New method to separate the different reflection contributions of reflective displays

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Abstract: *We present a new method to perform viewing angle measurements on LCD reflective displays. The method is based on the use of commercial Fourier optics viewing angle instruments capable of measuring simultaneously nearly all the incidence and azimuth angles and of controlling very precisely the illumination of the sample. The main advantage compared to other instruments is that a clever illumination procedure with two different conditions allows the separation of the intrinsic reflective contribution of the display and of its parasitic front end reflection contribution. Thus, intrinsic performances of the display can be obtained at any incidence and azimuth angles and realistic observer conditions can be simulated. In the present paper we present the new method and different measurement results. We examine in particular the influence of the illumination wavelength on the reflection properties of the displays.*

Keywords: Reflective displays, Fourier optics, Angle of view, Contrast.

Introduction

Precise optical characterization of the viewing angle of reflective displays is always a difficult task because it is not only necessary to collect the light coming from the display but also to illuminate it. Classical techniques using a mid integration sphere for illumination and a detector moving along a slit cannot discriminate the intrinsic LCD reflection properties from the additional contributions due to front end reflection and diffusion. Generally the illumination is made with white light to simulate day light (D65 for example), but the interest of monochromatic measurements is obvious. Unfortunately a complete viewing angle characterization versus angle, azimuth or wavelength is generally never done because it is too long and too tedious with this type of instrument.

We present here a method based on Fourier optics viewing angle instruments that allows making this characterization very rapidly and precisely [1-2]. First a simple theory concerning the optical answer of reflective displays is presented. Then the experimental setup is described in details and the optical imperfections inherent to Fourier optics instruments are discussed and calibrated. Finally some experimental results obtained on one Ipod displays is presented. We have used two kinds of illuminations. Measurements obtained under D65 illumination are useful to simulate realistic working conditions. Measurements obtained under monochromatic illumination allow better analysis of the reflective properties of the displays.

Theoretical model for reflective displays

Compared to standard transmissive LCD displays where the light is emitted by a backlighting system and modulated by the LCD cells, reflective LCD displays need external illumination to be used. So, the whole display structure (LCD stack + front materials) reacts to the incoming light and the "reflectance" of the display can be separated in two contributions following:

$$R = R_{LCD} + R_{FRONT} \quad (1)$$

So, the contrast at any given angle (Θ, Ψ) can be expressed as:

$$CR = \frac{R_{LCD-ON} + R_{FRONT}}{R_{LCD-OFF} + R_{FRONT}} \quad (2)$$

Where:

- R_{LCD-ON} is the reflection factor of the LCD stack itself when the LCD is in ON state. As the background reflective structure might react in a complex way to the incoming light (BRDF analysis most often shows a "hazy" behavior), this factor will depend strongly on the illumination geometry.
- $R_{LCD-OFF}$ is the reflection factor of the LCD stack itself when the LCD is in OFF state.
- R_{FRONT} is the reflection factor of the display front materials.

R_{FRONT} is the part of the total reflectance that does not depend on the voltage or signals applied to the LCD cells. As for the other factors, its behavior will depend on the illumination geometry and angles. For reflective displays, it is most probably specular and generally always rotationally symmetric (strong dependant versus incidence angle but low dependence versus azimuth angle). It can be easily seen from formula (2) that if R_{FRONT} becomes high with regards to the other factors; the contrast ratio can go down to 1. Then, a correct measurement of the display properties requires a precise determination of R_{FRONT} in addition to the intrinsic properties of the display (R_{LCD-ON} and $R_{LCD-OFF}$), otherwise the measurements are not significant for a real observer.

