21.1: Electro-optical Characterization of Reflective LCDs

Michael E. Becker, Jürgen Laur, Jürgen Neumeier
autronic-Melchers GmbH, D-76229 Karlsruhe, Germany

Abstract

The concept of the BRDF (Bidirectional Reflectance Distribution Function) is applied to analyze, characterize and understand the reflective properties of LCDs and their components in more detail. BRDFs are measured in the plane of light incidence with a goniometric apparatus ("in-plane BRDF") while the full 2-dimensional BRDF is measured with a conoscopic device. BRDF-curves of typical reflective LCDs clearly show the individual contributions of the first surface (unwanted reflections) and the component from the reflector, which is modulated by the LC-cell and is thus carrying the information to be displayed. The effect of anti-glare coatings on the front polarizer surface is analyzed via BRDF measurements.

Based on the acquired BRDF data we explain the function of a device for diffuse reflective illumination that can be considered as the correspondence to the "dark-room condition" in the case of transmissive LCDs since it is designed to effectively avoid disturbing unwanted reflections from the first display to air interface and, at the same time assuring illumination over a wide solid angle (up to 70°).

1. Introduction

With increasing mobility of telecommunication and data-processing devices there is also an increasing need for reduction of power consumption in such devices in order to extend battery lifetime and thus the functional period of the device. One way to contribute to a reduced power consumption of portable electronic devices is the application of reflective displays that make use of the available ambient illumination instead of using backlit transmissive LCDs which have to compete with the ambient illumination and thus require a strong backlight in bright ambient conditions (i.e. high power consumption). White paper with printed characters, signs and graphics observed in ambient light is still a premium visual display with extremely low power consumption. Many developments are currently on the way to realization of electronic displays with the same reflective properties as printed paper. To achieve this, a better understanding of the reflective properties of the display components, their cooperation and competition is required. However, reflective LCDs are difficult to measure and to characterize because details of the measuring arrangement, especially those of the illumination scheme are critically determining the results.

Also the perceived contrast and thus the ergonomic performance of reflective LCDs is strongly affected by the illumination conditions under which the display is operated. Typical applications cover a wide range of situations from indoor use (partly diffuse illumination mixed with discrete sources) to a variety of outdoor situations with different illumination conditions (e.g. position of the sun, clouds, fog, etc.). A large number of typical application scenarios must be analyzed in order to obtain representative data for different application situations (indoor office work, outdoors, automotive, avionics, etc.). When the distribution of ambient light sources (including their spectral intensity distribution) is known together with the BDRF of the display device, the reflected luminance can be computed for any position of the observer (i.e. viewing direction) [1].

2. Experimental

Sample LCDs
We have laminated two identical reflective LCDs with the same front polarizer, one of them carrying an additional scattering *anti-glare coating* (AGC).

Measuring instruments
We are using a motorized goniometric measuring instrument DMS-501 and a ConoScope™ for comparison, both instruments developed and manufactured by autronic-Melchers.

Illumination situations

◆ A directed conical illumination for simulation of discrete ambient sources is achieved with a device called VADIS (i.e. **V**ariable **A**perture **D**iffuse **S**ource). The aperture of the VADIS as measured from the measuring spot on the sample can be set to 1°, 2°, 3°, 5°, 10° and 15°.

◆ Diffuse illumination for contrast evaluation is achieved with a hemispherical device featuring a slit from the equator trough the north pole, called *"Diffusing Hemisphere, DHS"* [2, 3].

2.1. BRDF measurements

The BRDF (i.e. *Bidirectional Reflectance Distribution Function*) characterizes the reflective properties of surfaces by the ratio of reflected (differential) luminance *dLr* to incident (differential) illuminance *dEi* (*BRDF = dLr/dEi*) versus direction of light propagation. In most of the cases the BRDF is symmetric, i.e. source and receiver can be interchanged without changing the resulting BRDF. The BRDF can be measured with either a variable receiver di-

ISSN/0001-0966X/01/3201-0322-$1.00+.00 © 2001 SID

rection (source direction kept constant) or with a variable source direction (receiver direction kept constant). The complete BRDF of a sample comprises the hemispherical directional distribution of reflected luminance for all possible directions of light incidence (lots of data!).

Scattering properties of opaque surfaces are suitably characterized by the standard BRDF, but evaluation of visual displays requires a special approach due to the sandwich structure of several (at least partly) transparent layers [4, 5]. Scaling of the BRDF is achieved in this paper via two calibrated references: a diffuse reflectance standard with 99% reflectance and a calibrated front surface mirror made from polished black glass ($R_S = 4\%$).

