Reflective Color Displays for Imaging Applications

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Abstract

Electronic displays for the rendering of full-color images have to date relied solely on self-luminous display configurations. While self-luminous displays have evolved into effective devices for color imaging, they require relatively large amounts of power and, in general, do not respond naturally to changes in ambient illumination. These attributes place limiting constraints on future applications for self-luminous color displays, particularly in light of current trends toward mobile computing and the proliferation of color in hardcopy document imaging. Clearly, a low-power reflective color display technology is needed to broadly satisfy the needs of both mobile computing and electronic color imaging. Previous approaches to achieve a reflective color display have generally produced unsatisfactory results, typically yielding displays with a restricted set of primary colors and low luminance. In this contribution we determine the visual parameters required for effective, full color reflective displays. We analytically examine a number of contemporary liquid crystal technologies and associated optical configurations which hold promise for achieving reflective color displays. We conclude that reflective displays based on polymer-dispersed liquid crystals (PDLCs) and polymer-stabilized cholesteric texture liquid crystals (PSCT) are the most viable color-capable reflective technologies to date. A new type of PDLC offering highly selective and efficient spectral reflectance via Bragg reflection is described, and we show such materials can be configured as a full-color reflective display and optimized for color imaging applications.

Introduction

Color displays have become an essential element of today's computing and imaging systems. Color is vital for information coding and guiding visual search on complex information displays, and high-fidelity color displays are a prerequisite for most imaging applications. Rapid improvements in the quality and availability of color image capture and printing systems have further pushed the emphasis on full-color imaging. At the same time, 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). 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/perceptual 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 liquid crystal (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. High performance 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. Nevertheless, the prospects for such a display device are compelling, and the enabling display technologies and knowledge bases in color and vision science are well positioned for the development of high performance reflective color displays.

In this paper we review the current state-of-the-art in reflective color display technology. We provide an analysis of why existing approaches have at best produced only marginal results and attempt to define the colorimetric and visual requirements for effective color displays based solely on reflective ambient illumination. We offer an overview of a number of new developments in LC materials and optics which provide the building blocks for the future generation of reflective color devices. Finally, we describe a technical approach to the development of a high-performance reflective color display and provide the results of colorimetric and photometric modeling used to characterize and optimize the performance of this new display device.

Major Challenges for Reflective Full-Color Displays

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 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. Many 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 Laws[1] 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,[2] can not 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,[3] which rely on integral linear polarizers, absorptive color filters and spatial patterning of filter mosaics, are not suitable for color reflective displays. 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.

The additional obstacle of poor viewing angle, which is also present in selfilluminated LCDs, is also a crucial issue in the reflective mode operation. Current methodologies to alleviate viewing angle issues in conventional LCDs reduce the luminance and are therefore not feasible approaches in the reflective mode operation. Approaches based on absorbing black dye additives in cholesteric liquid crystals using only one polarizer, known as the phase change guest host (PCGH) mode, have been nominally successful in demonstrating limited color capability (magenta-green spatial filter scheme) and acceptable brightness levels.[4] Full color red, green and blue spatial filter schemes used with the PCGH mode greatly reduce luminance.[5] The key to practicality in the above approaches centers around the task of enhancing reflectance to acceptable levels which is largely limited by the absorption of the color filters and polarizers in conventional LCD technologies.

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. 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.[6] 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%.

Contemporary Reflective Display Technologies

The most promising contemporary approaches to reflective mode displays currently utilize liquid crystal-polymer dispersion material technologies. In addition to their reflective capability, these dispersions are easier to process, do not require polarizers, and have optimal viewing angle characteristics; therefore they are simpler to manufacture, capable of brighter images, and are superior to conventional polarizer based displays for wide-viewing applications. The materials currently receiving the most attention for reflective display applications either operate on the principle of light scattering or Bragg reflection. These liquid crystal- polymer dispersion materials are the most viable candidates for color reflective display applications to date.

