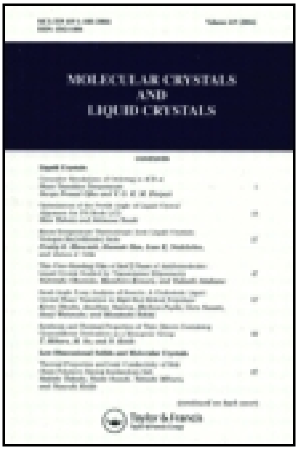

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Reflective Display Configurations Based on Total Internal Reflection and Grating-Grating Coupling of Holographic Polymer Dispersed Liquid Crystals (H-PDLC)

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We report on a novel electro-optical reflective configuration based on total internal reflection and grating-grating coupling fabricated in Holographic Polymer Dispersed Liquid Crystals (H-PDLC) materials. In this device, two symmetric slanted gratings are temporally multiplexed into a single film. A narrowband light is selected and diffracted from two coupled Bragg gratings creating a reflected image. These reflective configurations have switching voltages that are at least one-half that of H-PDLC reflective displays reported in the literature, and therefore have potential as low power, reflective display devices.

Keywords: display; HPDLC; liquid crystal; total internal reflection (TIR)

1. INTRODUCTION

Holographic-polymer dispersed liquid crystal (H-PDLCs) films are stratified composite materials composed of alternating liquid crystal rich and polymer rich planes [1–3]. H-PDLCs are created through a holographic exposure technique that photo-induces a counter-diffusion

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process [4]. When a homogeneous mixture of prepolymer, liquid crystal and photoinitiator is exposed to an interference pattern, a counter-diffusion process is set-up where the prepolymer polymerizes and diffuses to the high intensity regions of the interference pattern thereby forcing out the non-reactive liquid crystal to the low intensity region of the interference pattern. The polymerization locks-in the stratified structure indefinitely leaving a periodic index modulation in the film [1]. H-PDLCs having a pitch of ~150–250 nm can efficiently reflect visible light making them good candidates for reflective display applications [5]. By applying an electric field, the index modulation can be switched off in ~100 μs. These films are attractive for use in displays due to their high color purity, high efficiency and low cost [6]. Additionally, H-PDLC materials have been considered for use in projection display applications [7], digital camera applications [8], telecommunication applications [9], optical strain gauges [10], lasing [11,12] and photonic crystals [13–16].

Because of their potentially rich application space, there have also been a number of materials efforts focused on improving the electro-optic performance parameters [17–19]. DeSarkar and coworkers show three very different polymer morphologies, which can be droplet-like, the intermediate scaffolding morphology or pure channel-like structures [17]. Similar to H-PDLCs, polymer liquid-crystal polymer (POLYCRIPS) gratings also show channel-like structures in transmission grating modes [20–23].

Focusing in on the reflective display application, the benefits using H-PDLCs are not without their shortcomings. The reflection wavelength of an H-PDLC is limited by the wavelength of the recording beams. Since the recording laser is typically in the green or blue-green regime when using Ar^+ (488 nm) or Nd:Y (532 nm) laser technology, it is difficult to write holograms to reflect light in the deep blue regime (< 460 nm). Additionally, in order to achieve high efficiency, a high powered laser is required to create very small liquid crystal droplets in the liquid crystal rich layers [5]. Such small droplets require a relatively high driving voltage to switch the displays. The typical size of liquid crystal droplets are ~ 100 nm, and the switching voltage is typically >20 V/μm [24]. For a 5 μm cell, driving voltages typically exceed 100 volts in most cases.

In this contribution, we demonstrate a reflection-type display configuration based on two time sequentially recorded, superimposed, slanted H-PDLC gratings operating on the total internal reflection (TIR) mode [25] and grating-grating coupling as shown in Figure 1. When illuminated with a broadband light source, a narrowband peak is selectively diffracted by a slanted grating. This grating is slanted

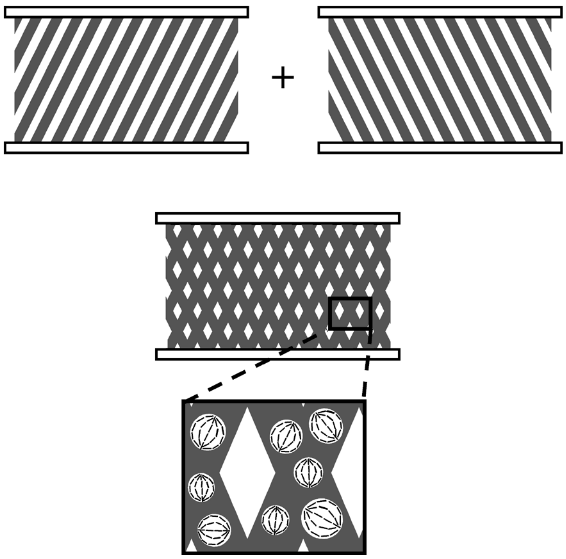

FIGURE 1 Two slanted H-PDLC grating operating on TIR mode can be superimposed in order to create a TIR grating that reflects selected wavelengths of normally incident light.