- The ***in-plane BRDF*** (receiver inclination is varied in the plane of light incidence only) is measured with the DMS (goniometric). The receiver is focused on the 1° diffusely emitting light source (VADIS smallest aperture) not on the sample surface!
- The complete ***2-dimensional BRDF*** (variation of receiver inclination and azimuth inside an almost hemispherical cone up to 80° of inclination) is measured with the ConoScope using the focal-plane illumination technique to produce a collimated test-beam.

3. Results and Discussion

The contrast of reflective LCDs is strongly reduced or even eliminated when an ambient light source is reflected by the first air-to-polarizer interface, thus adding a luminance that is not modulated by the LC-layer and that does not carry useful visual information (i.e. effecting *glare*).

It is well established that *glare* from ambient light sources can efficiently be reduced by application of a thin scattering coating (*anti-glare coating, AGC*) on top of the upper surface of the display, usually the front polarizer.

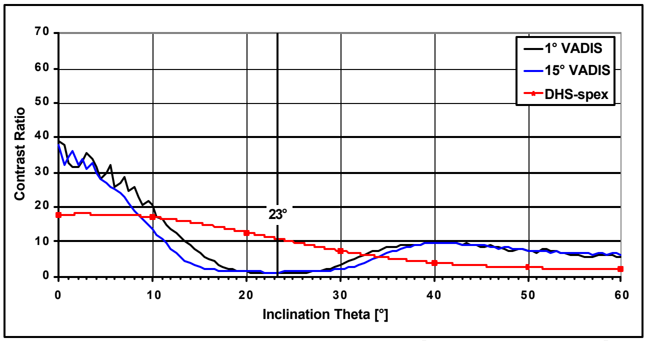

Figure 1: Contrast C_R versus viewing direction (i.e. angle of receiver inclination) for an LCD with AG-coating under directional (VADIS) and diffuse illumination (DHS).

We have measured the contrast C_R (i.e. ratio of luminance of the "bright"state to that of the dark state) of the two mentioned identical LCDs (except for the difference in anti-glare coating) as a function of the angle of receiver inclination θ_R for different aperture angles of the light source α (source inclination $\theta_S = 23°$). For all contrast evaluations the receiver is focused on the sample plane.

Figure 1 shows the contrast of the reflective TN-LCD with AGC on the front polarizer as a function of the viewing direction (i.e. receiver inclination θ_R) for two values of the VADIS aperture, 1° and 15°. The contrast at the *specular direction* (receiver inclination θ_R = source inclination θ_S = 23°) increases slightly with the aperture of the source from 1.15 to 1.35. In order to explain this effect (one might as well expect the contrast to decrease with the source aperture due to the scattering front surface!) we must have a closer look at the details of the reflective properties of such LCDs.

The IP-BRDF curves of both polarizers laminated to polished black glass together with the reference BRDF of the specular front-surface mirror and a calibrated reflectance standard ($\rho_{DIFF} = 99\%$) are shown in Figure 2.

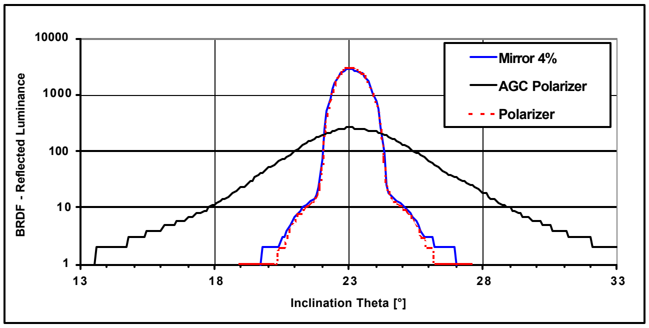

Figure 2: BRDF (reflected luminance) of polarizers with and without AG-coating laminated to a polished black-glass substrate in comparison to a calibrated mirror (4% specular reflectance).

We see that there is no difference in the directional reflectance of the polarizer without anti-glare coating and the reference mirror. In both cases light is only reflected in the direction of light incidence. The shape of the BRDF-curve of the specular mirror represents the characteristic directional resolution of the measuring setup and it is called *source-receiver signature*. The peak value of the reference mirror BRDF corresponds to 4% of specular reflectance. We also see that the anti-glare coated polarizer has a specular reflectance of more than a factor of 10 below that of the polarizer without AGC. Due to the scattering of the AGC the BRDF changes from a peaked (no AGC) to a bell-shaped curve. This scattering of the incident light flux into a wider range of directions reduces the light reflected in the specular direction and thus effects the increase of perceived contrast. At the same time the bell-shaped BRDF-curve indicates a "directional cross-talk", i.e. the reflected luminance is non-zero in directions different from the direction of light incidence. The ideal case of such a "directional cross-talk" is given by the ideal diffusing reflector where any incident light, no matter from which direction, is evenly distributed (scattered) into all directions of the hemispherical solid angle above the sample. Such a reflector is called a *Lambertian reflector*.