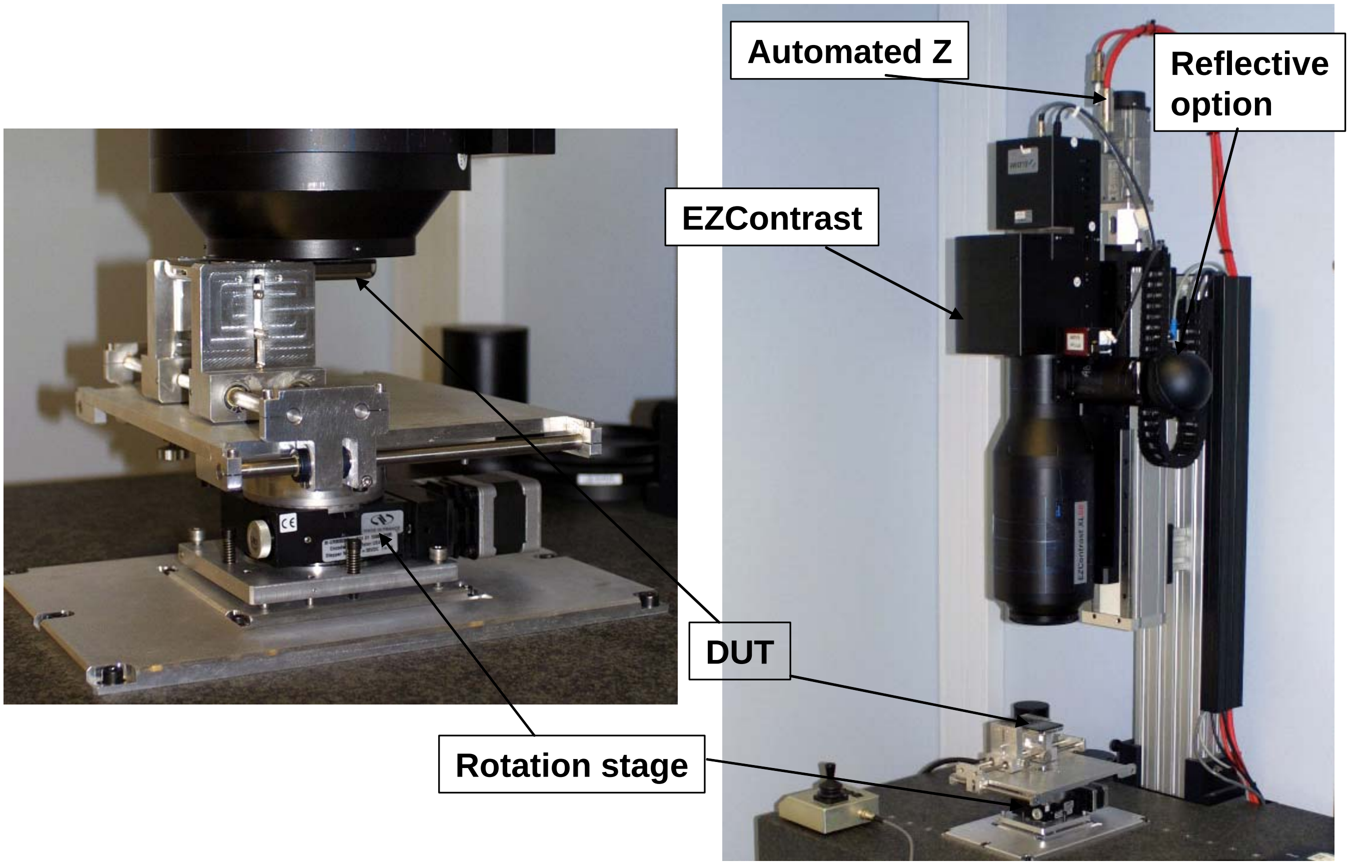


Figure 1: Measurement setup with the EZContrast mounted on a Z stage and the rotation stage for the display

The experimental system

a) Description

We use one of the EZContrast viewing angle systems proposed by ELDIM. Depending on the model, their angular aperture can be increased up to ±88°. As shown in figure 1, the system is mounted on a laboratory bench with motorized adjustment of the Z position. The display is installed on a rotation stage below the EZContrast system. The rotation axis of the display holder is carefully adjusted along the optical axis of the measurement system before making the experiments. The display holder integrates two manual translations X and Y that allow to measure different points on the surface of the display.

The optical setup of the viewing angle measurement system is schematically represented in figure 2. This patented configuration allows controlling the angular aperture of the system independently of the measurement spot size. In addition, the measurement spot size increases with the incidence angle to increase the efficiency (cosine compensation), making measurements up to 88° possible with a good signal over noise ratio. The illumination is made across the Fourier optics using a beam splitter and an additional focal system that reconstructs the first Fourier plane at the entrance of an integration sphere (cf. figure 2).

Light is injected inside the integration sphere using a Xe lamp and an optical fiber.