such that the diffracted beam is totally reflected off the air-glass interfaces. The reflected beam is coupled to the second TIR grating, which is identical and symmetric to the first TIR grating. Effectively this device can selectively reflect normally incident light at some specific wavelength of light. The reflection wavelength is not limited by that of the recording laser and full color displays can be fabricated using one laser. Since the holographic planes and the liquid crystal droplets are larger than conventional H-PDLC materials used in reflective displays for the same reflective regime, this unique configuration can also reduce the driving voltage by at least a factor of two.

2. EXPERIMENTS

2.1. Materials

The H-PDLC device was fabricated using a homogeneous mixture of multifunctional photopolymerizable pre-polymer and liquid crystal. The pre-polymer we used was prepared under dark room conditions and consisted of hexafunctional acrylate oligomer Ebecryl 8301 (UCB Radcure Chemicals) and epoxy NOA 72 (Norland) with mass ratio 4:1. The addition of the NOA epoxy is known to reduce the switching voltage of the resulting H-PDLCs [26]. These monomers were mixed with the nematic liquid crystal BL038 ($n_e = 1.799$, $n_o = 1.527$, $\Delta\varepsilon = +16.4$, EM Industries). A photoinitiator solution was prepared by mixing 3% Rose Bengal (RB), 7% *n*-phenylglycine (NPG) and 90% 1-vinyl-2-pyrrolidone (NVP), all of which are available from Sigma-Aldrich, Inc. Sorbitan mono-oleate, a surfactant from Chem Services, was also added in order to reduce the switching voltage [27]. The mass ratio of monomer, LC, photoinitiator solution and surfactant is 41:34:15:10. A droplet of homogeneous mixture was sandwiched between two glass substrates coated with transparent ITO electrodes. The thickness of the sample was controlled with 5 μm fiber spacers. There are several types of H-PDLC formulations which have been reported, all with the common components RB, NPG, and NVP [28–30].

2.2. Experimental Setup

The H-PDLC cells were exposed to 532 nm laser light with each beam having an intensity of approximately 400 mW/cm^2. Since the polymerization rate of NOA 72 is relatively slow, a high beam intensity was required in order to produce small liquid crystal droplets. The holographic apparatus is schematically illustrated in Figure 2(a). A coupling prism was used to achieve the desired incident angles. The use of a second prism avoids the trapping of the incident beam due to TIR on the glass substrates. A thin coating of xylene was used as a contact liquid between the glass substrates and the prism to match the refractive index of the optical components. The angle between two incident beams (outside of the prism) was $\sim 47^\circ$, and the slanted angle is designed to be 23°. Therefore, the Bragg diffracted beam through the resulting gratings had an incident angle of $\sim 46^\circ$ on the glass-air interface, which is beyond the TIR angle ($\theta_c = \sin^{-1}(1/n_{\text{glass}}) \sim 42^\circ$).

A temporal multiplexing technique was used to achieve a reflection-type pixel by creating two identical and symmetric TIR gratings [31]. This technique is expected to form two slanted gratings with similar diffraction efficiencies [31]. The first exposure time t_1 was set to be 1/15 second. After the first exposure, the cell, which was mounted on a x-y rotation stage, was rotated 180° as shown in Figure 2(b). The second grating was formed using the same apparatus; however, the second exposure time was 30 seconds in order to complete the polymerization. By rotating the holographic apparatus, samples reflecting different wavelengths can be fabricated without changing the direction of the exposing beams. By rotating the stage counterclockwise as shown

