

Full-Color Reflective Displays

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Abstract

Holographically formed polymer dispersed liquid crystal (H-PDLC) displays are investigated in terms of their electro-optic performance parameters and their potential as capable full color display systems. It is demonstrated that the transmission-voltage curve can be modified by low concentrations of chiral dopants, increasing the steepness of the response curve. To probe the details of full-color reflective H-PDLC displays, we invoke a generalized colorimetric/photometric analysis to estimate the display reflectance, white-point, and chromaticity diagram for a vertically integrated stack of red, green, and blue H-PDLC displays.

Introduction

Color displays have become an essential element of today's computing and imaging systems. Steady advances in liquid crystal display (LCD) technology have not only made color displays pervasive, but have permitted the migration of color technology from our working environments to our leisure environments, homes and vehicles.

These trends place increasingly stringent demands on existing color display technologies, which are all either emissive devices (e.g., shadow-mask color CRTs, electro-luminescent displays, color plasma displays) or contain some internal source of illumination (e.g. transmissive color LCDs with integral backlighting).¹ While self-luminous displays have evolved into highly capable devices for electronic color imaging, they suffer from a number of shortcomings which limit their future utility. First, self-luminous displays require relatively large amounts of power to achieve sufficient luminance for most visual tasks and many operating environments. As levels of ambient illumination increase, they typically exhibit degraded contrast and insufficient luminance. These adverse changes can be largely compensated by putting more power into the display, at least up to a limit. Second, the colorimetric characteristics of self-luminous color displays do not respond naturally to changes in the ambient environment. Natural objects and most reflective color reproductions exhibit predictable and consistent changes in their reflected spectral power distributions as the level and spectral composition of ambient illumination changes. This enables visual/percep-

tual mechanisms of color constancy and gain control to adapt the state of the human visual system to prevailing conditions of illumination. As the level of ambient illumination increases, natural objects become more luminous and typically more saturated in color. In contrast, self-luminous displays do not inherently increase in luminance with increased illumination and color saturation is generally reduced via diffuse broad-band reflections. Third, self-luminous color displays tend to be large and heavy, although recent trends in flat-panel displays have resulted in dramatic reductions in weight and volume. Finally, self-luminous color displays remain relatively expensive, at least in part due to the large number of display components and the need to handle significant power levels.

It is our contention that a transition to reflective color displays represents the next major paradigm shift in the evolution of display technology. Advances in LC materials and optical configurations have already produced reflective monochromatic displays with dramatically improved reflectance and resulting display visibility. These new displays, which are just now beginning to enter the marketplace, represent a significant advance over the now commonplace twisted-nematic (TN) and super-twisted nematic (STN) LCDs.² Reflective color remains an elusive goal at present, as the technical challenges to achieving a large color gamut, high excitation purity and sufficient reflective luminance for a broad range of viewing conditions are formidable.

The major challenges for successful high-performance reflective color displays center around the requirement for extremely high levels of spectral reflectance. These high levels are necessary to simultaneously achieve good color selectivity and adequate levels of reflected luminance. Previous approaches have not satisfied these requirements. The use of polarizers results in poor levels of reflectance since even high-efficiency linear polarizers only transmit approximately 40% across the visible spectrum. This limits the reflectance of the display to an absolute maximum of 40% before any other light losses within the display or spectral filtering are applied. Most previous approaches have also relied on absorptive filters to achieve color selection. This further limits the display reflectance because, in accord with the Beer-Lambert Laws³ of absorbing materials, good color selectivity in absorptive filters requires high dye concentrations and/or increasingly thick absorbing layers.

High absorbance results in low transmission and, since reflected light must pass through the color filters twice, leads to very low reflectance. Additionally, spatial color synthesis, which is by far the predominant approach to synthesizing color in electronic displays,³ cannot be used successfully in reflective displays since only a fraction of the available display substrate (typically 1/3) is devoted to each primary color component. Thus, the methods for synthesizing color which have proven so successful in transmissive active-matrix color LCDs,⁴ which rely on integral linear polarizers, absorptive color filters and spatial patterning of filter mosaics, are not suitable for color reflective displays. Typical photopic transmission of full-color TN displays is in the range of 3 - 5%, while these configurations result in a photopic reflectance of approximately 1 - 1.5% due to additional double-pass losses. Unlike self luminous color displays where light losses can be compensated by an increase in power to the device or internal illumination source, reflective color displays must provide good color selectivity while making highly efficient use of the available ambient illumination.