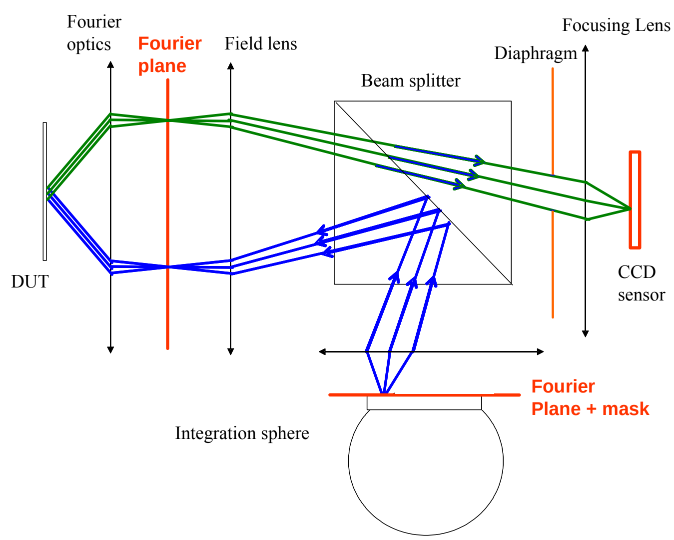


Figure 2. Optical layout of the EZContrast system: white or monochromatic light is injected inside the integration sphere. A mask placed at the exit of the integration sphere controls the display illumination.

Monochromatic and white illuminations are available. In the following we use D65 filtering to simulate outside lighting. Additional masks directly on the Fourier illumination plane can be used to control the angular illumination pattern independently of the measurement region. This major advantage of the system is used hereafter to discriminate the different reflection contributions of a reflective display.

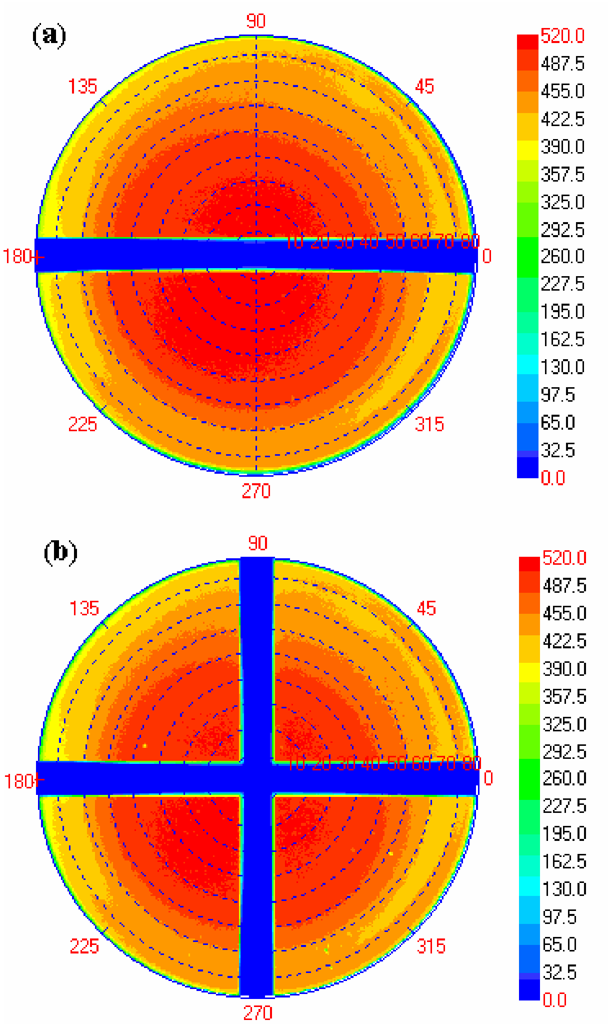


Figure 3. EZContrast measurements on a mirror surface with Ulbricht mask (a) and cross mask (b).

b) Calibration of the internal diffusion

The fact that the illumination of the sample is made across the same Fourier optics that is used for the collection and detection is extremely useful to measure the entire Fourier plane. Nevertheless the counterpart is that some parasitic light associated to the illumination can be detected which does not correspond to the sample signature. One part of this parasitic light can be corrected easily making a measurement in the same conditions using a light trap instead of the sample. With an ideal system the collected light should be zero. It is of course, not the case and this contribution is subtracted systematically from all the measurements. However, after reflection on the sample surface the light is crossing again the different optics and some parasitic reflections and diffusion can occur before reaching the detector.