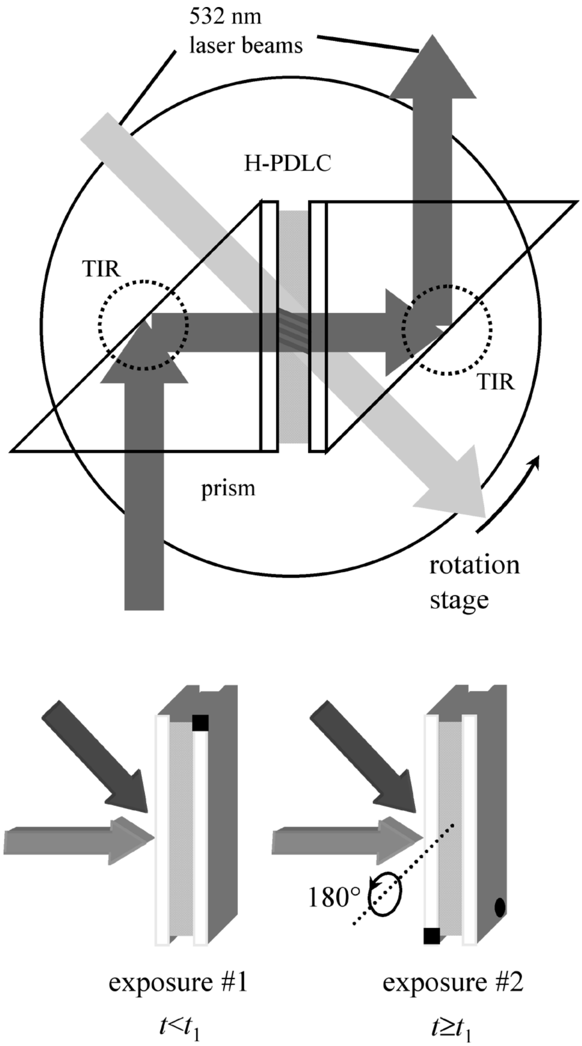

FIGURE 2 (a) The schematic illustration of experimental setup. The entire holographic apparatus sits on a rotation stage and the diffraction wavelength is controlled by rotating the stage. (b) A schematic illustration of the temporal multiplexing temporal multiplexing technique employed. After formation of the first grating, a rotation stage is utilized to rotate the sample 180° in order to record asymmetric TIR gratings.

in Figure 2(a), the reflection wavelength of the resulting samples shifts to a shorter wavelength. The pitch of the gratings varies from 390–530 nm, which is at least twice than that of reflective H-PDLCs.

3. RESULTS

A PhotoResearch 705 spectroradiometer with a resolution of 2 nm was used to characterize the reflection of our H-PDLCs. A collimated white light generated by an arc lamp (Oriel) was used as a broadband illumination source. The incident light was nearly normal to the glass substrates. In Figure 3, typical reflection spectra of our blue, green and red samples can be seen. The peak wavelengths of these samples are ~484 nm, 544 nm and 640 nm, respectively. These reflection spectra have a width of 40–60 nm, which is slightly broader than that of conventional reflective H-PDLCs. This broader spectrum is a general characteristic of slanted grating [32] and improves the overall photopic reflectance of our devices [33]. Our experimental data is plotted on a CIE 1976 Color Gamut Chart as shown in Figure 4. While the color of blue sample is not as deep when compared to a standard Sony Trinitron, it can be improved by adjusting the exposure geometry.

A 1 kHz square wave voltage was applied to the transparent electrodes to switch the multiplexed TIR grating. The reflection efficiency of the sample, η, is expected to be proportional to the product of diffraction efficiencies to two gratings:

$$\eta(V) \propto \eta_s^2(V) \tag{1}$$

where η_s(V) is the diffraction efficiency of a single TIR grating under applied voltage V. We assume that the efficiencies of the two gratings are the same. In principle, the electro-optic response curve of grating-grating coupling sample should have a higher degree nonlinearity and faster response times when compared to a single slanted grating fabricated under identical conditions.

In Figure 4, we plot the normalized reflectance of three primary color samples as a function of applied RMS voltage. A high contrast ratio of >100:1 is achievable. This corresponds to the grating-grating coupling mechanism (Eq. (1)). Similarly, with reflective H-PDLCs, the switching voltage of the red sample is lower than that of the blue sample, since the average droplet size in the red sample is expected to be larger [34]. The threshold voltage of our samples is ~15–20 V and the grating is nearly erased ~30–35 V, which is much lower than the switching voltage of conventional reflective H-PDLCs (at least a factor of 2). Using the model developed by Wu and others [34], the dependence of the critical voltage on the size of the LC droplets can be seen. The critical voltage can be expressed by the following equation

