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W. D. St. John
Kent State University - Kent Campus

Z. J. Lu
Kent State University - Kent Campus

J. William Doane
Kent State University - Kent Campus

Bahman Taheri
Kent State University - Kent Campus, bahman@alphamicron.com

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Cholesteric liquid-crystal displays illuminated by diffuse and partially diffuse light

W. D. St. John, Z.-J. Lu, J. W. Doane,[a] and B. Taheri
Liquid Crystal Institute, Kent State University, Kent, Ohio 44242

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We report on the photometric and colorimetric properties of surface and polymer network stabilized reflective cholesteric displays. Both diffuse and partially diffuse illumination are used, the latter being an experimental approach to emulating typical room light conditions. It is shown that addition of polymer increases the field of view while decreasing angular dependence of the color quantities: hue, chroma, and lightness. Total luminance and contrast ratio, however, are also decreased. Therefore, it is concluded that optimum polymer concentration is dependent on the viewing geometry. Luminance and contrast ratio of the surface stabilized cells exceeded that of polymer stabilized cell when viewed in a geometry void of specular reflection. Colorimetric quantities in surface stabilized cells are less sensitive to illumination geometry. This suggests that for displays in which specular reflection has been suppressed, surface treatment represents the best method of stabilization. If the viewing angle allows specular reflection, polymer stabilization yields the largest luminance and contrast ratio. This behavior is explained in terms of angular distribution of helical axes due to presence of the stabilizer. *© 1996 American Institute of Physics.* [S0021-8979(96)07412-9]

I. INTRODUCTION

The cholesteric liquid-crystal display, (Ch-LCD), is a reflective display which exploits the selective reflection properties of cholesteric liquid crystals.[1] Such a display cell has two stable states, the planar and the focal conic textures.[2] In the perfect planar texture all helical axes of the cholesteric liquid crystal align normal to the cell substrates accomplished by using a homogenous alignment layer. In this state, the cell is a Bragg reflector. Circular polarized light with a helicity equal to that of the liquid crystal in which it is propagating is reflected in accordance with the Bragg law.[1] Suitably prepared polymer networks or surfaces can break up a perfect planar texture structure into a layer of microdomains. This collection of micron size planar domains results in an imperfect planar texture. While Bragg scattering remains the dominant reflection mechanism, angular dispersion of the reflected light is altered by the presence of the domains. The imperfect planar texture represents the ''bright'' state of the reflective display. Application of a sufficient electric field results in a change from the planar texture to the focal conic texture. Here the optic axis is ill defined. Optically, this texture is strongly forward scattering and the selective reflection property vanishes. By affixing an absorbing layer on the back plane of the display cell this texture appears dark and is referred to as the ''dark'' state.

Presence of the microdomains results in stability of the focal conic state at zero field. Displays in which both the planar and focal conic texture are stable at zero fields are classified as bistable reflective Ch-LCDs. Currently, bistability can be achieved via polymer introduction or surface treatment. Displays with homogeneously aligned surfaces containing a low concentration of dispersed polymer network as stabilizer are referred to as polymer stabilized LCDs.[3–5] Displays with a homeotropic or inhomogenously aligned surfaces without a polymer network are termed surface stabilized LCDs.[6,7] If the two contrasting states are stable with zero field, the display does not require a power source to retain an image. If, in addition, the display does not require back lighting, as in the case of reflective cells, displays with low power consumption can be realized. The challenge in designing these types of displays is to induce bistability while preserving the desired optical reflective properties of both states. Ideally, for paperlike appearing displays, the dark state has zero backward scattering and the bright state has a high reflection coefficient. Additionally, in most cases one would like such a display to also have a wide viewing geometry. This suggest that the photometric and colorimetric properties should have a small variance with the viewing perspective. Since these cells operate as Bragg reflectors, the latter property poses the greatest challenge.

