Design of Hologram for Brightness Enhancement in Color LCDs

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Abstract

Transmission holographic film for brightness enhancement in full color reflective LCDs is proposed. The hologram is attached to the front of the LCD. The goal is paper-like brightness within the viewing zone under typical ambient lighting conditions. Optimum viewing and illumination angles have been identified. Modeling and measurements on holograms show that a viewing zone of 20° × 40° will provide a 12X film gain which is adequate to maintain a wide color gamut and brightness.

Introduction

It is generally agreed by those working in the area of reflective displays that the ultimate goal is an electronic display that looks like paper. White, 24 lb., office paper reflects 80% of the incident light with a contrast of 10:1 for laser print. Glossy, magazine quality paper has an even better contrast of 25:1, though with lower reflectance. The viewing angle is ±90° in all directions with no perceptible change in contrast or brightness.

On the other hand, reflective, color LCDs are at a significant disadvantage when compared to paper due to optical losses and glare. For example, modeling [1] indicates that the color LCD of the type shown in Fig. 1 reflects only 8% of the incident light. Front surface glare further reduces the effectiveness of the useful reflected light.

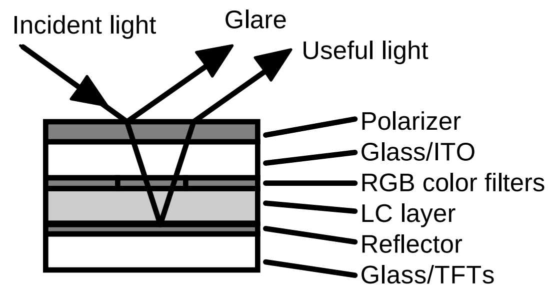

Figure 1. Simplified stackup of a reflective color LCD with an internal reflector [2]. Total reflected light is about 8% of the incident light. Note that the reflected light, useful for viewing the display, is aligned with glare making the display unreadable where the reflected useful light is maximum. [The diffuser is not shown for clarity]

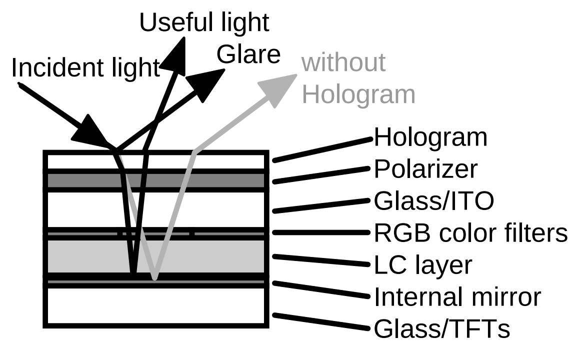

Figure 2. Proposed stackup of color reflective LCD with a transmission hologram on the top. Light path shown as black lines. Gray line indicates light path without hologram. The hologram both steers and scatters the incoming light.

Our proposed approach to make a color LCD more paper-like is depicted in Fig. 2. A transmission holographic film is used on the front of the LCD to overcome losses and avoid glare. Transmission holograms are inherently broadband or achromatic, unlike reflection holograms which are essentially narrowband optical elements. A simple distinction between these two types of holograms is that a transmission hologram is designed to allow the useful light to be

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transmitted while the reflection hologram is designed to reflect light. A key advantage of the proposed front film approach is that it can be used with most reflective displays including those with the reflector inside the cell.

Glare Management and Gain

An ideal light management solution for reflective LCDs has to accomplish three operations on the incident light: reflect the light, provide gain‡ to overcome LCD loss, and manage glare. In monochromatic LCDs these functions are accomplished by the metallic reflector which reflects the light, diffuses (scatters) it to provide gain and allow viewing away from glare. Another approach, for color LCDs, employs a mirror-like reflector in the cell for reflection and a light scattering film on the front of the display [4]. In monochromatic LCDs, the Optimax™ holographic LCD [3] accomplishes all three operations [4].

Optimax™ holographic LCDs manage glare by steering the useful light away from the glare angle. Even though beam steering avoids glare effectively, some scattering is still required to broaden the viewing cone and to avoid imaging the light source. However, as the scattering cone is widened, less light is available per unit angle, which reduces the luminance of the display. This introduces a tradeoff between viewing cone width and brightness.

It is possible for an LCD to equal the brightness of paper within a narrow viewing cone in spite of the losses. Display losses can be overcome at the expense of the viewing cone angle if the extent of the scattering cone angle can be controlled. The more lossy the display, the narrower the scattering cone must be to maintain a given brightness.

‡ Gain is the defined as a luminance ratio of the display to a diffuse, white standard.

The metric used here for the amount of scattering is optical *gain*. Gain is the ratio of the luminance of the display to the luminance of a white Lambertian (paper-like) standard (Labsphere Spectralon SRS-99-010). As an example, a display of the type shown in Fig. 1 will reflect 8% of the light. Without a scattering element the light will be sent into a very narrow cone. The white standard, on the other hand will reflect 99% of the light uniformly over ±90°. However, only 0.16% of the light is sent into the similarly narrow cone mentioned above [5]. Therefore, the gain of the display is 8%/0.16% =50X. Clearly, this amount of gain provides room to widen the scattering cone and yet maintain adequate brightness.

