A FULL-COLOR FIELD-SEQUENTIAL COLOR DISPLAY

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Abstract—A full-color field-sequential display using a "monochrome" CRT and a color switch based upon a very fast liquid-crystal cell, the "pi-cell," is described. Possible configurations and display-viewing characteristics are discussed.

I. INTRODUCTION

Field-sequential full-color displays utilizing liquid-crystal technology can potentially offer a number of attractive features relative to more conventional color-display systems such as the shadow-mask CRT. Figure 1(b) shows a picture taken from the screen of a high-resolution shadow-mask display, while Fig. 1(a) shows a picture taken at the same magnification from a field-sequential display. The lack of screen patterning in the field-sequential display yields an image having superior definition. A second feature of the field-sequential display is that the display goemetry is not constrained by shadow-mask considerations. This allows devices of wide size ranges and peculiar aspect ratios. These two features are highly desirable for desk-top computer or instrumentation-equipment displays.

Liquid-crystal-based color switches have been proposed by a number of authors. These include multiple dye-cell configurations,[1] multiple twisted-nematic cells used in conjunction with birefringent films,[2,3] tunable birefringence liquid-crystal cells used in conjunction with neutral polarizers,[4] and twisted-nematic cells used in conjunction with color-selective and neutral polarizers.[2,5,6,7] The latter of these approaches provides the best color saturation and the largest cone of view. Field-sequential color systems using dye cells have been proposed,[8] as well as systems using twisted-nematic cells and color-selective polarizers.[5,9,10] To be able to operate these color switches fast enough to be used in a field-sequential system, two-frequency liquid-crystal materials have been employed. It is, however, difficult to obtain uniform switching of large displays, plus the temperature range is limited and drivers are costly. Another rapidly

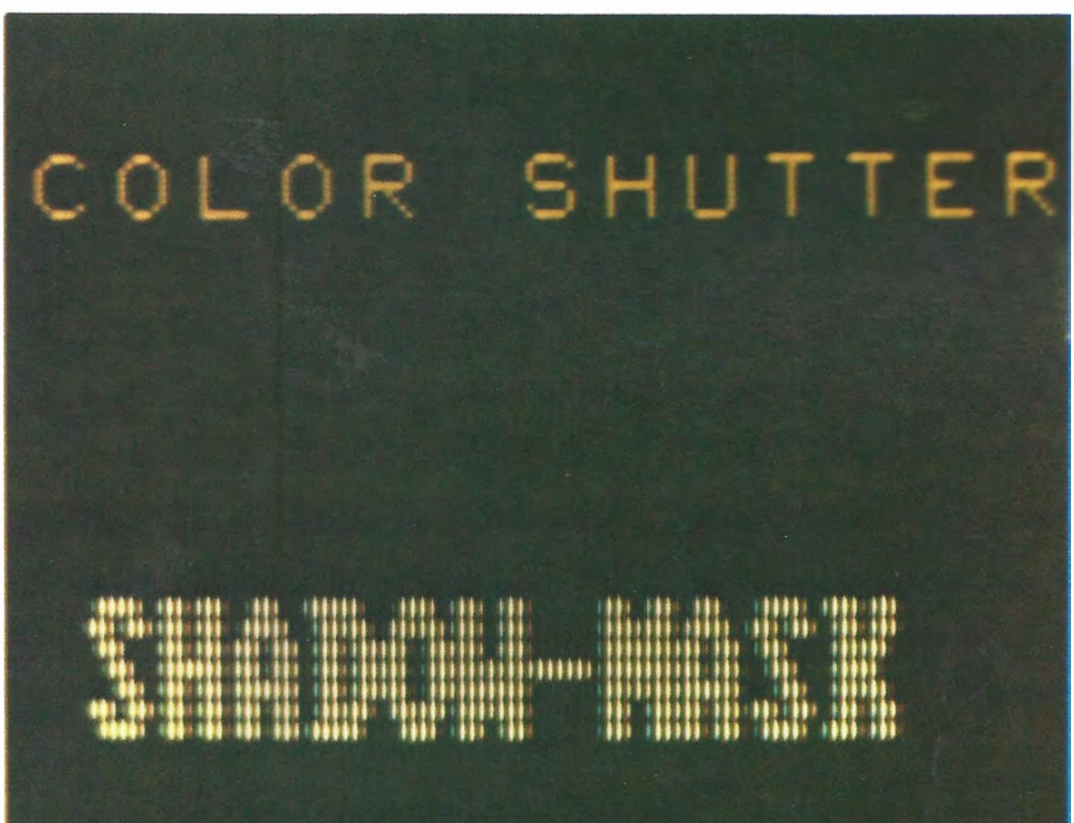

FIG. 1. Pictures taken from the screen at the same magnification from (a) a field-sequential display and (b) a shadow-mask display.