This paper focuses on holographically formed PDLC materials for reflective color applications. These materials have promise for high performance reflective displays because of their reflection capability and tunable reflection peaks. Results on the electro-optic performance parameters of H-PDLC are presented and modeling of H-PDLC in full-color configurations.

Experiment

Polymer dispersions were fabricated out of EM Industries PN393 series photopolymer and TL205 liquid crystal which have been optimized for high performance displays. Both conventional light scattering based PDLCs were fabricated along with those formed holographically. The conventional PDLC materials are fabricated using standard UV curing techniques, while those formed holographically require an additional visible photoinitiator and coinitiator. The visible photoinitiator used in this study was H-NU 470 from Spectra Group Limited. The mixture was sandwiched between two pieces of ITO conducting glass substrates and maintained at 10-12 mm cell gap. The samples were exposed to an expanded argon-ion laser beam (488 nm). A mirror was placed behind the sample to establish constructive and destructive interference within the sample to form the volume hologram.

A conventional PDLC device is schematically shown in Figure 1. After the liquid crystal and reactive monomer form a homogeneous solution, UV radiation initiates the polymerization process resulting in the liquid crystal phase separating out into droplets. In the zero-voltage state, the symmetry axis of the droplets is randomly oriented and there is a mismatch in the index of refraction between the surrounding polymer and liquid crystal droplets. This

condition results in a strongly light scattering (opaque) appearance. By matching the ordinary refractive index of the liquid crystal, n_o , with that of the surrounding polymer matrix, n_p , a transparent condition is achieved when a sufficient voltage is applied to reorient the liquid crystal droplets (see Figure 1).

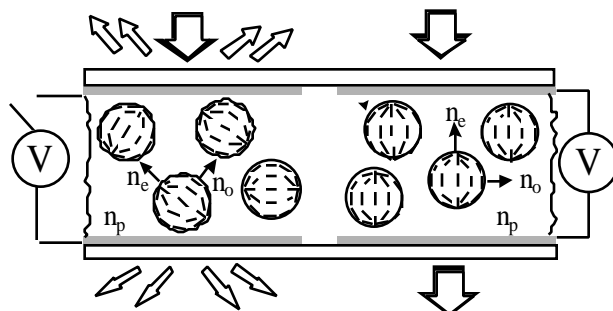


Figure 1: Conceptual illustration of a conventional PDLC. In the zero-voltage state the pixel is strongly light scattering (opaque). When a sufficient voltage is applied, the index matching condition results in a highly transparent condition.

The transmission curve as a function of electric field for the conventional PDLC is presented in Figure 2. Notice that the electric field required to switch the sample to the transparent state is less than 1 V/mm. The droplets sizes for the PN393-TL205 system are typically on the order of 1-2 μ m in diameter. The transient response time is typically between 5-40 ms which strongly depends on the applied voltage and morphology of the liquid crystal-polymer dispersion (i.e. rate of cure and liquid crystal-polymer formulation). For direct-view applications, the contrast ratio is between 5-10:1 and the photopic reflectance is 12-15%. Both of these parameters strongly depend on the cell gap, and the values quoted above are achievable for cell gaps in the 8-12 μ m range. Absorptive dichroic dyes have also been used to improve contrast⁵. Commercially available passive light shaping elements⁶ have been implemented into PDLC displays to improve brightness. There is probably no clear pathway to a high performance color reflective display using conventional PDLC technology. With reasonable switching voltages that are compatible with off-the-shelf display drive circuitry, conventional PDLC materials are more appropriately poised for monochrome applications.