In the next step we have measured the BRDF of both LCDs with and without AGCs on the front polarizer surface. In addition to the light reflected from the first air-to-polarizer interface we now include light reflected by the reflector that is laminated to the rear surface of the lower substrate glass of the LCDs. This is the reason for the increase of luminance reflected from the LCD without AGC compared to the calibrated mirror as shown in Figure 3.

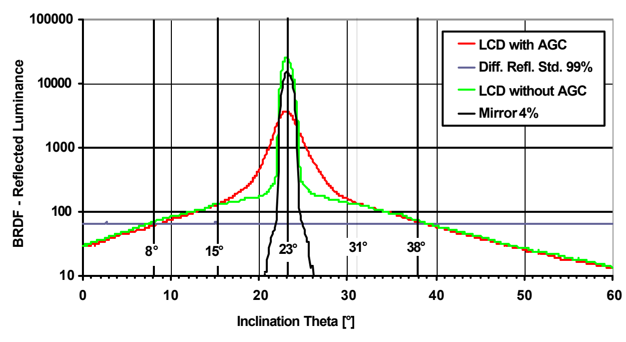

Figure 3: BRDF (reflected luminance) of the same LCD with and without AG-coating on the front polarizer in comparison to a calibrated reference mirror (4% specular reflectance) and a diffuse reflectance standard (99% reflectance).

Outside the *source-receiver signature* and up to ± 8° from specular the luminance reflected by the AG-coated LCD is higher than the reflectance of the LCD without AGC. Outside this range (± 8° from specular) there is no significant contribution of the scattering AG-coating to the total reflectance of the LCD, which is then rather determined by the reflectance of the reflector. By comparison with the BRDF of the calibrated diffuse reflectance standard (horizontal line = constant BRDF) we see that the LCD looks "brighter" than the diffuse reflector up to an inclination of ±15° from specular. The slowly decreasing BRDF of the LCD-reflector indicates *light collection* from a broad range of incidence angles. Figure 3 shows that light incident with an inclination of 60° still reflects like an ideal diffusor of approx. 10% reflectance (compare the BRDF of the 99% diffuse reflectance standard and of the LCD at an inclination of 60°). The "light collecting capability" of a reflector can be described by integrating the BRDF over the complete hemispherical solid angle of 2π.

Returning to the question raised by the results of Figure 1 we can now provide an explanation for the increase of contrast with source aperture: even though the luminance reflected from the first air-polarizer interface increases with source aperture, the luminance reflected by the reflector behind the LC-layer increases even more since it collects light from a wider range of directions than the AG-coating does. The competition between unwanted reflections from the first air-polarizer interface and the intended reflectance of the reflector is in favor of the intended component in this special case and for the reflectance properties of AGC and reflector as shown above. For other combinations of the reflective properties of these two components the effect might as well be inverted.

A maximum angular range of illumination can be achieved with integrating spheres or alternatively with a hemispherical device featuring a slit from equator to equator trough the north pole and named *Diffusing Hemisphere, DHS*. Such a device illuminates the sample LCD under measurement within a solid angle of 70° maximum inclination. At the same time the slit through the north pole (angular width of ± 5° out of the plane of incidence) coincides with the plane of receiver inclination and thus effectively excludes specular reflections from the first air-polarizer interface.

The contrast versus angle of receiver inclination for the AG-coated LCD is shown as the third curve in Figure 1. With the receiver normal to the LCD ($\theta_R = 0^\circ$) the contrast under DHS-illumination is reduced to half of the contrast measured with the VADIS for two reasons: (1) the luminance reflected by the AG-coating is increased by the DHS and (2) there is no distinct shadow cast by the LCD-segments onto the reflector (the shadow of dark segments on the reflector can effect a strong increase of contrast). For receiver inclinations above the specular direction ($\theta_R > 38^\circ$) the contrast measured under DHS illumination remains at a constant factor below the contrast measured with the VADIS. Within a considerable range around specular ($10^\circ < \theta_R < 33^\circ$) the contrast measured under DHS illumination is higher than the contrast measured with the VADIS.

These results illustrate that its easy to **"generate"** contrast values that are much higher than those measured under diffuse illumination simply by a proper choice of the combination *angle of light incidence / receiver inclination*.

The effect of the illumination situation on the contrast of the same LCD but without AG-coating is shown in Figure 4. In this case the contrast at normal receiver orientation is approx. 20% lower under DHS illumination compared to the VADIS case because no distinct shadow is cast on the reflector. For receiver inclinations above 12° the contrast under DHS illuminations is much higher than under VADIS illuminations due to strong unwanted specular reflections from the first air-polarizer interface in the VADIS case (specualr reflectance in the range of 4% - 5%). The contrast evaluated for the 1°-source in the specular direction is 1.0 (i.e. no perceived contrast!), while it is 1.3 for the 15°-source (small but visible!). For inclinations above 35° the contrast measured under both illumination schemes is almost identical and not dependent on source aperture. This is due to the fact that the reflector element behind the measuring spot is outside the shadow in the VADIS case and there is no distinct shadow generated in the DHS case.