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switching liquid crystal device has been described by Fergeson.[11] However, the cone of view of this device is somewhat limited.

The pi-cell, described by one of the authors in a previous paper,[12] can be used in systems that overcome many of these shortcomings and that exhibit excellent color gamut, wide viewing angles, fast switching speeds, wide operating-temperature range, low power consumption, and simple liquid-crystal cell driving schemes.

The approach described in this paper uses the pi-cell in conjunction with pleochroic polarizers. The basic idea involves the use of a CRT with a phosphor having mulitple emission peaks that can be individually selected for transmission through the pleochroic polarizers by sequentially energizing selected liquid-crystal cell combinations. Figures 2 and 3 show examples of two such full-color systems. The configurations shown are only examples of a wide range of polarizer orientations and spectral combinations that can result in usable full-color systems. As will be shown later, certain configurations offer significant advantages relative to others, and a careful analysis should be made in order to arrive at an optimal system based upon pi-cell, polarizer, phosphor, and system considerations.

II. THE PI-CELL

In a three-field-sequential system, each frame must be switched at a 60-Hz frame rate (180-Hz field rate) in order to prevent flicker. Single-frequency twisted-nematic devices do not switch rapidly enough to be used in such systems. Two-frequency devices have been used in two-field-sequential systems but have exhibited problems with uniform switching over a large area, temperature range, and electrical driver requirements.

The pi-cell is a single-frequency tunable birefringence device. Conventional tunable birefringence devices relax slowly due primarily to the optical-bounce phenomenon described by van Doorn[13,14] and by Berreman.[15] The bounce is the result of a torque being applied to the director by molecular flow in the relaxing device. In the pi-cell, the alignment is modified such that the effects of flow alignment do not impose a torque on the directors near the center of the cell, and the device relaxes quickly (Fig. 4). The electro-optical response of a pi-cell between parallel polarizers is shown in Fig. 5. The thickness of the device is controlled such that it produces a half-wave retardation for normally incident light when the director field is in the off-state configuration. The cone of view of the device is quite large as a result of the previously described optically self-compensating nature of the director configuration in the off state.

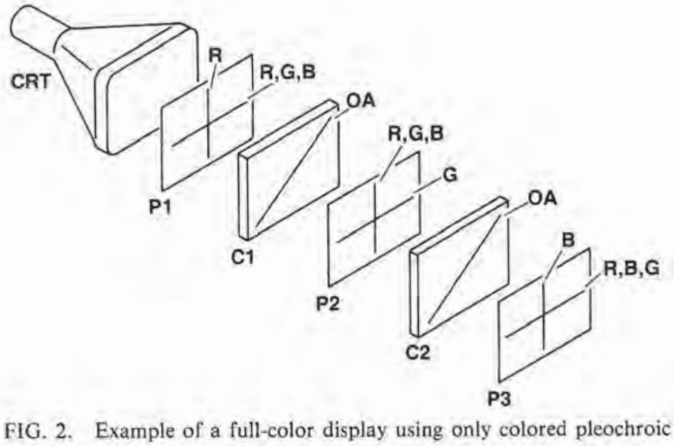


FIG. 2. Example of a full-color display using only colored pleochroic polarizers. Note that each polarizer transmits only one color along one axis and all (RGB) colors along the other. These transmission characteristics are matched to the emission characteristics of the CRT phosphor. By selectively energizing C1, C2, or both, the system can transmit red (R), green (G), blue (B), or white (RGB) to the viewer. The optic axis of the pi-cell is labelled "OA."