A more recent application of PDLC materials are those that are photopolymerized in visible light using holographic techniques. In this application, the liquid crystal droplets can be selectively phase separated out into planes as shown in Figure 3. The spacing of the planes is governed by the wavelength of visible light used to perform the photopolymerization. The optical interference of this multilayer, periodic structure reflects the Bragg wavelength in the zero-voltage state and transmits the rest. In the applied voltage state, the ordinary refractive index of the liquid crystal, n_o , matches that of the surrounding polymer, n_p , so

that the gradient in the refractive index vanishes; therefore the sample is optically homogeneous and transparent.

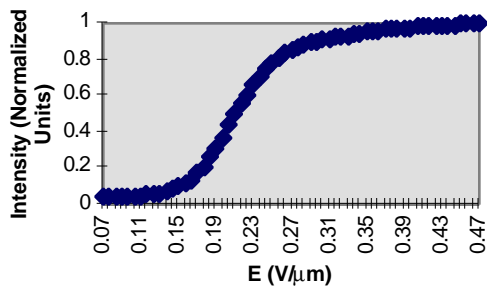


Figure 2: Transmission versus electric field for a conventional PDLC display with a 15 μm cell gap.

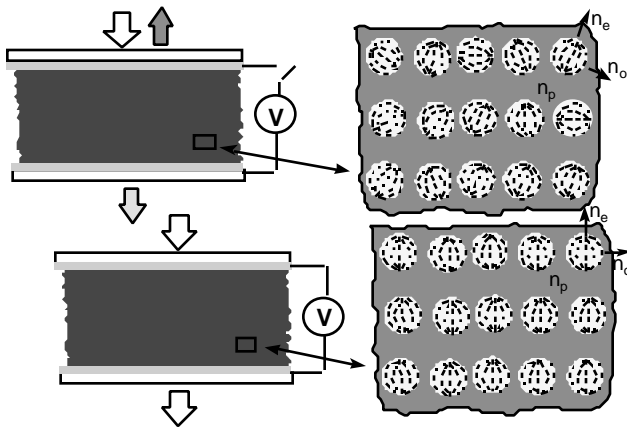


Figure 3: Conceptual illustration of a holographically formed H-PDLC display. In the zero-voltage state the display is Bragg reflecting and in the applied voltage state the materials becomes transparent.

The reflection curve as a function of electric field for the H-PDLC is presented in Figure 4. Notice that the electric field required to switch the H-PDLC sample to the transparent state is noticeably larger than the voltages needed to switch the conventional PDLC in Figure 2. The underlying reason for this phenomena can be largely attributed to the smaller droplet sizes in the H-PDLC systems. The switching threshold field has been shown to be strongly correlated to droplet size and its aspect ratio. Please note that the conventional PDLC display data plotted in Figure 2 was recorded in a transmission experiment while the H-PDLC data in Figure 4 was recorded in reflection. Here we are only comparing the drive voltages between Figure 2 and 4.

The reflection wavelength of the H-PDLC was recorded at $\lambda \sim 475$ nm with a width at half maximum of approximately 25 nm. The grating was formed with an argon ion laser at $\lambda = 488$ nm and the difference between the measured reflection peak and the formation wavelength is believed to be due to shrinkage during the curing process. This small discrepancy was also reported by Bunning and

coworkers.⁷ For normally incident light, the films are governed by the Bragg Condition, $\lambda = 2 n d$, where d is the grating spacing and n is the average index of refraction. For our measured $\lambda = 475$ nm and taking $n \sim 1.55$, the d spacing is roughly 153 nm. This d spacing is consistent with our initial electron microscope experiments. The reflection efficiency for the samples plotted in Figure 4 is $\sim 70\%$.

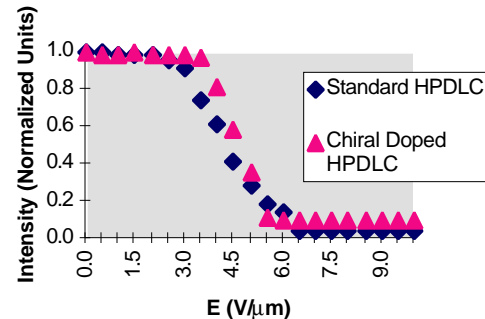


Figure 4: The reflection curve as a function of electric field for H-PDLC samples. The chiral dopant has a strong influence on the steepness of the curve.