$$V_C = \frac{Ad}{r} \tag{2}$$

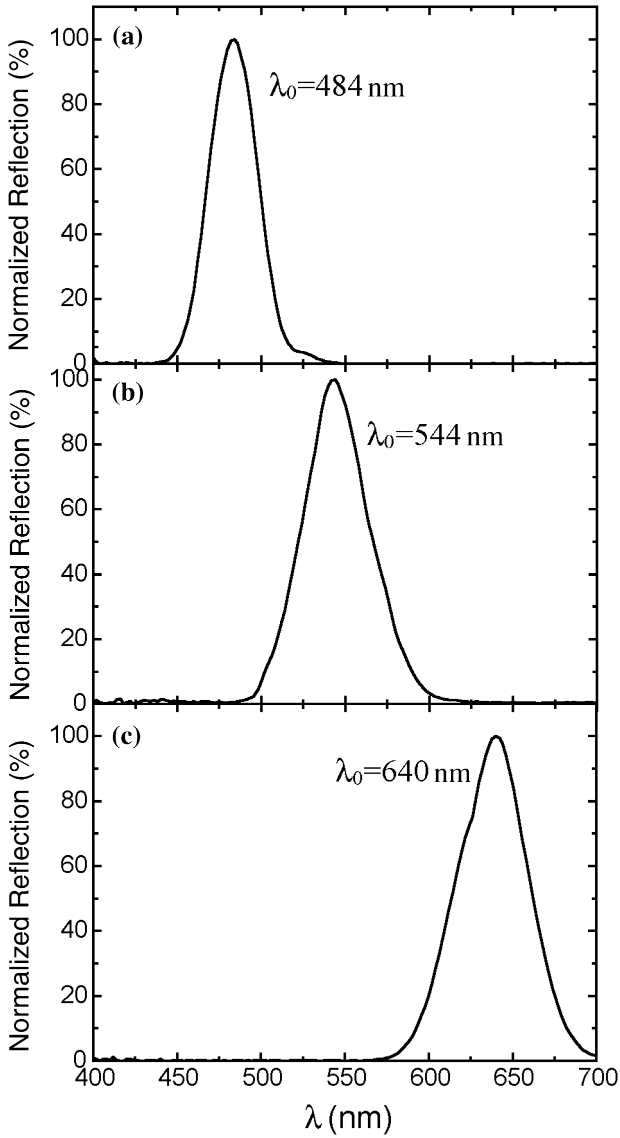

FIGURE 3 The typical reflection spectra of (a) blue, (b) green, and (c) red samples. These reflection spectra have the width of 40–60 nm, which is broader than that of reflective H-PDLCs.

where d is the sample thickness and r is the diameter of the liquid crystal droplets. A is the constant related to H-PDLC material properties, such as the elastic and dielectric properties of liquid crystal, and the

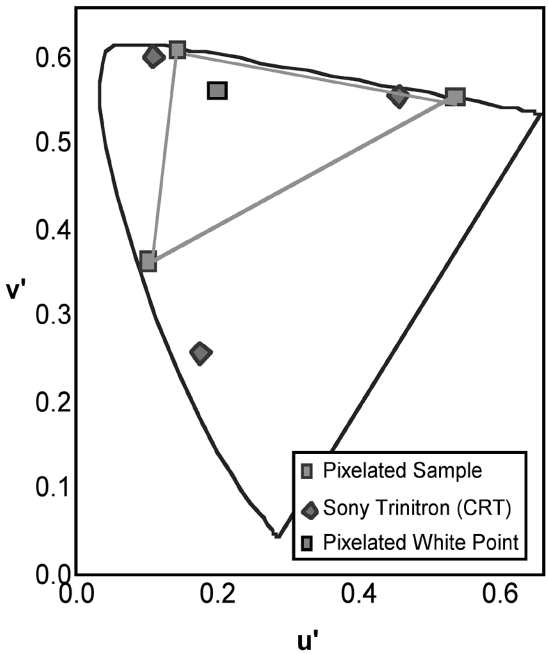

FIGURE 4 CIE 1976 Chromaticity Chart shows three primary color samples compared with a Sony Trinitron standard.

conductivity of polymer and liquid crystal. From the above equation it can be seen that the critical voltage is inversely proportional to the radius of the LC droplets. The low switching voltage of our samples corresponds with the larger LC droplets.

The electro-optical response curves of the red and green samples are not as sharp as that of the blue sample (i.e. the nonlinearity of curves in Figure 5. This may be due to the existence of a relatively broad distribution of droplet sizes. The nonlinearity of the red and green samples may be improved by further optimizing the exposure process. Improving the coupling between the two gratings or controlling the morphology of the liquid crystal droplets may even further increase the nonlinearity of the electro-optic response curve [5].