III. TWO FULL-COLOR COLOR-SWITCHING SYSTEMS USING THE PI-CELL

While the pi-cell switches rapidly, a complicating factor results because its optical effect is based upon the phenomenon of variable retardation rather than on optical activity as in the twist cell. This means that only one

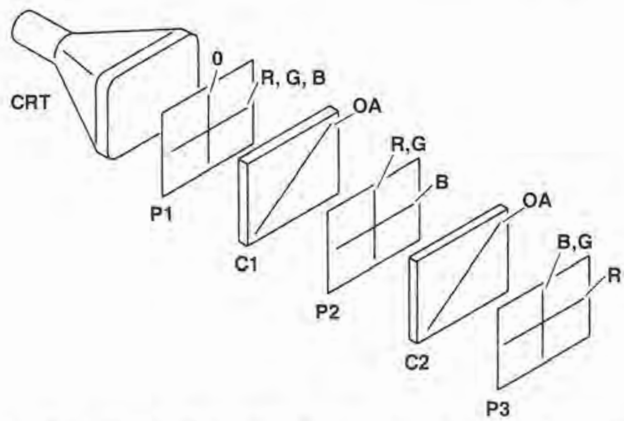


FIG. 3. Example of a color display using both pleochroic color polarizers and a neutral plechroic polarizer. The axis labelled "0" in P1 is the absorption axis of the neutral pleochroic polarizer.

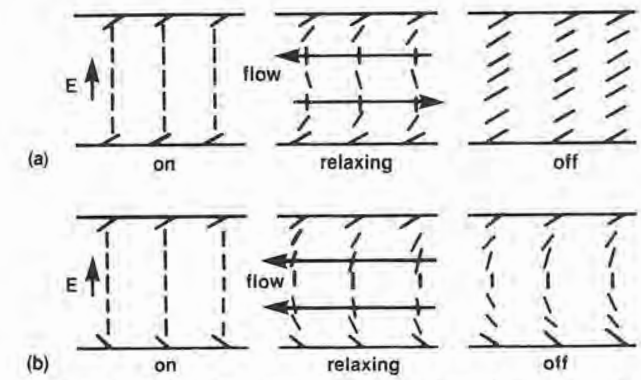


FIG. 4. (a) Material flow occurring in a relaxing uniformly aligned cell. A consequence of this flow is the application of a "backwards" torque on the local directors near the center of the cell. This effect slows the relaxation to the off state. (b) The material flow occurring in a relaxing pi-cell. No torque is applied to the local directors near the center of the cell, and the director field relaxes quickly to the off-state configuration.

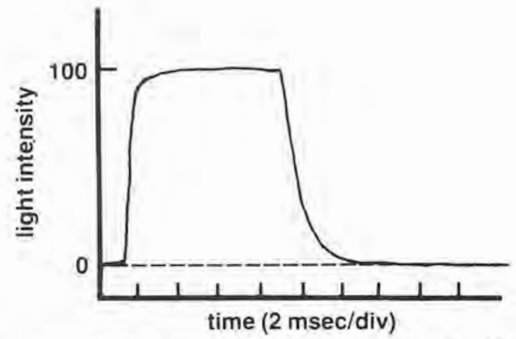


FIG. 5. Electro-optical response of a pi-cell. The light transmission ($\lambda = 0.545$ nm) was measured for the cell placed between parallel polarizers at 45° to the liquid-crystal surface-alignment direction.

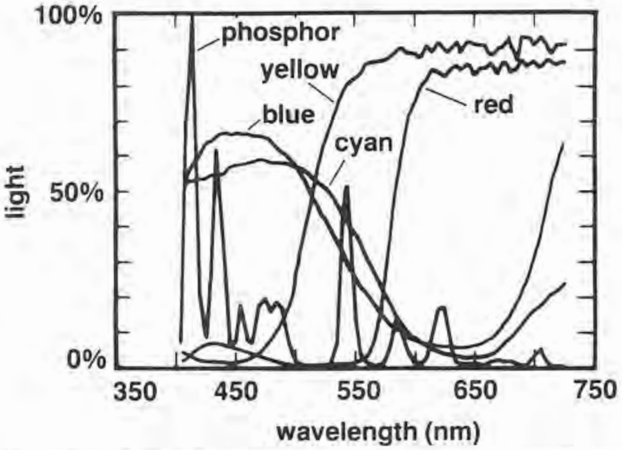
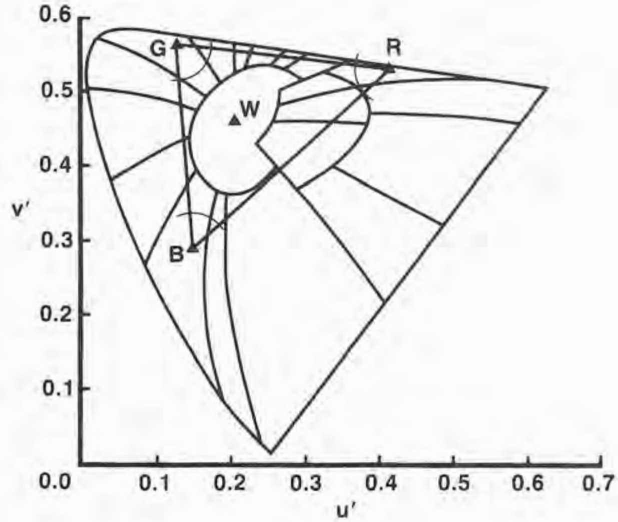