The steepness of the reflection curve in Figure 4 is important for simple passive matrix driving schemes. By doping the H-PDLC with a chiral additive, the transmission curve can be modified as shown in Figure 4. Another way to modify the transmission curve is by doping the H-PDLC with surfactants. This technique also reduces drive voltages. Surfactants reduce the interaction energies between the liquid crystal and the polymer binder.⁹

Full-Color Reflective Displays

The photopolymerization for all of the above measurements was carried out at $\lambda = 488$ nm using an argon-ion laser. Experiments are currently underway to fabricate reflecting panels in the green and the red. This can be most conveniently done by changing the laser and photoinitiator, or by fabricating Bragg layers at slanted orientations.¹⁰ A full color display can be fabricated by stacking three red, green, and blue reflecting H-PDLC displays as shown in Figure 5.

We have used an adaptation of a previously developed model of display visibility to estimate the reflectance requirements for a high performance reflective color display.¹⁰ This model predicts the visibility of displayed information as a function of spatial frequency, maximum and minimum levels of emitted display luminance, maximum and minimum levels of display reflectance, display contrast polarity, incident ambient illumination, and the adaptation luminance present in the dominant forward-field-of-view.¹² As a point of departure for our visibility modeling, we assume that a reflective color display for imaging applications should at a minimum achieve VGA resolution (approximately 15 cycles-per-degree maximum spatial frequency at a nominal 50 cm viewing distance) and

color performance equal to or exceeding that of a shadow-mask CRT or active-matrix color LCD. In addition, the display must be capable of operating in ambient environments ranging from typical indoor office illumination to the higher levels present in bright outdoor conditions. Considering these parameters, we have estimated that a successful high-performance reflective color display must achieve a minimum photopically-weighted peak-white reflectance of approximately 40%.³

This approach has many advantages over spatially synthesized color schemes typically used in emissive displays. The resolution and brightness is not compromised by vertically stacking the panels as compared to spatial color synthesis. There are however disadvantages associated with vertical integration of three panels to achieve full color that must be overcome: (1) alignment and plate-to-plate registration issues; (2) parallax issues; and (3) drive circuitry. Many of these issues are currently under investigation and at this point do not seem insurmountable.

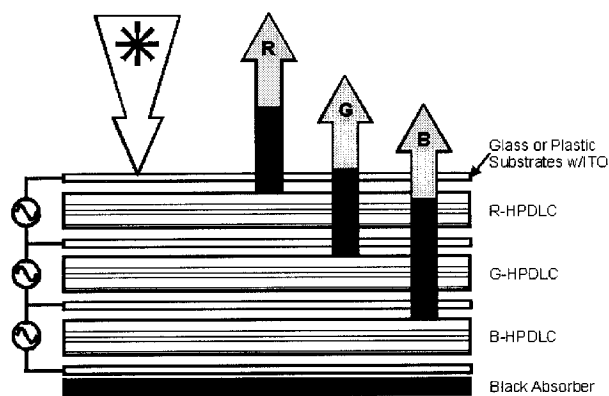


Figure 5. Basic Configuration of full-color H-PDLC display.

In the results presented here, we use a spectral power distribution (SPD) for a standard D50 illuminant and have optimized the spectral reflectance functions (SRFs) to achieve the best combination of color primary dominant wavelength and excitation purity, photopically-weighted-peak-white-reflectance, and balanced white point for the configuration in Figure 5. A complete 4 by 4 propagation matrix approach is employed.¹¹ Figure 6(a) shows the SRFs for an optimized three-primary H-PDLC reflective color display. Figure 6(b) illustrates the colorimetric capability of the modeled H-PDLC display.

The gamut of a typical high-performance color CRT monitor with P22 phosphors is shown as a reference. It can be seen from these results that with proper optimization the H-PDLC display can achieve color performance significantly exceeding that of a color CRT with P22 phosphors. The photopic peak-white reflectance of this H-PDLC configuration is estimated at approximately 34%.