The response times of our samples were also measured. Figure 6 shows the on time τ_{ON} and off time τ_{OFF} of a multiplexed TIR red sample as functions of applied voltage. One can see sub-millisecond response times are achievable. The off time τ_{OFF} is larger than conventional reflective H-PDLCs (100–200 μs), which is also in agreement with the lower switching voltage of our new configuration [34].

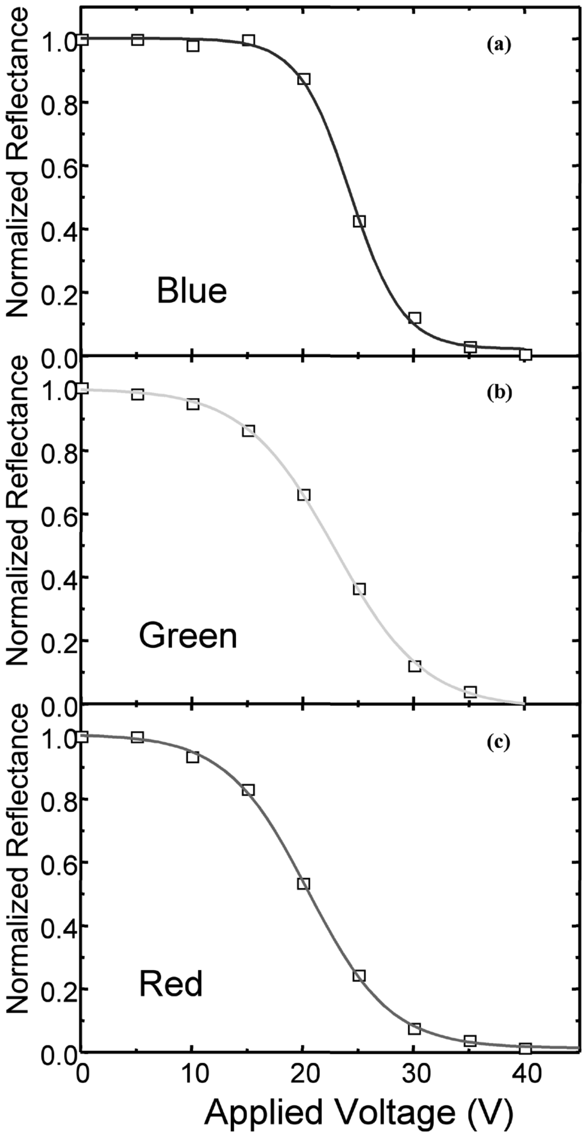

FIGURE 5 The electro-optic response of temporally multiplexed samples.

4. SUMMARY

Reflective H-PDLCs show promise for use in reflective display applications. We have demonstrated a new reflection display configuration

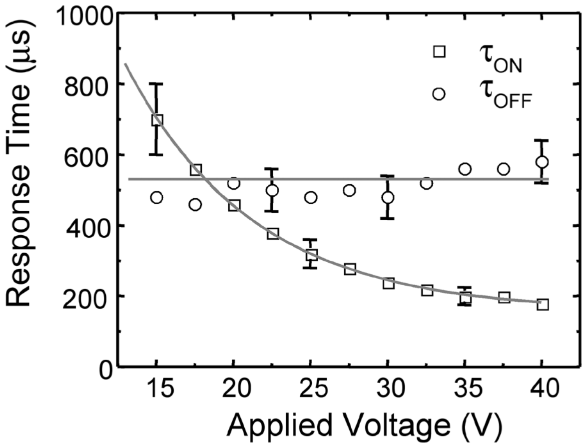

FIGURE 6 The on time τ_{ON} and off time τ_{OFF} of a multiplexed TIR red sample as function of applied voltage.

based on TIR H-PDLC technology and grating-grating coupling. Compared to conventional reflective H-PDLCs reported in the past [24,25], our new configuration shows much lower switching voltage and higher contrast ratios. This reduction in driving voltage is due to larger pitch (i.e. larger droplets) in our slanted gratings as compared to conventional H-PDLCs for the same λ-reflection (e.g. slanted grating pitch 454 nm as compared to reflective grating pitch 177 nm for a 550 nm reflection). The attractive features include versatility in fabrication and materials selection (different laser wavelengths can be used). Many other material sets can be evaluated that have more attractive features (lower anchoring energies, higher voltage holding ratios, etc.). In addition, the same 'tricks' used to broaden the viewing angle of conventional reflective H-PDLCs, can also be employed here [35].

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