Preferential reflection characteristics of Bragg scattering mean that both the viewing and the illumination geometry play a vital role in the performance of these displays. Measurements on the reflective properties of both types of displays using collimated light have been reported.[8] The results have suggested that the roles of specular and diffuse reflection are quite different for the two stabilization mechanisms. In this context, the terms specular and diffuse refer to the display cell as opposed to the liquid-crystal medium. In other words, in specular reflection the angle of reflection is equal to the angle of incident with all angles measured relative to the cell normal. Diffuse reflection encompasses all reflections which are not specular. In this case, diffuse reflection is classified into Bragg and non-Bragg components. In the former, the reflected light satisfies the Bragg condition stated earlier. The latter encompasses all other scattering mechanisms which are present such as scattering from defects, etc.

In this article we present reflective properties of both cell types under diffuse and partially diffuse lighting schemes. As

[a]Electronic mail: alcom1@kentvm.kent.edu

described below, the latter configuration is an attempt at emulating typical room light conditions, that is, broadly diffuse illumination minus the specular component over a relatively large viewing cone. Luminance and colorimetric properties of the reflective state are presented for both types of cells as a function of the viewing angle. Although we do not examine, in this article, the focal conic texture, or dark state, we do examine the angular dependence of the contrast which is the ratio of the bright luminance to dark luminance. The results are discussed in terms of psychophysical properties which have been used extensively in correlating the experimentally measured luminance and color coordinates with subjective estimates of display quality.[9] We note that our use of psychophysical metrics is somewhat unique in that we are attempting to characterize a display which is intended to be colorful as opposed to one which is not wavelength selective.

II. EXPERIMENT

A. Cell preparation

The liquid-crystal material used in both polymer and surface stabilized cells is a chiral-nematic mixture with a relative chiral composition of 28 wt%. This results in a helix pitch of 0.33 μm or a vacuum wavelength of 0.53 μm (green). The cell construction for both types of displays is similar with the exception of the alignment layer. Both are constructed from indium tin oxide (ITO)-glass substrates coated with SiO_2 for insulation. In the polymer stabilized cells an additional layer of rubbed polyimide is used to induce homogeneous surface alignment of the liquid crystal. A consequence of this homogeneity is that the focal conic texture is unstable. To achieve bistability, a dispersed polymer network is introduced to the liquid-crystal medium. This is accomplished by adding a low concentration of monomer, 4,4′-Bisacryloyloxy biphenyl (BAB), and UV sensitive photoinitiator to the liquid-crystal material prior to filling the cell. Cells with monomer concentrations of 0.37, 0.52, 0.74, 1.02, and 1.21 wt% are used in this study. Upon vacuum filling the cell, an electric field is applied and the cell is exposed to UV light thus forming a polymer network.

In contrast to the polymer stabilized cells, surface stabilized cells do not require polymer network for stabilization. In these cells, inhomogeneities induced by an additional unrubbed polymer film layer between the SiO_2 layer and the liquid crystal result in stable imperfect planar and focal conic textures at zero field. Here, cells whose surfaces are treated with silane, polymethylmethacrylate (PMMA), cellulose acetate butyrate or CAB, and polyimide without rubbing are investigated. The relative anchoring tilt stated for each polymer has been determined through capacitance measurements.

B. Measurements

The experimental apparatus is shown in Fig. 1. We use an integrating sphere with light derived from a tungsten halogen lamp and focused through a diffuser. The cell is mounted in the center of the sphere, the mount extending from a rotation stage external to the sphere. Luminance (Y) and color coordinates (u',v') are measured using a SpectraScan PR704 spectrophotometer equipped with a telescopic lens and positioned opposite the entrance aperture. This configuration provides a means of measuring the reflection as a function of the viewing angle with diffuse illumination. Although such an illumination geometry is commonly used for colorimetric measurements, in practical instances it is not a true representation of a perception of a viewer who is looking at the display. For such a person in a diffusely lit room the finite dimension of the person's face may severely limit the specular reflection. To simulate such conditions, a disk of absorbing material is placed around the detector. We refer to this geometry as partially diffuse lighting scheme. The goal is to minimize specular reflection arising from a cone of light around the center of the detector. Within this cone ($\pm 10°$), henceforth referred as the normal viewing cone, specular component of reflected light is minimal. Light reaching the detector in normal viewing cone is, therefore, diffusely reflected light. In general, both inhomogeneities and Bragg scattering may contribute to this reflection. However, as is shown here, the reflection is dominated by Bragg scattering.