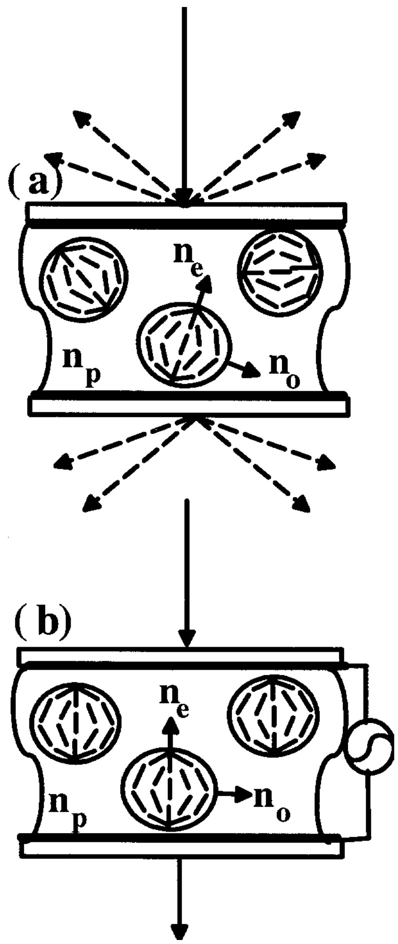

Figure 1. PDLC display in the opaque off-state (a) and transparent on-state (b).

Polymer-Dispersed LC Material

The polymer-dispersed liquid crystal (PDLC) material operates on the principle of electrically controlled light scattering.[7] Liquid crystal droplets (1-2 µm in diameter) are embedded in a polymer matrix. In the off-state, the alignment of the liquid crystal droplets (symmetry axes) is random (see Figure l(a)) resulting in an opaque, scattering film because of the mismatch between the ordinary, n_o, and extraordinary, n_e, refractive index of the LC with that of the polymer, n_p. Upon application of an electric field (~1 V/µm), the liquid crystal within the spherical inclusions aligns parallel to the electric field (see Figure l(b)), and if $n_o \sim n_p$, the composite material is index matched and becomes transparent. Typically, a black absorbing material is placed at the rear of the PDLC cell such that the display is dark in the field-on state. Contrast ratios in the reflective mode are in the 5-15:1 range which are strongly cell thickness dependent. The reflectivity of the PDLC display under ambient lighting conditions is 12-15%, and can be enhanced to values approaching 40% using passive brightness enhancing films behind the PDLC cell.[8] Incorporation of dichroic dyes into the liquid crystal droplets results in enhanced contrast ratios and colored displays. In the off-state, the light is strongly scattered and absorbed resulting in color. In the on-state, the dye molecules align and only weakly absorb resulting in a transparent state. The additional use of color reflectors behind the colored PDLC enables a limited color capability. Fergason and coworkers[9] have proposed a means to achieve a multiple color display by a magenta and yellow dyed PDLC optically coupled in parallel for a limited subtractive color scheme. Full color PDLC systems have also been suggested by Fergason et al.[9] using a cyan-magentayellow stack of PDLC displays but this approach has not been reduced to practice.

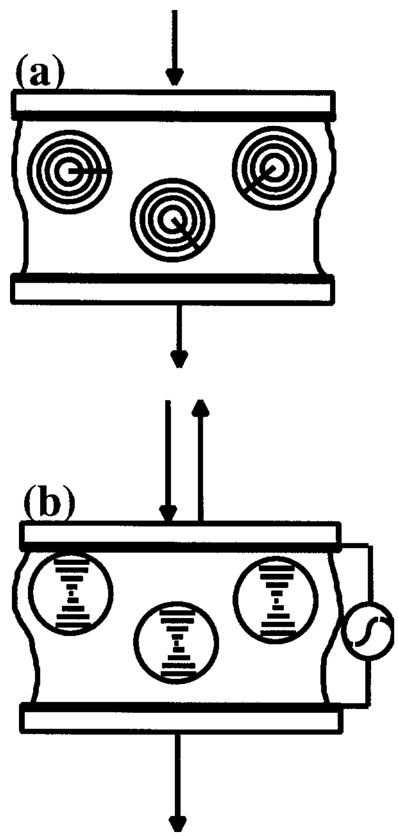

Figure 2. PDCLC display in the transparent off-state (a) and the reflecting on-state (b).

Polymer-Stabelized Cholesteric LC Material

The polymer dispersed cholesteric liquid crystal (PDCLC) is similar in construction to the PDLC, however, the PDCLC operates on the principle of Bragg refection (see Figure 2).[10] In the off-state, a stable concentric arrangement of the liquid crystal inside the spherical inclusions results in a nearly transparent display (see Figure 2(a)), and upon application of a voltage, a stable planar helical arrangement of liquid crystal that results in selective reflection (see Figure 2(b)). The planar texture in Figure 2(b) selectively reflects at the Bragg Wavelength, λ_B=nP, where n is the average index of refraction and P is the pitch length of the helical structure; all other wavelengths are transmitted. Cholesteric liquid crystal in the planar configuration in Figure 2(b) can ideally reflect 50% of λ_B. The contrast ratio of the PDCLC has been reported to be 10:1 with a reflectivity of 13% under ambient lighting conditions and 40% at λ_B. Kato and coworkers[11] have demonstrated an additive color scheme by stacking a reflecting red-green-blue PDCLC display as a means to achieve full color.