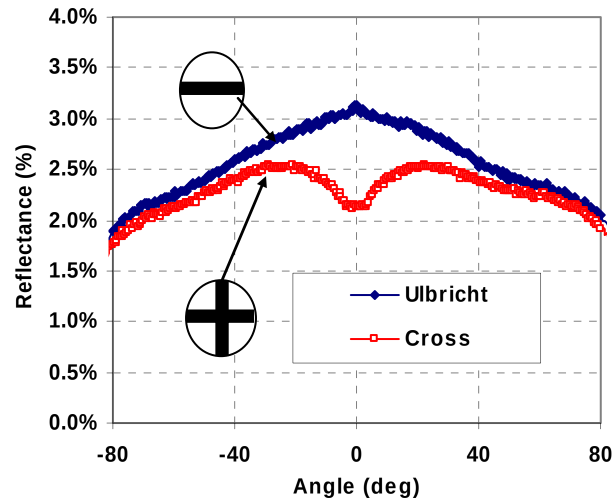


Figure 4. Parasitic light measured along the meridian on a mirror surface with Ulbricht mask and cross mask.

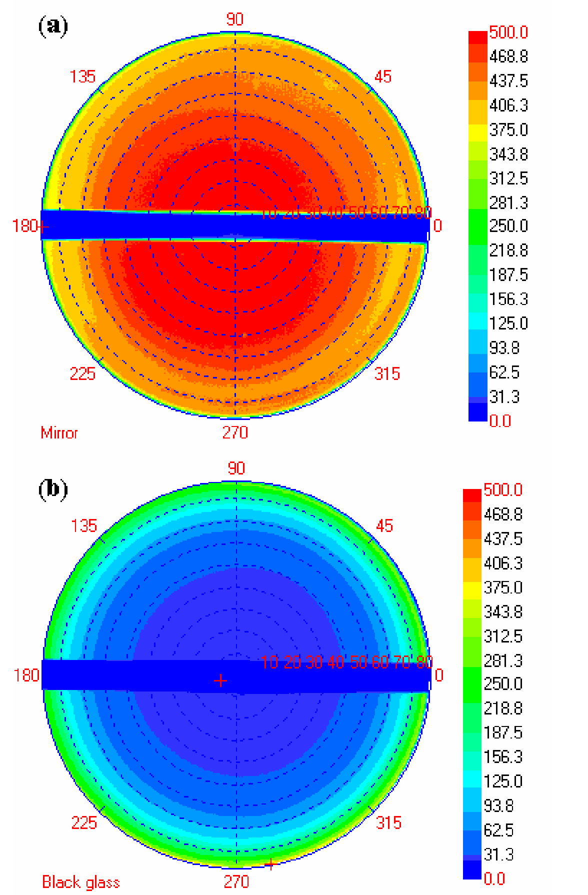
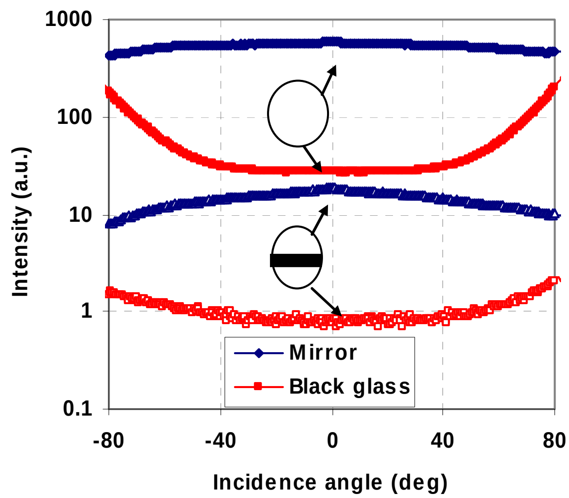


Figure 5. EZContrast measurements on a mirror (a) and a black glass (b) with Ulbricht mask.

The second parasitic contribution is depending on the illumination conditions and can be precisely evaluated using a perfectly specular surface. As shown in figure 3, we have measured the reflection pattern of a mirror surface using Ulbricht type mask and cross mask. For an ideal system, since the diffusion of the mirror is insignificant, the intensity detected along the horizontal meridian should be zero. In practice it is of the order of few percents of the incident flux and depends on the angular position and of the experimental system (cf. figure 4). A close observation of the two signatures of figure 4 shows that the contribution is dependant on the local illumination conditions. At normal incidence, the illumination conditions are strongly different for the two masks but become comparable for high incident angles.