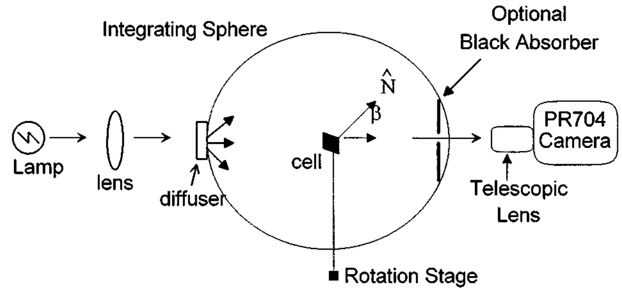

FIG. 1. Experimental apparatus for diffuse and partially diffuse lighting. Partially diffuse illumination is accomplished by placing the optional black absorber, with a small aperture in the center, internal to the integrating sphere in front of the exit aperture.

III. CALCULATIONS

The photometric quantities of interest are the luminance and contrast while the colorimetric quantities are the Center for Integrated Electronics (CIE) 1976 ($L^*u^*v^*$)-space color-difference formulae. Quantitatively, these are given by:[10]

$$L^*(\beta)=116\left[\frac{Y(\beta)}{Y_n}\right]^{1/3}-1 \tag{1a}$$

$$u^*(\beta)=13L^*(\beta)[u'(\beta)-u'_n] \tag{1b}$$

$$\nu^*(\beta)=13L^*(\beta)[\nu'(\beta)-\nu'_n], \tag{1c}$$

where $Y,L^*,(u',v')$ are the luminance, lightness, and color coordinates, respectively, and (u^*,v^* are scaled color coordinates. The subscript n designates the measurement of a nominally white diffuse reflector, in this case $BaSO_4$ ($R > 98\%$), at $\beta=0°$. Viewing angle variations are calculated relative to the normal viewing angle response, that is

$$\Delta L^* = L^*(\beta) - L^*(0) \quad (2a)$$

$$\Delta u^* = u^*(\beta) - u^*(0) \quad (2b)$$

$$\Delta v^* = v^*(\beta) - v^*(0). \quad (2c)$$

In this system, the change in total color (ΔE^*_{uv}, hue (ΔH^*_{uv}, and chroma (ΔC^*_{uv} are given[10] by

$$\Delta E^*_{uv} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2} \quad (3)$$

$$\Delta H^*_{uv} = \sqrt{(\Delta E^*_{uv})^2 - (\Delta L^*)^2 - (\Delta C^*_{uv})^2} \quad (4)$$

$$\Delta C^*_{uv} = \sqrt{[u^*(\beta)]^2 + [v^*(\beta)]^2} - \sqrt{[u^*(0)]^2 + [v^*(0)]^2}. \quad (5)$$

From Eq. (4) we have that

$$\Delta E^*_{uv} = \sqrt{(\Delta L^*)^2 + (\Delta H^*_{uv})^2 + (\Delta C^*_{uv})^2} \quad (6)$$

Lastly, the change in saturation is given by,

$$\Delta s^*_{uv} = \frac{\Delta C^*_{uv}(\beta)}{\Delta L^*(\beta)} - \frac{\Delta C^*_{uv}(0)}{\Delta L^*(0)}. \quad (7)$$

We note that we have used the familiar colorimetric formulae to describe the color-difference response for these Ch-LCDs. However, these formulae are calculations performed on the luminance and color coordinates to describe the human perception of changes in color relative to a white diffuse reflector. For transmissive displays where wavelength sensitivities are undesirable a white diffuse standard is appropriate. However, for a display, be it transmissive or reflective, which is intentionally colorful the use of a white standard may lend such calculations misleading. We do not compare with a chromatic standard, thus the magnitude of the aforementioned quantities is meaningless while the relative dependence on viewing angle is not.

IV. RESULTS

We show the photometric and colorimetric (color-difference) response as a function of the viewing angle (β) for both diffuse and partially diffuse illumination. Prior work on these types of display cells suggests that the two types of cells differ significantly with respect to their specular and diffuse components of reflection.[8] The polymer stabilized cells have a significant specular component and relatively weak diffuse component while the surface stabilized cells have nearly equal specular and diffuse reflection. To establish the effect of our illumination geometry on the relative strength of specular and diffuse reflection, a purely specular (mirror) and a purely diffuse reflector (a plate coated with $BaSO_4$) were used as standards. Response from these standards establishes the optical characteristics of both illumination and viewing geometries.