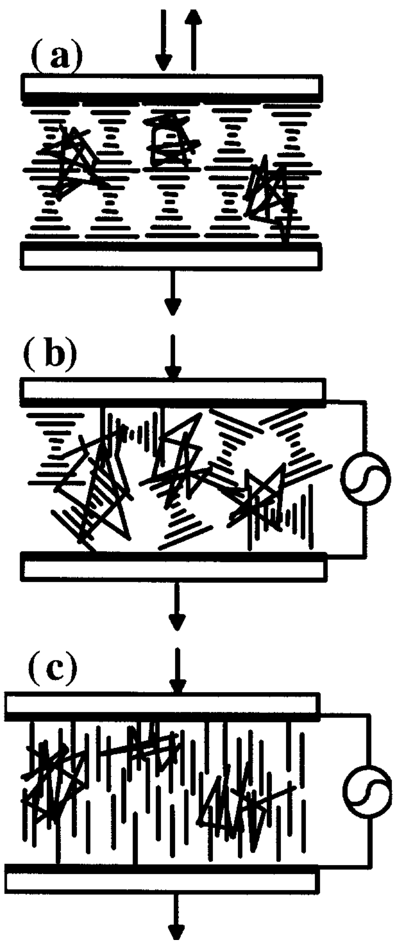

Figure 3. PSCT display in the reflecting off-state (a), focal conic state (b) and highly-aligned state (c). The thin coiled lines depict the polymer network

Polymer-Stabilized Cholesteric LC Material

The polymer stabilized cholesteric texture (PSCT) reflective display presented in Figure 3 employs only a small amount of polymer additive (1-4 wt. %) in the cholesteric liquid crystal medium which assembles into a stabilizing network.[12] In the off-state (see Figure 3(a)), the planar texture is stable with the helical axes nearly perpendicular to the display substrate. The planar texture selectively reflects at the Bragg wavelength, λ_B. When a low voltage is applied to the display (see Figure 3(b)), the cholesteric liquid crystal is transformed into a focal conic texture (randomly aligned helical axes) and the cell is nearly transparent. At this point (Figure 3(b)), the voltage can be removed and the focal conic texture remains bistable due to the stabilizing effect of the polymer network. Upon application of a larger field (see Figure 3(c)), the cholesteric liquid crystal becomes completely aligned, and after removal of the voltage, the cholesteric liquid crystal relaxes back to the planar texture in Figure 3(a). This approach is very attractive because of its bistable memory capability which greatly reduces the power consumption of the display. Since the display operates on the Bragg reflection principle, it is capable of reflecting up to 50% at the peak Bragg reflection wavelength (λ_B) and 10-15% broadband reflection under ambient lighting conditions. Contrast ratios have been reported between 20-30:1 and bistable gray scale memory is also achievable. In principle, the same red-green-blue stacked displays configuration for additive color can also be applied to PSCT but this has not been reported thus far.

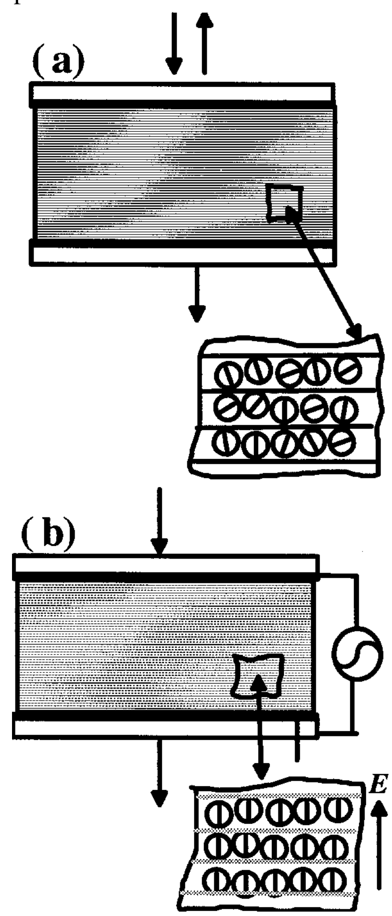

Figure 4. H-PDLC display in the reflecting off-state (a) and transparent on-state (b)