LCD Performance Requirements

Tests under office fluorescent lighting indicate that there is an optimum illumination angle and optimum viewing angle for handheld devices that utilize a display. In viewing the display, the

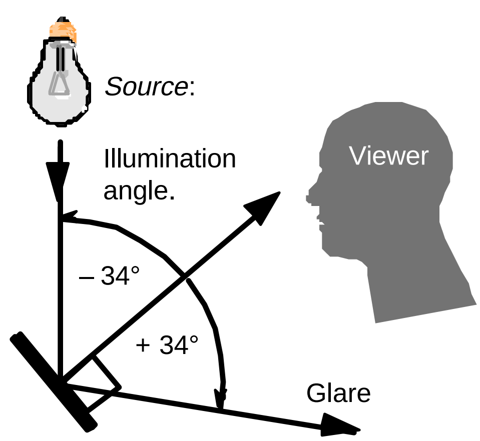

Figure 3. Optimum design angle for incidence of source illumination on the display is 34° as determined by tests based on variations in overhead lighting and comfortable head positions. It is assumed that the preferred viewing angle is perpendicular to the display. Illumination angles are measured from the normal. Source-normal angle is defined to be negative.

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user will usually position the display at an angle that optimizes both brightness and contrast. Subconsciously, the user adjusts the display to arrive at an optimum viewing position. This process often involves moving the body to better catch a light source. Our tests indicate that for such products, the display should be designed to accept light at approximately 34° to the normal and produce a viewing cone near the display normal as shown in Figure 3.

Different tests confirm that approximately 34° is the optimum illumination angle. One test determined the effect of the variation in the location of overhead lighting. It was assumed that the preferred viewing angle was perpendicular to the surface of the display. With this as a constraint, a study was conducted in a typical office environment with overhead fluorescent light fixtures. The minimum and maximum illumination angles were measured directly beneath the lights and in-between the lights, respectively. From the maximum (-48.5°) and minimum (-18.5°), the average source-eye angle was determined to coincidentally be -34 degrees.

The range of angles for viewing is limited in handheld, reflective displays by glare on one side and illumination angles on the other. Viewing the display at an angle beyond the display normal is less probable as the light source and user's head will then be in the same quadrant and will lead to a less bright display. The display normal then becomes one boundary of the viewing zone. The other side of the viewing zone is bounded by the glare zone. The glare zone is a range of angles over which the image of the light source, reflected from the front surface, interferes with viewing. Experimentally, we have found that the glare zone is less than 20° for most ambient lighting. These boundaries are not rigid and will vary slightly with viewing conditions. Nevertheless, for design purposes, there is a relatively small zone for comfortable viewing as shown in Figure 4.

Brightness and color of reflective displays is complicated by the fact that the source spectrum varies (fluorescent, incandescent) unlike with a backlit, transmissive LCD. Paper, however, has the ability to appear white under most lighting conditions. In effect, the human visual system seems to discount the source lighting for paper.

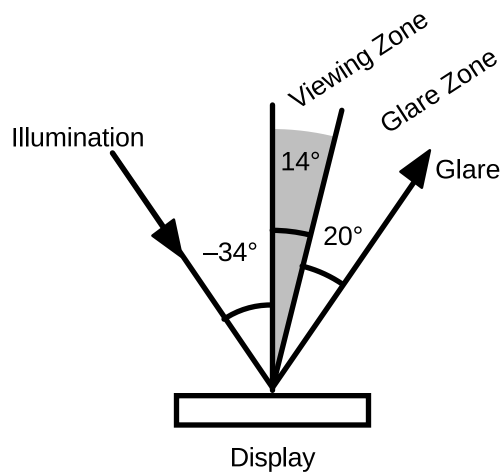

Figure 4. For illumination at -34° the viewing zone is confined to a small range of angles near the display normal, which forms one boundary. The other boundary is the glare zone which is a range of angles (20°) over which glare interferes with viewing.

In order for the performance of a reflective display to be independent of the light source it must provide paper-like behavior *within the viewing zone*. There are three requirements for paper like behavior: 1) the luminance as a function of angle needs to be Lambertian or flat, 2) the luminance has to be comparable to paper and, 3) the spectrum of the reflected light has to be close to the spectrum of the source. If these three requirements can be met, then it is expected that the display should appear to be independent of the lighting conditions, much like paper.

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Hologram Design and Performance

The ideal viewing and illumination cones for a display dictate the degree of beam steering required. These cones require that the hologram, when illuminated by a light source at 34°, steer the light through an angle such that it falls within the viewing zone indicated in Figure 4.