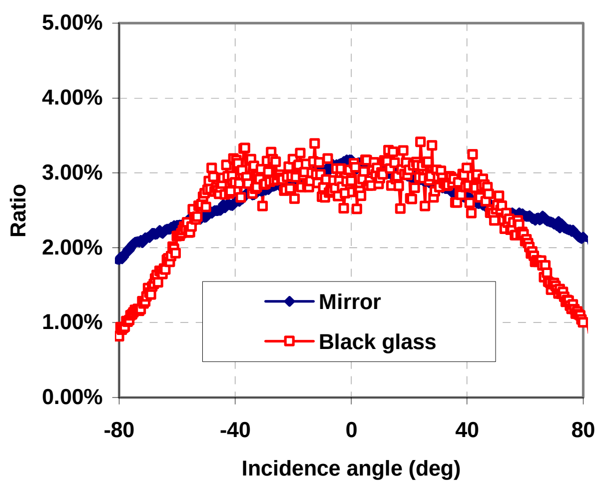


Figure 6. Parasitic light measured along the meridian on a mirror surface and black glass surface with Ulbricht mask and in full diffused illumination (top). The ratio of the two measurements is quasi independent on the sample surface (bottom).

It is reasonable to assume that the parasitic light observed on the meridian is proportional to the illumination intensity observed at the mask borders. We have verified this point making the same measurement with the Ulbricht mask on the mirror surface and on a black glass (cf. figure 5). Both surfaces are quasi perfectly specular (only the reflected intensity is different, ~90% for the mirror and ~4% for the glass at normal incidence). The local illumination conditions are also extremely different in the Fourier plane for the two samples due to very different angular behaviors of the specular reflectance of the two samples. In figure 6, the parasitic light measured along the meridian is reported for the two samples with also the reflectance observed along the same meridian for full diffused illumination. In spite of the very different angular behavior of the two measurements their ratio is constant within 1% for the two samples. This confirms our assumption that the parasitic light is proportional to the local illumination. In the following, the meridian values measured in the same conditions on different samples surfaces are corrected using the correction factor obtained using figure 6. This calibration procedure is only necessary to make ones for a given experimental system and a given illumination mask.

Measurements on reflective displays

a) Measurement procedure

For one display position, we perform two measurements in full diffused illumination and with Ulbricht mask. The sequence is repeated for different azimuths of the display to cover 0-180° and for the ON and OFF states. Two measurements in the same conditions are also performed on a mirror in order to correct from the parasitic diffusion inside the optics as explained previously. These data are also used to normalize the data to absolute reflection factors knowing the absolute reflection of the mirror. Using equation (1) we can write:

$$R_{ON\text{-}FULL} = R_{ON\text{-}LCD} + R_{FRONT}$$
$$R_{OFF\text{-}FULL} = R_{OFF\text{-}LCD} + R_{FRONT}$$

FULL and UBS are for full diffused illumination and Ulbricht mask respectively. If we assume that the intrinsic reflection of the LCD is proportional to the illumination it follows:

$$R_{ON\text{-}UBS} = K\, R_{ON\text{-}LCD}$$
$$R_{OFF\text{-}UBS} = K\, R_{OFF\text{-}LCD}$$

K is factor dependant of the incidence angle which is taking into account the fact that the illumination using Ulbricht mask is always less that in full diffused illumination. This factor takes into account that light seen along the slit from the LCD results from the hazy nature of the background reflector. Using equation [2] and the different measurements:

$$K = \frac{R_{ON-UBS} - R_{OFF-UBS}}{R_{ON-FULL} - R_{OFF-FULL}}$$

And so RFRONT can be derived:

$$R_{FRONT} = R_{ON-FULL} - \frac{R_{ON-UBS}}{K}$$

For one set of four measurements this calculation is realized for each incidence angle along the meridian. The same procedure is repeated rotating the display at different azimuth angles.