The mirror-like reflectance of the air-polarizer interface is obvious by the steep transitions from specular to non-specular directions.

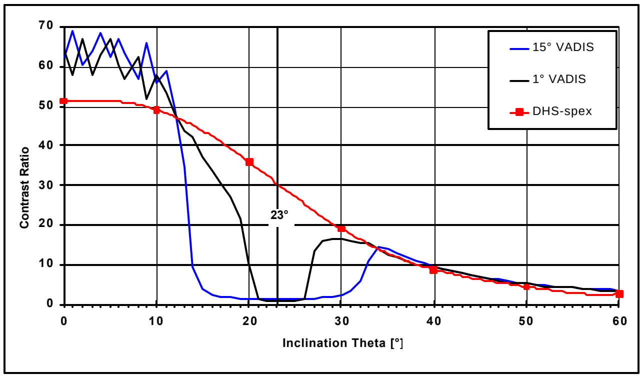

Figure 4: Contrast C_R versus viewing direction (i.e. angle of receiver inclination) for an LCD without AG-coating under directional (VADIS) and diffuse illumination (DHS).

For both LCDs with and without the scattering anti-glare treatment of the front polarizer the contrast is a continuous function of the viewing direction only under DHS illumination with suppression of specular components (i.e. DHS-spex). The contrast values evaluated under *DHS-spex* conditions are not "numerically optimized" but they are more realistic than those values that are obtained under "special conditions" with any directional source.

The drop of contrast for normal viewing direction caused by the luminance reflected from the AGC layer as shown in Figure 1 can be effectively further reduced by adjusting the width of the slit through the north-pole to the width of the BRDF of the AG-coating (here ± 8° instead of ± 5°).

Suppression of unwanted specular reflections as obtained with the polar slit of the "Diffusing Hemisphere" can be realized in conoscopic instruments in a corresponding way: here, a shadow is generated in the diffuse illumination of the sample by introduction of a suitable mask into a conoscopic figure plane, e.g. a non-transparent stripe through the center of the conoscopic figure. The width of such a stripe mask defines the angular width of the shadow and the luminance is measured e.g. as a function of inclination inside this shadow.

4. Conclusions

Analysis of the reflective properties of LCDs and their components in terms of the BRDF provide a quantitative explanation for the visual improvements obtained with a suitable anti-glare coating on the front polarizer. The scattering of such an AGC also eliminates the image of ambient light sources and thus prevents re-focusing of the eye of the observer, which is known to cause visual fatigue.

We have shown that the Diffusing Hemisphere with open polar slit (DHS-spex) illuminates the object of measurement in an almost ideal way over a wide range of directions and, at the same time, effectively reduces reflections from the front surface which otherwise would cause contrast reduction and even elimination (i.e. $C_R = 1$). The DHS thus represents the closest possible reflective approximation of the "dark-room condition" normally used for measuring the maximum contrast of transmissive LCDs.

Furthermore, the DHS is ideally suited for measuring the variation of reflective contrast with viewing direction due to the degree of motional freedom (inclination of receiver with rotation of sample).

By comparison of contrast evaluations obtained with DHS illumination with those obtained with a variable aperture diffuse source (VADIS) we have shown that it is possible to measure increased contrast values with a directional source due to (1) generation of a distinct shadow on the reflector element which serves as light source for the light entering the receiver and (2) due to forced exclusion of unwanted surface reflections. Illumination with the DHS however produces lower contrast values, but provides continuous results without specular singularities as in the case of directional sources.

From the above results we can state that the contrast of reflective LCDs is sensitive to the geometry of illumination and receiver and thus, the **contrast of reflective LCDs is not an intrinsic property of the sample itself**, but the contrast has to be evaluated under specific and well defined geometric conditions. **Any contrast value or distribution supposed to characterize the performance of reflective LCDs is meaningless without the exact specification of the measuring conditions.**

5. References

[1] Edward F. Kelley: "Flat-Panel-Display Measurements and Standards", Applications Seminar SID 2000, A-4/1 -A-4/51

[2] M. E. Becker, J. Neumeier: "Electro-Optical Properties of Reflective Positive-Contrast LCDs: How to Obtain Meaningful Results", Proc. IDRC 1991, pp.195

[3] M. E. Becker: "Viewing-cone analysis of LCDs: a Comparison of Measuring Methods", SID 1996 Digest, pp. 199

[4] M. E. Becker: "Evaluation and Characterization of Display Reflectance", Displays 19 (1998), p. 35-54

[5] M. E. Becker: "LCD Visual Performance: Characterization and Evaluation, SPIE 3636 (1999), p. 170-183