Holographically Structured Polymer-Dispersed LC Material

A new approach to reflective display technology has recently been reported by Tanaka and coworkers.[13] They have successfully fabricated a multi-layer PDLC device (see Figure 4) that can ideally reflect 100% of the Bragg wavelength and transmit all others. This holographic polymer dispersed liquid crystal (H-PDLC) is formed using optical interference techniques to form planes of droplets at predesignated positions within the sample setting up a modulation in the liquid crystal droplet densities. The resulting optical interference of this configuration reflects the Bragg wavelength, λ_b in the off-state when the droplets are misaligned (see Figure 4(a)). The reflectance under ambient conditions will therefore be larger than for the PDCLC or PSCT technologies. Upon application of an applied voltage, the periodic refractive index modulation vanishes if n_o of the liquid crystal is approximately matched with n_p of the polymer and all incident light is transmitted (see Figure 4(b)).

The effective refractive index can be varied with different applied voltages and therefore the reflected intensity can be controlled electrically. The spectral reflectance of the H-PDLC is determined during the fabrication process and can in principle be chosen to reflect any visible wavelength. Tanaka and coworkers[13] have demonstrated this phenomena with single H-PDLC layers exhibiting a full-width-athalf-amplitude (FWHA) spectral bandwidth of approximately 20 nm and a peak reflected intensity of 70%. To date this is the most promising reflective technology because of its high reflective intensity capability. A full color display fabricated out of H-PDLCs is presented in Figure 5.

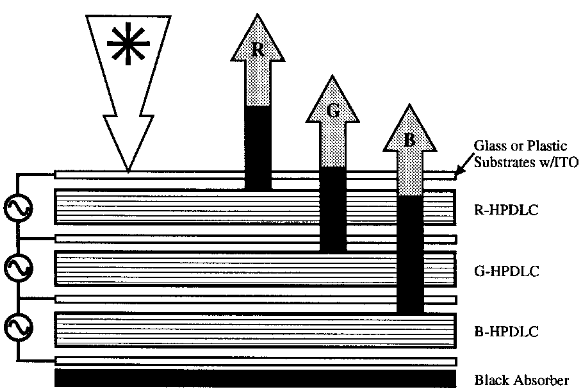

Figure 5. Basic configuration for full-color, holographic PDLC display

We have recently developed a generalized colorimetric/photometric model of reflective color displays. Since the H-PDLC materials appear to have the most desirable characteristics for achieving high performance, full-color reflective displays, we have applied this model to the H-PDLC technology using the display optical configuration described in Figure 5. In accord with **basic optical** characteristics of H-PDLC materials, the spectral reflectance functions (SRFs) for each primary color are modeled as Gaussian distributions with tunable center wavelength, peak reflectance and FWHA spectral bandwidth. The model currently allows for three color primary layers with up to three sub-layers per primary and contains a library of illuminant spectral power distributions (SPDs). In the results presented below, we use a SPD for a standard D50 illuminant and have optimized the SRFs to achieve the best combination of color primary dominant wavelength and excitation purity, photopically-weighted-peak-white-reflectance, and balanced white point.

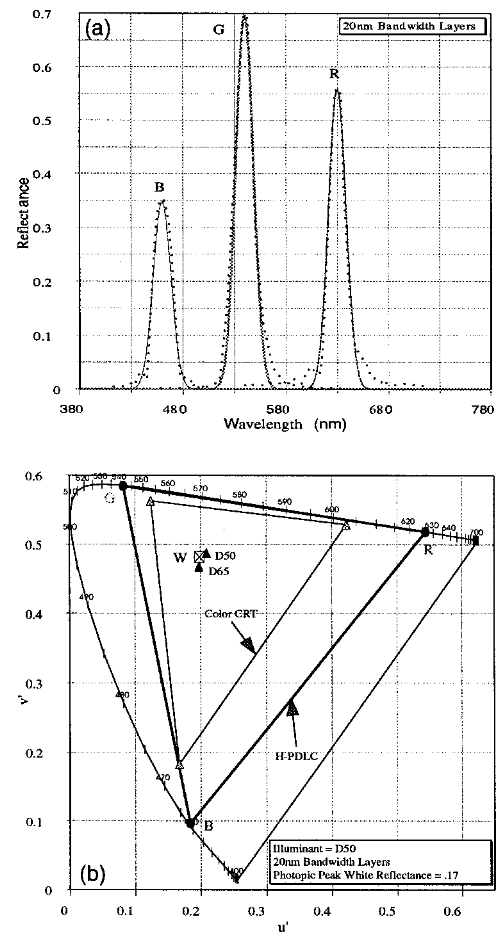

Figure 6. Modeled SERFS for an optimized, H-PDLC display with 20nm FWHA spectral bandwidths (a). CIE 1976 color gamut of the 20 nm H-PDLC display (b).