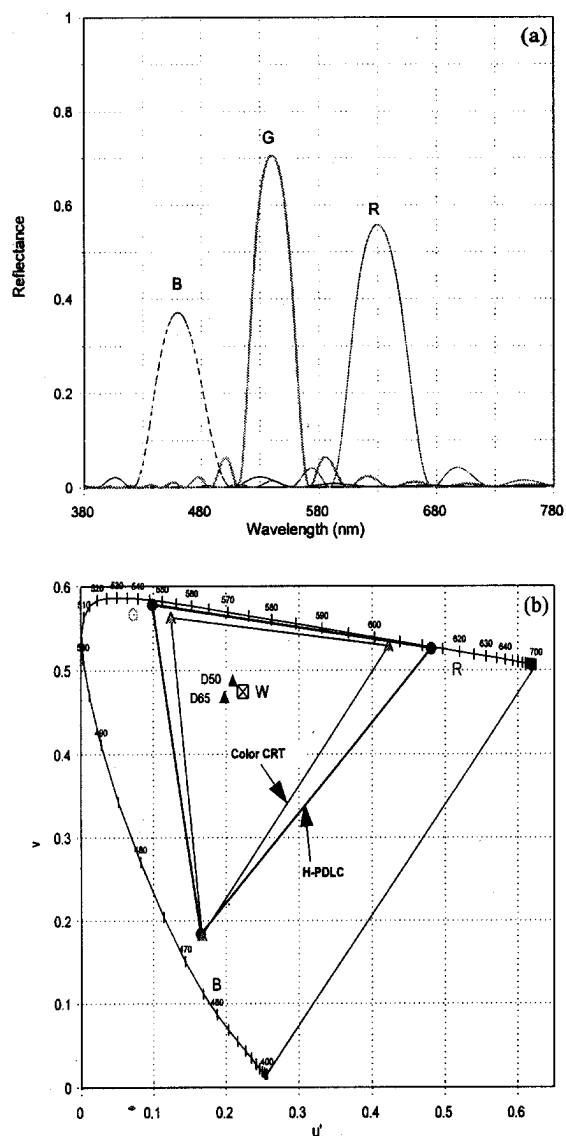


Figure 6. Optimized spectral reflectance functions (a) and resulting color gamut for a modeled, three primary H-PDLC reflective color display (b).

As discussed in a previous publication, our display visibility modeling indicated that a successful high-performance reflective color display which can be used in a broad range of viewing environments must achieve a minimum photopically-weighted peak-white reflectance of approximately 40%. The modeled H-PDLC configurations presented above did not achieve this level of reflectance, but they certainly came close. In theory the Bragg reflection of an H-PDLC layer can be increased to approach 100%, yielding significantly higher peak-white photopic reflectance. However, in practice this would be difficult to achieve given the large number of Bragg reflecting unit-cell planes required with the nominal refractive index difference between available liquid crystal and photo-polymer materials. Increasing the full-width-at-half-maximum

(FWHA) spectral bandwidth of the Bragg reflecting color primary layers can also result in a reflectance increase. The increased spectral bandwidth can be achieved by reducing the overall thickness of the color primary layers or by introducing variations in the angles of the unit cell reflecting planes within each color primary layer. These approaches tend to result in marginal net increases in peak-white photopic reflectance since the peak reflectance at the center wavelength decreases with increased spectral bandwidth. In addition, simply increasing the FWHA spectral bandwidth results in significant compromises to the color gamut when the FWHA spectral bandwidth is increased much beyond 40 nm.

Conclusions

We have presented a comparison of H-PDLCs and conventional PDLCs for reflective display applications. Although the voltages to drive H-PDLCs are still much higher than conventional PDLC materials, their high reflection capability and tunable spectral reflection peaks make them very attractive for full-color reflective display systems. In addition we demonstrated that the steepness of the electro-optic reflectance curve could be modified by chiral doping. Our modeling indicates that the color performance of the vertically integrated stack of H-PDLC materials exceeds conventional emissive technologies, and that photopic peak white reflectances are approaching the 40% required for capable color reflective displays.

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