The extent of diffusion, or light scattering, determines the gain and consequently the brightness of the display. Assuming that paper brightness is the target, the required gain is determined by the display losses. An LCD that reflects 8% of the incident light requires a gain of 10.7 within the viewing zone to attain the brightness of paper (80% of the white standard). Gain calculations using a viewing cone of 20° vertical and 40° horizontal suggest a theoretical maximum gain of 16X, so this goal is achievable.

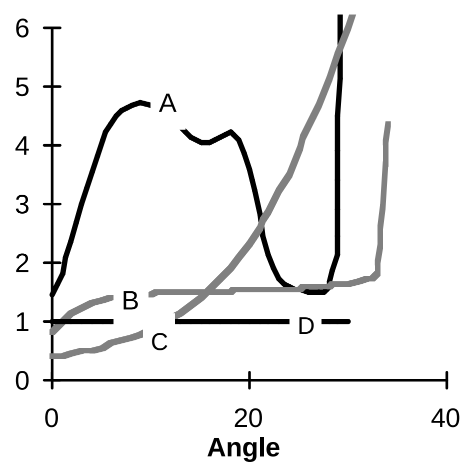

Figure 5. Measured luminance gain of a transmission hologram (A)]. The hologram is affixed to a specular reflector for the measurement. Source is at -34° . For comparison, a Polaroid LIFT green reflection hologram (B) is included along with a typical metallic reflector for LCDs (C). The luminance gain is relative to the white, diffuse, reflectance standard, Spectralon [D].

Holograms were fabricated to meet the LCD requirements discussed earlier. These were mounted on mirrors to evaluate their performance. Figure 5 compares the performance of the transmission hologram with the Polaroid LIFT (Light Intensifying Film Technology) green holographic reflector and a typical metallic LCD reflector. Though the target gain for the transmission film design was 12X the measured peak gain was just under 5X. However, optical measurements on the sample indicate that 12X is still achievable.

For a display, illuminated by a single point source, that reflects 8% of the light, a gain of 12X will produce a display that has 120% the brightness of white paper. However, under typical ambient lighting, with multiple sources, the gain is expected to drop significantly. This is because lighting is additive for a Lambertian reflector, like paper, but not so for a gain reflector like the hologram. In other words, increasing the number of nearby light sources increases the luminance of the Lambertian reflector but creates *additional viewing cones* for a high gain reflector. Thus, the luminance of the Lambertian reflector will increase faster than the luminance of the gain reflector. This will result in the gain decreasing with multiple light sources. In this event the display will appear darker than paper. One solution is to compensate through increasing the LCD throughput by reducing the color gamut. LCD modeling indicates that the throughput can be doubled while still retaining a wide gamut as shown in Fig. 6. This will provide a display with twice the brightness of paper under a point source and adequate brightness under ambient lighting.

Summary

A brightness enhancement method for reflective color LCDs has been proposed that uses a transmission hologram on the front of the display. This hologram steers the light away from glare and into the desired viewing zone. It also provides gain by controlled

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scattering. Early samples show a gain of approximately 5X over a white standard.

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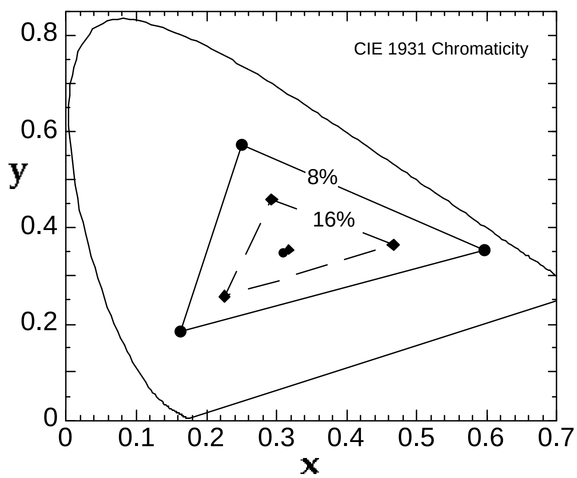

Figure 6. Calculated color gamut tradeoff for increased amount of useful reflected light. The model is for a display with an internal mirror reflector [1].

References

[1] Model parameters: Nitto Denko polarizer film NPF-F1025DU; Brewer Sciences PIC color filters: Red 02, Green 02, Blue 02; 8•/Sq. ITO on glass; 100% reflector; flat spectrum light source.

[2] T. Uchida, T. Ishinabe, M. Suzuki, *SID Digest*, Vol. 27, p. 618, 1996.

[3] Optimax™ is the Motorola trademark for holographically enhanced LCDs

[4] A. G. Chen, K. W. Jelley, G. T. Valliath, W. J. Molteni, P. J. Ralli, M. M. Wenyon, *J. of the SID*, Vol. 3, No. 4, 1995

[5] Lab measurement comparing the luminance of a specular mirror to Spectralon. The resulting ratio was 0.16%. This is a function of the detector acceptance angle which was 3°.