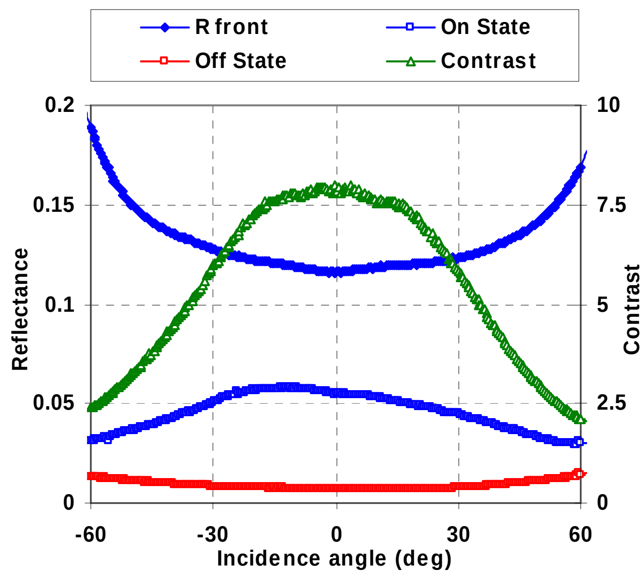


Figure 7. On state, off state, contrast and R front measured along azimuth 0 for the Ipod reflective display under D65 illumination.

b) Measurements with D65 illumination

One example of measurement made on an Ipod display using D65 illumination is reported in figures 7 and 8. Figure 7 only reports the results obtained along one meridian. On the contrary, on figures 8.a and 8.b the measurements made at 15 different meridians have been recombined on the same Fourier plane. This display shows an important front reflection due to the double protection. Indeed the display top glass is protected by a transparent plastic covering. Thus, the front reflection has three components of about 4% each. Its angular dependence is similar to what we wait for glass surface. The intrinsic reflection coefficient of ON state is quite high and the intrinsic contrast also.

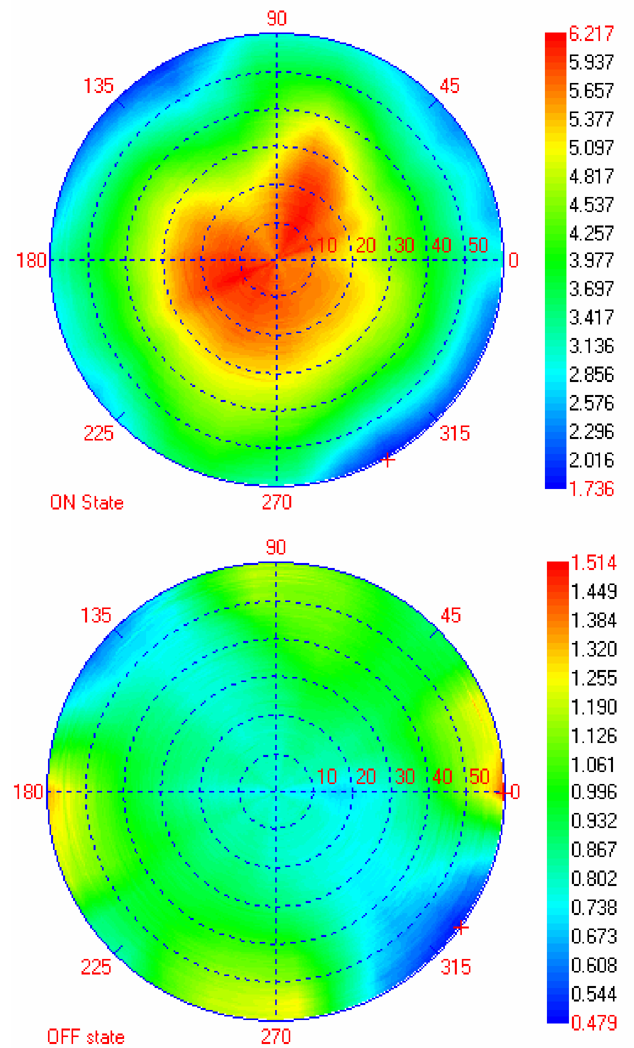


Figure 8. On state (top) and off state (bottom) absolute intrinsic reflectance of an Ipod display under D65 illumination. The measurements have been made on 15 meridians at various azimuths between 0 and 180°. The values have been interpolated in between.

c) Measurements with monochromatic illumination

The same Ipod display is measured in the conditions but using monochromatic illumination instead of D65 illumination. The sequence of measurements is repeated for eight wavelengths ranging from 420 to 700nm. Measured normal incidence reflection coefficients are reported versus wavelength on figure 9. The already observed quite high front reflection coefficient around 12% is nearly independent of the wavelength. This is not surprising since the most important contribution is due to specular reflection on the display top surface. The intrinsic ON state reflection is only about 6% and decreases in the blue region. The OFF state reflection is below 1% which results in a contrast ratio between 6 and 10 depending on the wavelength (cf. figure 10).