FIG. 6. Typical phosphor spectrum and pleochroic polarizer transmissivities for a full-color LC/CRT system.

wavelength of the incident linearly polarized light will be transformed to be linearly polarized with the polarization direction orthogonal to that of the incident light. As a consequence, it is not obvious that each of the color states of a color switch using the pi-cell will transmit pure colors devoid of contaminating leakage from colors of the other switch states.

A later paper will show the general-case color switch and how to use variable retarders with it. Here, by way of two examples, it is shown that it is possible to obtain the three primary colors using the pi-cell.

For the system shown in Fig. 2 and with both cells on, it is evident that only green light is transmitted by the switch as the cells have no effect on the polarization state of the light. When cell C1 is on and cell C2 is off, light exits the first polarizer and passes unaffected through cell C1. Exiting the middle polarizer, there is the red light vertically polarized and green light horizontally polarized. If cell C2 is tuned to be a half-wave retarder for green light in its off state, the effect of the cell will be to transform the linearly polarized green light to be vertically linearly polarized. The final polarizer will then absorb all of the green light and transmit purely red light. Similarly, when cell C1 is tuned to be a half-wave retarder for green light in its off state, the state when cell C1 is off and cell C2 is on can be seen to transmit purely blue light.



	u'	v'	fL
R	0.413	0.537	12.5
G	0.121	0.564	18.6
B	0.148	0.289	9.8
W	0.208	0.459	40.1

FIG. 7. Color gamut of the full-color LC/CRT display.