A. Response from a mirror and $BaSO_4$

Figure 2 shows normalized luminance of mirror and $BaSO_4$ as a function of the viewing angle for both illumination schemes. The angular dependence of the response of the mirror using diffuse illumination remains constant with a standard deviation (σ) of 1.9%. This indicates that the light

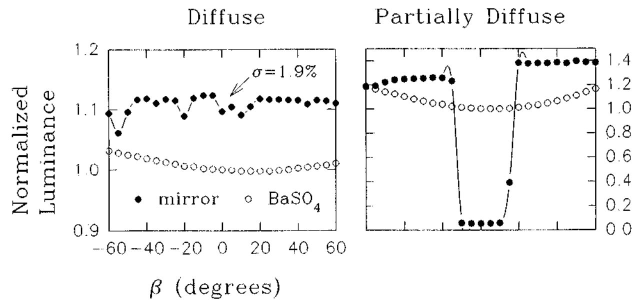

FIG. 2. Luminance as a function of the viewing angle (β) for a mirror and a white standard, $BaSO_4$, using diffuse and partially diffuse illumination. The term σ denotes the standard deviation indicating the diffuse source is diffuse within ~1.9%. The horizontal axes are scaled the same.

within the integrating sphere is purely diffuse. Using partially diffuse illumination we see that the mirror response is zero about the normal viewing cone and returns to a constant value outside of this region. This indicates that within the viewing cone containing the absorber, specular reflection has a insignificant contribution in the reflected light. Therefore, in the partially diffuse geometry, luminance within the normal viewing cone arises from diffuse reflection. Furthermore, the response of the mirror outside the normal viewing cone suggests that presence of the absorber placed inside the integrating sphere does not perturb the uniformity of the light field outside the normal viewing cone. Using $BaSO_4$, a constant luminance ($\pm$10%) is observed regardless of geometry. Obstruction of a portion of the sphere, thus, does not disturb the diffuse nature of the light within the cone at any angle. All measured luminance is then normalized with respect to the response of the $BaSO_4$ at $\beta=0°$ in each illumination scheme.

B. Response from polymer network stabilized cholesteric liquid-crystal displays

Figure 3 shows the results of the normalized luminance (compared to $BaSO_4$) and contrast using both illumination

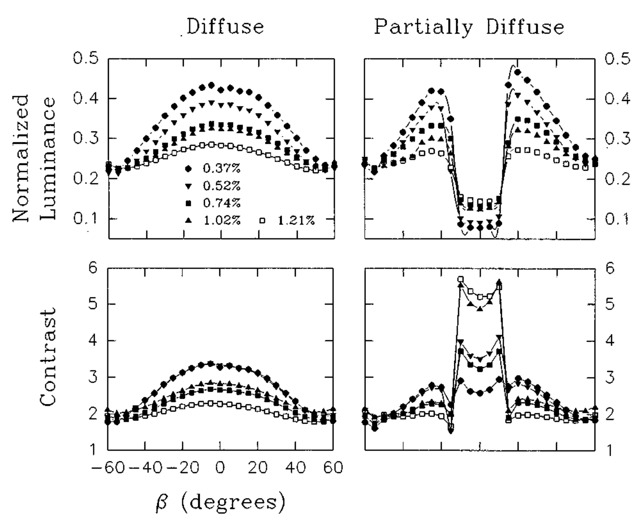

FIG. 3. Luminance and contrast as a function of the viewing angle (β) for the polymer network stabilized cells using diffuse and partially diffuse illumination. All horizontal axes are scaled the same.

schemes for the polymer network stabilized Ch-LCDs. In diffuse illumination, the luminance at small angles decreases with increasing polymer concentration. At large angles, however, no change is observed. The general trend observed in concentration dependence of luminance is also present in the contrast ratio measurements presented. As polymer concentration increases, both luminance and contrast ratio decrease. The effect of polymer concentration on these values is a function of the viewing angle. In particular, larger angles experience a smaller change by the presence of the polymers. Comparison between the luminance and contrast curves suggests that the contrast is predominantly controlled by the bright state luminance.