Figure 6(a) shows the SRFs for an optimized three-primary H-PDLC display with a 20 nm FWHA spectral bandwidth for each primary layer. The measured SRFs of Tanaka et al.[13] for single 20 nm layers are shown as the dotted functions. The center wavelengths of Tanaka et al.'s measured SRFs have been shifted to coincide the center wavelengths of our optimized SRFs. It can be seen that our model closely matches the SRFs of individually-formed H-PDLC layers. 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 with proper optimization the H-PDLC display can achieve color performance significantly exceeding that of a color CRT with P22 phosphors. However, the photopic peak-white reflectance of this H-PDLC configuration is estimated at only approximately 17%.

The reflectance of H-PDLC Bragg reflectors can be increased substantially by increasing the FWHA spectral bandwidth of each color primary layer. We illustrate this by increasing the FWHA spectral bandwidth to 40 nm and showing the resulting SRFs and CIE 1976 chromaticity coordinates in Figures 7(a) and (b), respectively. As shown below, increasing the spectral bandwidth results in a decrease in the HPDLC color gamut but almost doubles the peak white photopic reflectance to 33%.

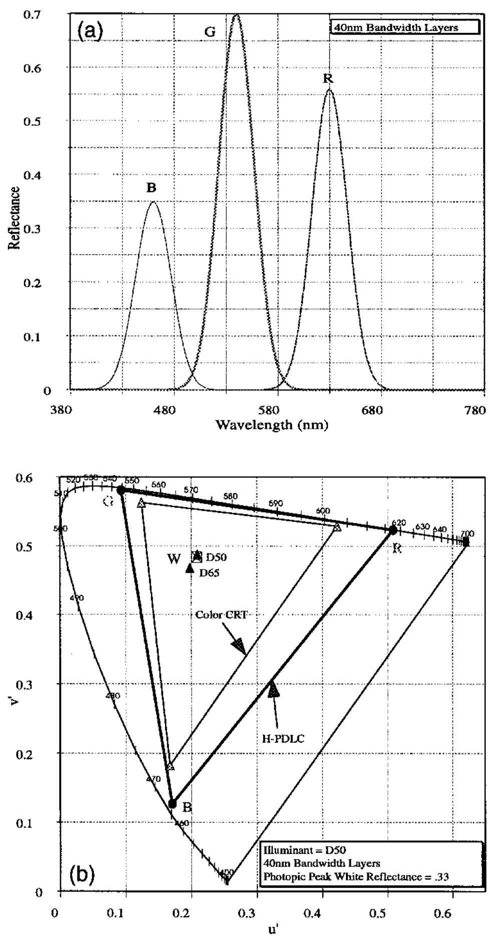

Figure 7. Modeled SRFs for an optimized, H-PDLC display with 40 nm FWHA spectral bandwiths (a). CIE 1976 color gamut of the 40 nm H-PDLC display (b).

As discussed above, our display visibility modeling indicated that a successful high-performance reflective color display usable in a broad range of viewing environments must achieve a minimum photopically-weighted peak-white reflectance of approximately 40%. Neither of the modeled H-PDLC configurations achieved this level of reflectance. In theory the Bragg reflection of an H-PDLC layer can be increased to approach 100%, yielding peak-white photopic reflectances for the 20 nm and 40 nm H-PDLC configurations of 24% and 47%, respectively. 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 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 either the thickness ratios or angles of the unit cell reflecting planes within each color primary layer. These approaches tend to result in only small 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 Gaussian FWHA spectral bandwidth results in significant compromises to the color gamut when the FWHA spectral bandwidth is increased much beyond 40 nm.

Through our modeling, we have recently developed several unique H-PDLC configurations which preserve the extended color gamut of these display devices while improving the peak-white photopic reflectance up to a minimum of 45%. The fabrication of these new configurations currently appears to be straightforward, although much work remains to integrate these new materials into a full-color, high-resolution reflective color display. High performance reflective color displays for imaging applications are now on the horizon. We believe the H-PDLC display is an extremely promising approach with a particularly bright future.

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