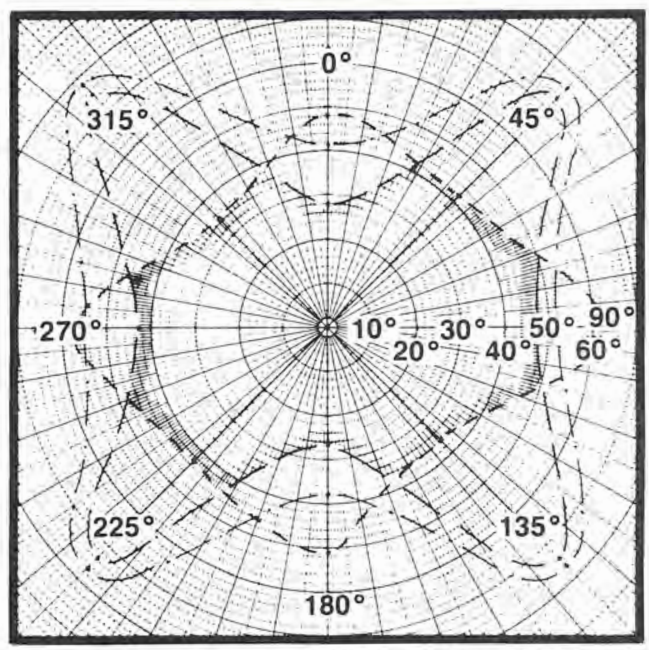
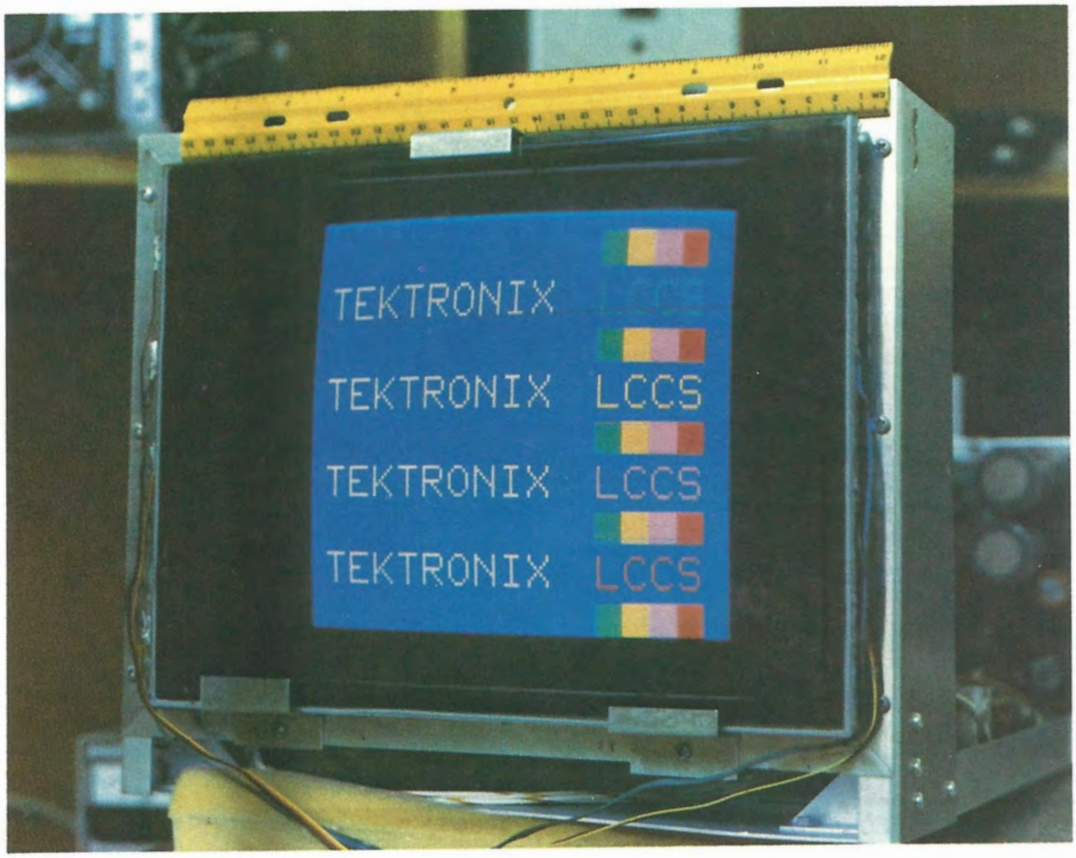
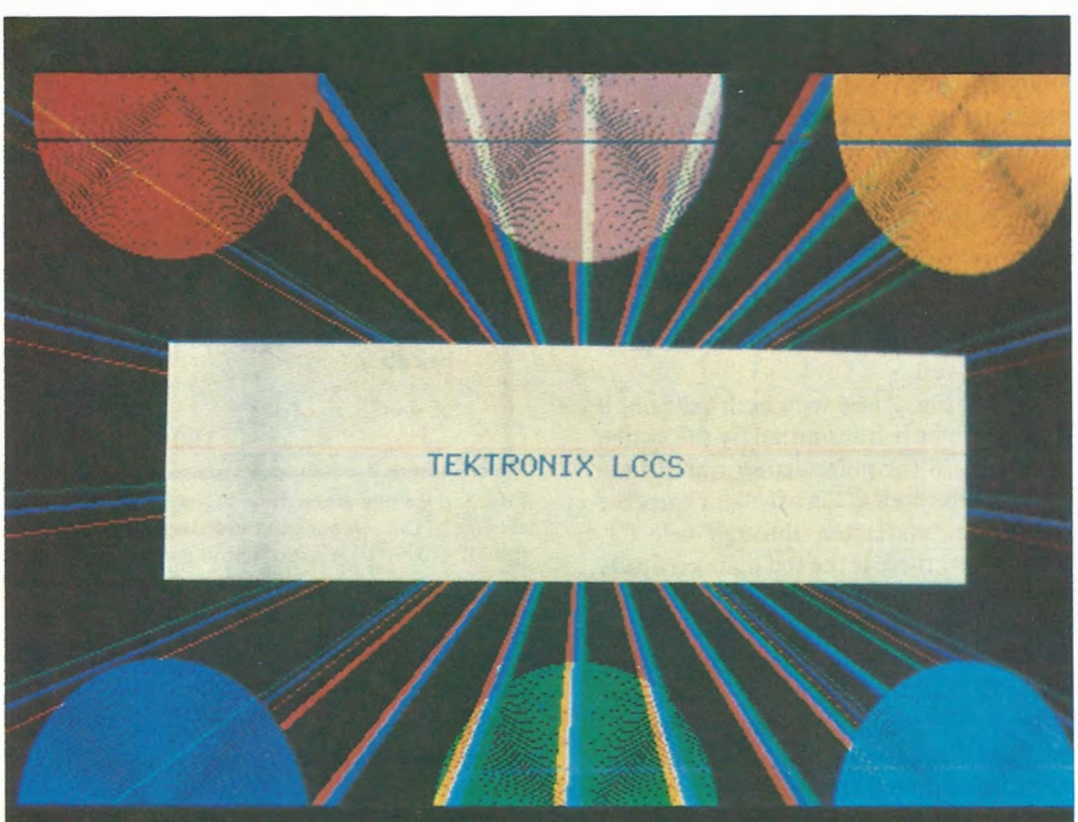