The results observed in the partially diffuse lighting scheme can be divided into: (i) inside the normal viewing cone ($\beta < \pm 10$) and (ii) outside the viewing cone regions. Within the viewing cone the magnitude of luminance increases with polymer concentration. Outside of this cone those cells with the lowest polymer concentration again have the highest luminance values. Since specular reflection is suppressed in the former region, it is concluded that an increase in the polymer concentration results in an increase in the diffuse reflection. The contrast ratio within the viewing cone increases with polymer concentration. Outside of the cone, the reverse is true. The pronounced contrast within the viewing cone suggests that the dominant mechanism in diffuse reflection with the normal viewing cone is Bragg scattering. For non-Bragg scatterng a small contrast ratio between the ''on'' and the ''off'' states is expected.

Figure 4 shows the color-difference response of polymer stabilized cells under both lighting schemes. Cells with higher polymer concentrations exhibit smaller variations in all colorimetric quantities. In a diffuse lighting scheme, angular dependence of changes in the total color are predominantly dictated by changes in the hue. In the partially diffuse illumination, on the other hand, the change in total color appears to be predominantly influenced by the structure in lightness and chroma. That is to be expected since variations in lightness and chroma are strongly dependent on luminance, whereas any variations in hue result from a change in the color coordinates. Since changes in the color quantities are presented, rather than actual values, the results obtained outside the normal viewing cone are strongly dependent on the illumination geometry. In the partially diffuse illumination, large changes in the luminance and chroma are obtained as the viewing angle is increased from normal viewing angle (void of specular) to larger angles (where both diffuse and specular reflections present). The large, discontinuous changes in the luminance and chroma as the viewing angle is increased enhance the total color changes between the normal and large viewing angles.

C. Response from surface stabilized cholesteric liquid-crystal displays

In this section the photometric and colorimetric properties of the surface stabilized cell are presented. Because this work is strongly motivated towards applications[11] in partially diffuse lighting schemes, the effects of surface stabilization are compared to those of polymer stabilization. For the basis

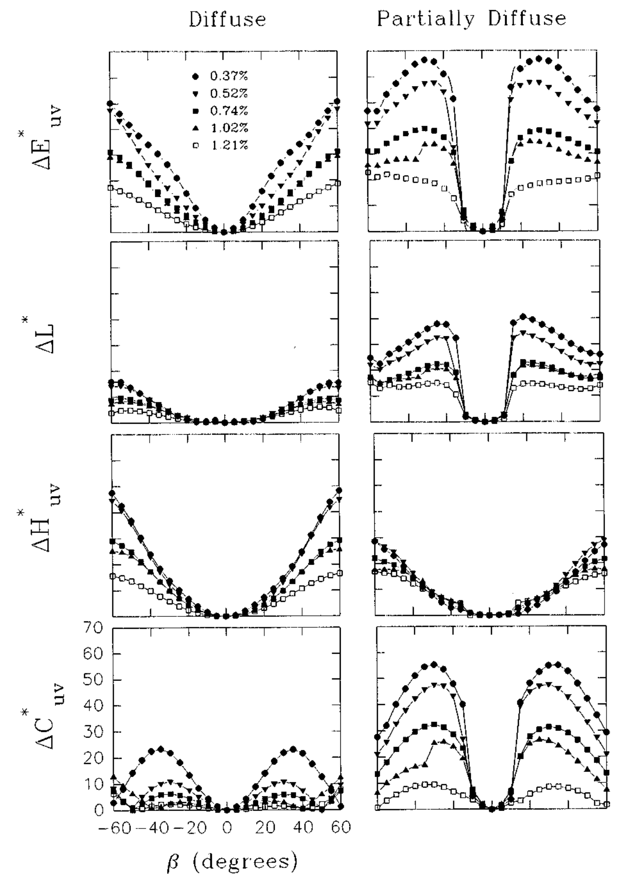

FIG. 4. Change in total color (ΔE^*_{uv}), change in lightness (ΔL^*), change in hue (ΔH^*_{uv}), and change in chroma (ΔC^*_{uv}) as a function of the viewing angle (β) for the polymer network stabilized cells using diffuse and partially diffuse illumination. All vertical and horizontal axes are scaled the same.

of this comparison results from cells with largest polymer concentration (1.21%) are included. This cell was chosen since it demonstrated the least angular dependence.