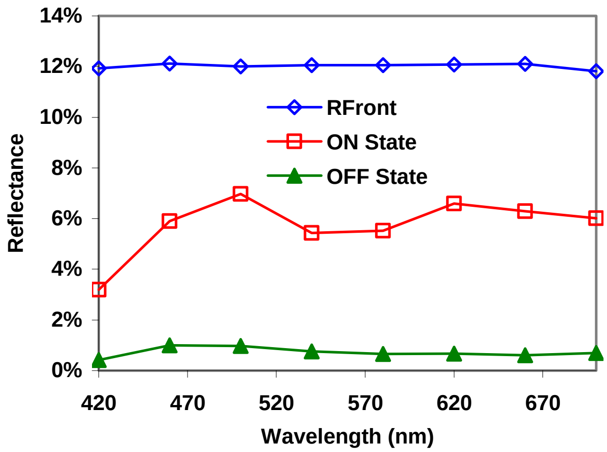


Figure 9. Normal incidence reflectance components of an Ipod display versus wavelength in the visible range.

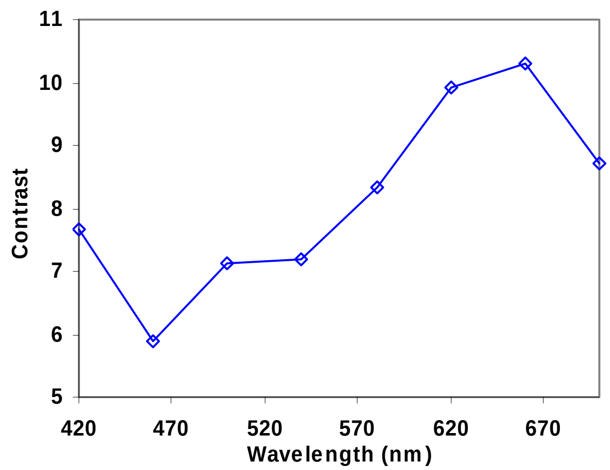


Figure 10. Intrinsic Contrast of an Ipod display versus wavelength and at normal incidence.

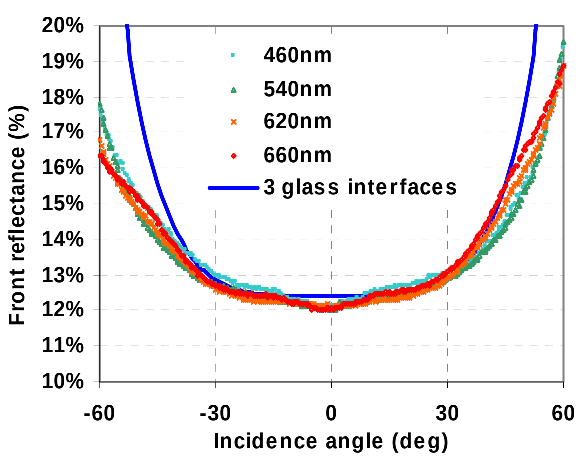


Figure 11. Front reflectance of an Ipod display versus incidence and four wavelengths. Theoretical reflectance of three glass interfaces is also reported.

The angular dependence of these measurements is also of interest. As shown in figure 11, the front reflectance is nearly independent of the wavelength at any incidence angle and shows the expected angular behavior characteristic of the specular reflection on three glass interfaces. The departure from the specular model is only effective above 40° where the diffusion contributions are probably more important. This result is important because it justifies a posteriori our analysis method based on two component contributions.

The ON state and OFF state intrinsic reflection contributions are reported in figures 12 and 13 respectively. The angular dependence of the ON state intrinsic reflection is not very dependent on the wavelength but the OFF state dependence shows more important contributions in the blue region. This is probably due to the more efficient diffusion mechanisms in this region but it affects the contrast and therefore the quality of the blue images of this type of display.

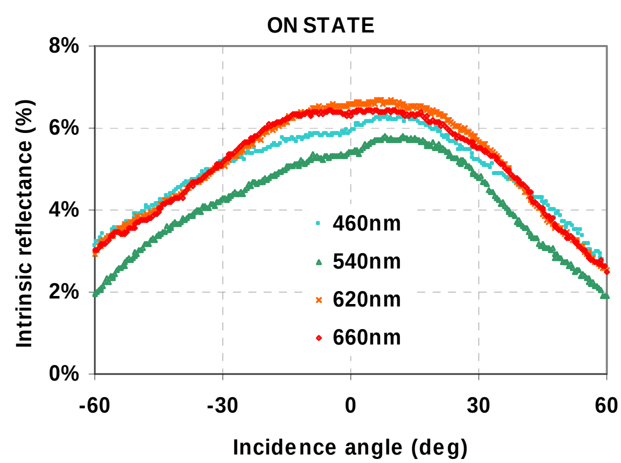


Figure 12. ON State intrinsic reflectance of an Ipod display versus incidence at four wavelengths.