FIG. 8. Viewing angle versus azimuthal angle for a 0.05 chromaticity variance. The chromaticity variance is calculated from $CV = [(\Delta u')^2 + (\Delta v')^2]^{1/2}$ where u' and v' are the chromaticity coordinates. - - - red; — • — green; — — blue.

As another example, consider the system shown in Fig. 3. When cell C1 is on and cell C2 is off, the combination of the first and middle polarizers (cell C1 has no effect) causes only blue horizontally polarized light to be transmitted to cell C2, which rotates the polarization direction of the blue light to be nearly vertical so that it is transmitted by the final polarizer. Similarly, it can be seen that when cell C2 is



(a)



(b) FIG. 9. Laboratory 13-in. field-sequential color monitor.

on and cell C1 is off, purely green light is transmitted. In the case where both cells are off, cell C1, if tuned to be a half-wave retarder for blue light, will cause only green and vertically polarized red light to be transmitted by the middle polarizer. When cell C2 is tuned to be a half-wave retarder for green light, the polarization direction of the green light will be transformed to be exactly horizontal and the green light will be absorbed by the final polarizer. Consequently, only red light will be transmitted in this state.

IV. SYSTEM RESULTS

Figure 6 shows the phosphor spectra and transmissivities of the set of color-selective polarizers used in the full-color liquid-crystal color-switch system. The phosphor is sharply peaked to improve color separation, and the polarizer densities are chosen to provide optimal tradeoff between color purity and brightness.

The colors and their brightness values resulting from this phosphor/polarizer combination are shown in Fig. 7. The red and green primaries are very close in chromaticity to the standard television red and green. Blue is somewhat less saturated due primarily to the inefficiency of the blue polarizer.

The brightness values listed in Fig. 7 are for an input CRT brightness of 720 fL. Since the white brightness is 40 fL, the white efficiency of the display is approximately 5.6%. The theoretial maximum efficiency of the full-color LC/CRT display is 16.7%. The shortfall between actual and theoretical display performance is due mainly to limitations in the dichroism of the dyes used in the polarizers.

The contrast of the LC/CRT display is very high. This is a consequence of the time-averaged transmissivity of the color switch being rather low. Thus, the color switch acts as a low-transmission "faceplate" for the CRT, severely attenuating unwanted ambient reflections.

The polar viewing angle of the display has been measured as a function of azimuthal direction and color state. The polar viewing angle has been defined as the polar angle at which the deviation in chromaticity space is equal to 0.05 chromaticity units. This deviation is referenced to the chromaticity coordinates of each primary color viewed normal to the CRT screen. Chromaticity variances of 0.05 are shown for each primary as arcs in Fig. 7. The polar angle that results in chromaticity variance of 0.05 is plotted in Fig. 8 along the radial direction. Figure 8 shows that the viewing angle is minimum at approximately 27° along the 0° and 180° azimuths. The green primary is the viewing-angle limiter along these azimuths. The red and blue primaries do not exceed the 0.05 variance until beyond 40°.

Figures 9(a) and (b) show our laboratory 13-in. system from which the data in this section is obtained.

ACKNOWLEDGEMENTS

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