Figure 5 shows the normalized luminance (compared to $BaSO_4$) and contrast ratio of surface stabilized Ch-LCDs in both illumination schemes. In diffuse lighting geometry, it is seen that CAB outperforms other surface treated cells. While its luminance is equivalent to that of the reference polymer stabilized cell, its contrast ratio can be twice as large. With the exception of CAB treated cell the contrast ratio does not follow luminance. This suggests that the dark scattering is also a function of the surface treatment.

Using partially diffuse illumination all surface stabilized cells show greater luminance, in the normal viewing cone, than all polymer stabilized cells. The performance of all surface treated cells are equivalent within this cone. While this trend continues at larger angles, the relative performance of different surface treatments does not mimic that observed in diffuse lighting. In particular, in angles larger than the normal viewing angle, unrubbed polyimide (PI) outperforms CAB and polymer stabilized cell. The origin of this is not understood. Contrast ratio in the viewing cone suggests that Bragg scattering is the dominant mechanism for diffuse reflection within this region. As in the case of diffuse lighting

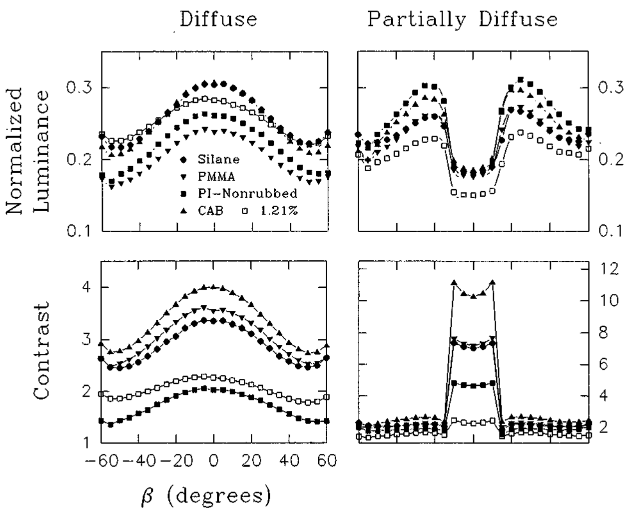

FIG. 5. Luminance and contrast as a function of the viewing angle (β) for the 1.21% polymer network stabilized cell and all surface stabilized cells using diffuse and partially diffuse illumination. All horizontal axes are scaled the same.

illumination, contrast ratio of CAB treated surfaces is greater than other cells. Unlike luminance, the ordering of contrast ratio performance follows that observed in the diffuse lighting geometry. This is a further indication that surface treatment affects the response of the focal conic state (dark state). Finally, there does not seem to be any correlation among surface tilt and luminance with either lighting scheme.

Colorimetric properties of surface treated cells using diffuse and partially diffuse illumination are presented in Fig. 6. Using diffuse illumination, all colorimetric properties of surface stabilized cell are larger than the reference polymer stabilized cell. However, the surface treated cells outperform cells with smaller polymer concentrations. In particular, changes in the hue and chroma of the surface stabilized cells are less than cells with small polymer concentrations. In this illumination, the total color is predominantly influenced by a variation in the hue and chroma as opposed to lightness. Finally, colorimetric response of unrubbed PI has smallest variation with viewing angle.

Results from partially diffuse illumination show that within the normal viewing cone all colorimetric parameters experience little change. Changes outside this cone resemble in shape to that obtained from reference polymer stabilized cell. Recall that the reference cell was chosen since it demonstrated the smallest angular dependence. Changes in the total color outside the normal viewing cone appear to be most influenced by the hue structure. Comparing the change in hue in Fig. 4, it is seen that changes in hue structure of the surface stabilized cells are less sensitive to the lighting scheme than the polymer network stabilized cells.

Lastly, Fig. 7 summarizes changes in saturation for both cell types, in both lighting schemes. In diffuse lighting, it can be seen that addition of polymer results in a decrease in the saturation. Saturation changes in the surface stabilized cells are opposite in sign to that of cells with low polymer concentrations.

