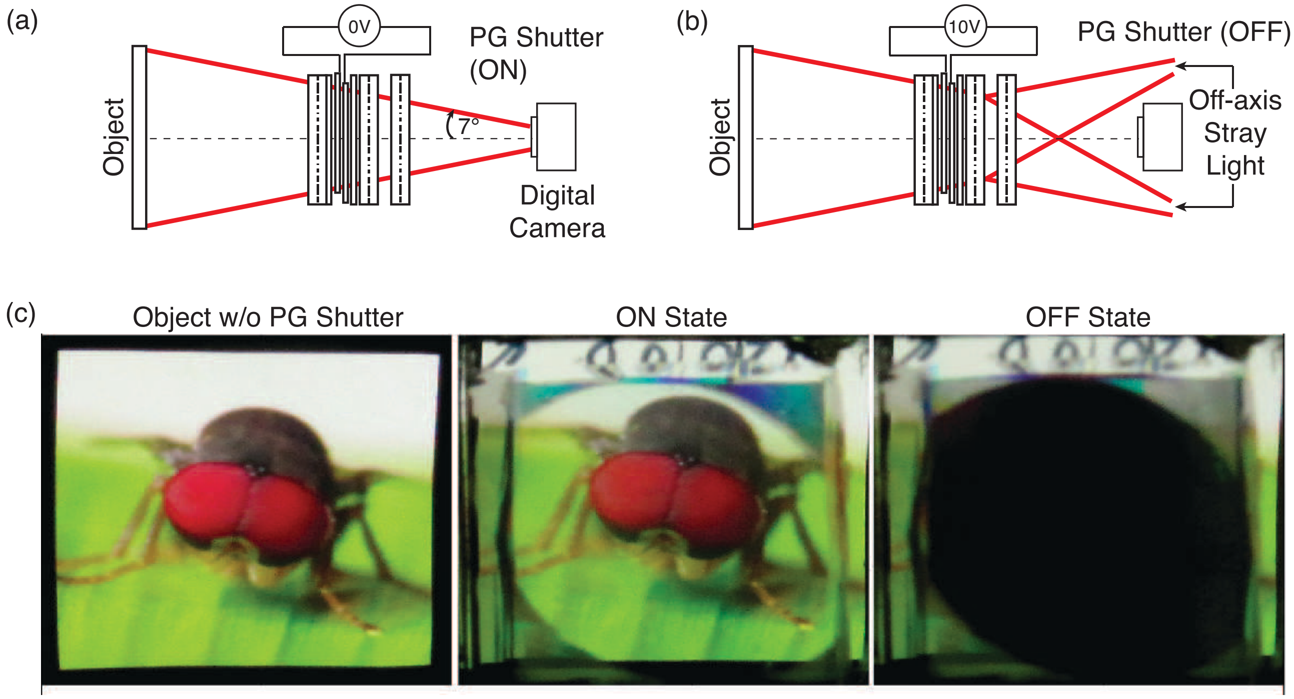

Figure 6. Measured images through the PG shutter, where in all cases, an unpolarized broadband object scene was created by a CRT monitor and limited to $\pm 7°$ aperture: illustration of measurement and light propagation for the (a) transmissive or ON state and (b) blocking or OFF state. (c) Several images are shown of the (*left*) original image observed by the camera without the shutter, and the image observed through the (*center*) transmissive-state and the (*right*) blocking-state of the shutter.

In Fig.6(c), we show the original image captured by the camera without the PG, along with the image captured when the shutter is in its transmissive and blocking-states. Most notably, the original image (left) and the image through the active area of the PG shutter in its transmissive (ON) state (center) are extremely similar, without obvious image artifacts. There is no observable spatial offset, which indicates that the chosen values of the grating periods and the relative distances matched our expected calculations. The color is also largely preserved. In the blocking (OFF) state, the shutter diffracts most of the light off-axis and is not captured by the camera, as observed by the dark active area (right).

Overall the light shutter performs as expected and confirms the performance measured in the previous section.

5. CONCLUSION

The polymer PG light shutter described here utilizes the polarization-sensitive diffractive properties of PGs to direct two orthogonal polarizations through a conventional polarization modulator, along with angular discrimination of the output. It operates on unpolarized light equally well as polarized, which results in roughly twice the brightness for unpolarized light compared to a polarizer-based shutter. We demonstrate 80% peak transmittance and 230:1 peak contrast ratio, for a PG shutter designed for $\pm 7°$ angular aperture, and which employs a commercial TN LC cell. Further improvements are anticipated in performance as PG diffraction spectra is improved, and larger angular apertures are possible primarily by adjusting the grating periods. The PG shutter depends on both the broadband nature of the thin-film PGs for the polarizing/analyzing function, and the broadband opto-electronic function of the polarization modulator (which may be entirely off-the-shelf LC cells, among other technologies). We expect this nonmechanical shutter to be explicitly useful to many applications where robust, low-power, compact, fast, and efficient modulation of unpolarized light is needed, including cameras, goggles, scopes, and various optical remote sensors.

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