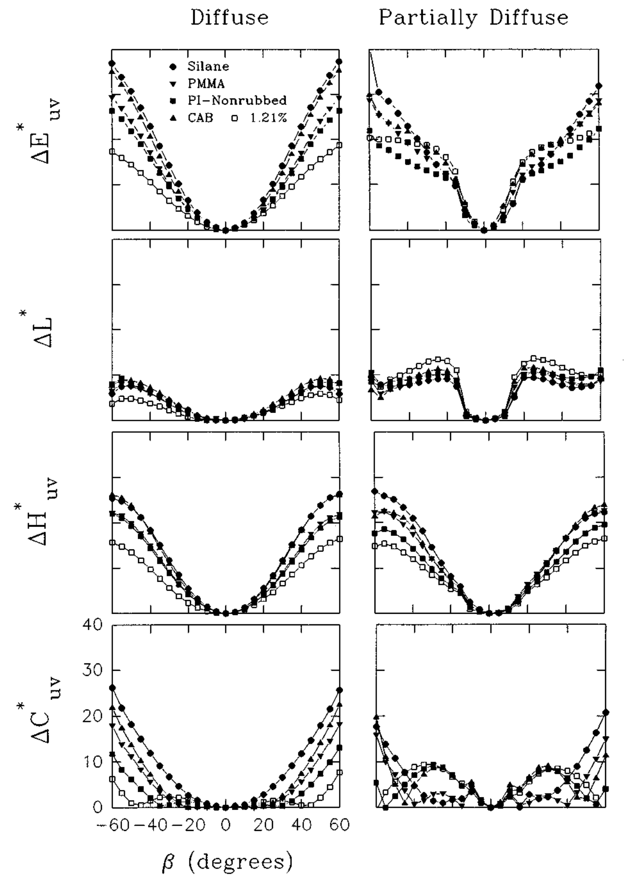

FIG. 6. Change in total color (ΔE^*_{uv}), change in lightness (ΔL^*), change in hue (ΔH^*_{uv}), and change in chroma (ΔC^*_{uv}) as a function of the viewing angle (β) for the 1.21% polymer network stabilized cell and all surface stabilized cells using diffuse and partially diffuse illumination. All vertical and horizontal axes are scaled the same.

V. DISCUSSION

The observed behavior in the photometric and colorimetric properties of these cells can be explained in terms of Bragg reflectors. In perfect planar texture, the Ch-LCD can be thought of as a finite number of wavelength selective mirrors placed parallel to the surface of the cell. These mirrors totally reflect circularly polarized light with helicity equal to that of the cholesteric material. Change in the angular distribution of these mirrors results in an increase in the field of view of the detector. In other words, light incident on the display at larger angles with respect to the normal is detected. In an integrating sphere all angles of incidence are present for the white light source. If the total number of reflectors remains constant, total intensity of the light incident on the detector does not change. The wavelength of the light, on the other hand, will now contain a blueshifted component in accordance with angular dependence of the Bragg condition.

The simple model presented above can be used to explain the observed behavior of the cells. Focusing first on the polymer stabilized cells, addition of polymer to the mixture results in a decrease in the peak luminance and contrast ratio from these cells. Direct interpretation of this is that introduc-

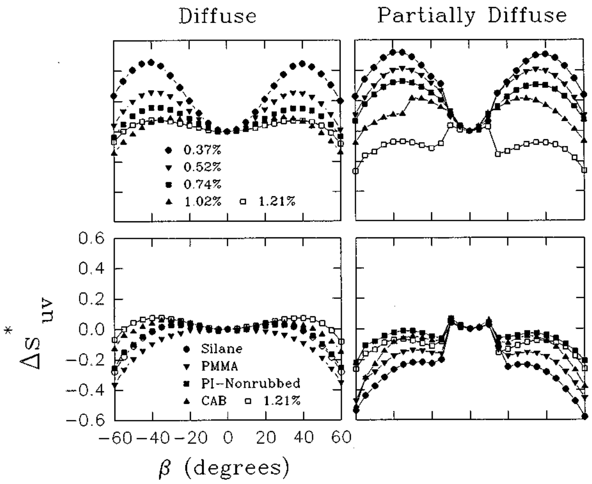

FIG. 7. Change in saturation (Δs^*_{uv}) as a function of the viewing angle (β) for all cells using diffuse and partially diffuse illumination. All vertical and horizontal axes are scaled the same.

tion of polymers increases diffuse scattering. Recall that diffuse scattering (nonspecular) arises from Bragg and non-Bragg scattering mechanisms. The former was discussed above and the latter may arise from other effects such as defect scattering. Decrease in total luminance at $\beta=0°$ suggests that addition of polymer reduces the number of Bragg reflectors by increasing the defect concentration. Luminance at $\beta=60°$ remains constant in all polymer stabilized cells, suggesting that the reflective properties at large angles are not affected by the polymers. The number of Bragg reflectors at large angles, thus, is not significantly altered by the presence of polymers. Information about the angular distribution can be obtained from partial illumination geometry data. There, luminance observed in the normal viewing angle is void of specular and is thus purely diffusive. Within this region, the luminance increased with polymer concentration. This reiterates that addition of polymers increases the diffuse scattering of the cell. The contrast ratio in the normal viewing angle suggests that Bragg scattering dominates the diffuse scattering response. An increase in the non-Bragg reflections would increase the backward scattering of the focal conic state (dark state) resulting in a smaller contrast ratio than observed. Therefore, it can be concluded that addition of polymer concentration reduces the number of Bragg reflectors while at the same time widening the angular distribution of Bragg reflectors present. The constant luminance at larger angles suggests that even though the distribution of the Bragg reflectors is increased by polymer concentration, they are still confined to a small cone around the cell normal.

The angular dispersion effect is in agreement with the observed angular dependence of the colorimetric properties. A large hue change is observed for cells with small polymer concentrations. This is consistent with an angular distribution of the Bragg reflectors confined to a small region around the cell normal. As the observation angle is increased, the Bragg reflected wavelength is also changed. Higher polymer concentrations with wider distribution are less sensitive to angular distribution. It should be noted that hue changes are the dominant mechanism for total color change in these cells.

The important feature which distinguishes the response of surface from polymer stabilized cells is the offset observed with different surfaces. While the angular dependence of luminance does not change considerably with surface treatment, there is a total shift in luminance curve for different surface stabilized cells. As in case of polymer stabilized cells, shift in total luminance can be understood as a change in the number of reflectors present. Unlike polymer stabilized cells, the luminance at large angles is also decreased. This suggests that the angular distribution of Bragg reflectors is larger in the surface stabilized cells. Furthermore, the number of reflectors present is a function of the surface treatment. This behavior is also observed in the partial illumination geometry. In both illuminations, the highest luminance and contrast ratio is obtained for CAB treated surfaces.

The similarity in the angular dependence of luminance between different surface treatments is also present in the colorimetric properties. Observed color changes are in general similar to that of the reference cell (high polymer concentration). Maximum hue changes of 20%–25% at $\beta=60°$ are much smaller than low concentration polymer concentration stabilized cells. Surface stabilization, therefore, can induce large angular distribution of helix axes.

An important issue which remains unclear is the effect of surface treatment on the focal conic state. The large variation in performance of different surface in regards to luminance and the contrast ratio suggests that surface treatment may affect the scattering efficiency of the focal conic state. This is currently under investigation.

It should be emphasized that the application of the usual colorimetric calculations used to characterize these displays is unique in that these displays are colorful as opposed to being preferentially wavelength independent. Without the use of a chromatic standard such calculations may be misleading. Therefore, angular dependence, rather than absolute values, are used for analysis.

VI. CONCLUSION

Photometric and colorimetric properties of polymer and surface stabilized bistable cholesteric displays were studied using two illumination geometries. Luminance, contrast, and color-difference calculations are presented as a function of the viewing angle in the two geometries. The results indicate that suitability of the stabilization technique is dependent on the illumination geometry. In particular, for displays in which specular reflection has been suppressed in the viewing cone, surface treatment represents the best method of stabilization. If the viewing angle allows specular reflection, polymer stabilization yields the largest luminance and contrast ratio. Additionally, the hue variation with viewing angle for the surface stabilized cells is less dependent on the lighting scheme. This is desirable for applications involving arbitrary lighting schemes.

ACKNOWLEDGMENT

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