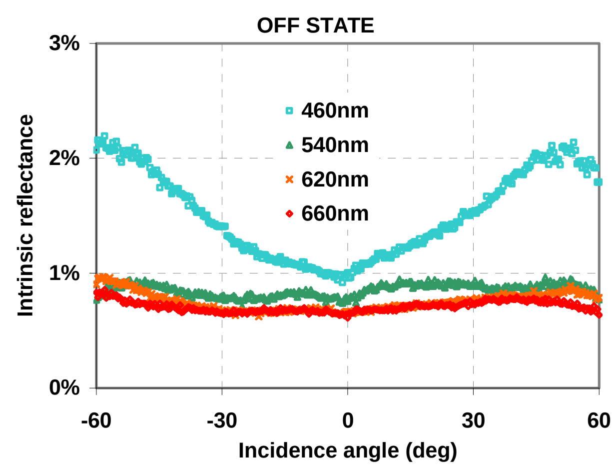


Figure 13. OFF State intrinsic reflectance of an Ipod display versus incidence at four wavelengths.

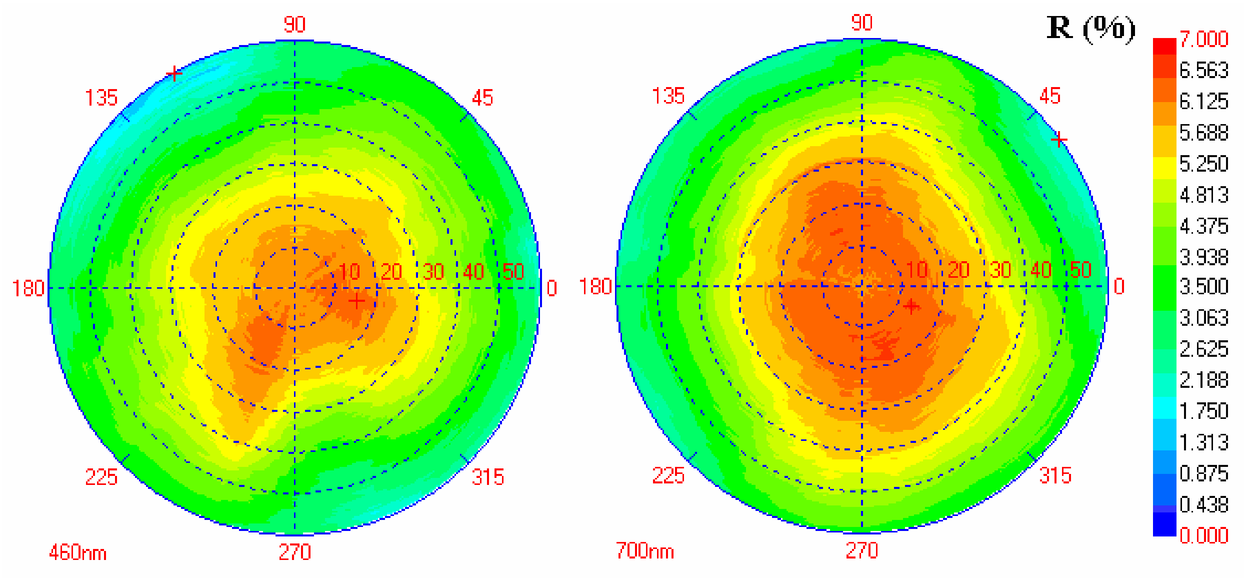


Figure 14. ON state intrinsic reflection of an Ipod display: full angle of view is measured at 460 and 700nm.

Full viewing angle measurements

We have also achieved full viewing angle measurements at two wavelengths 460 and 700nm on the same Ipod reflective display. The measurements are performed along 18 different azimuths to cover all the Fourier space. ON state intrinsic reflection observed for the two different wavelengths is reported in figure 14. As already noticed for single azimuth measurements, the amplitude of the intrinsic ON state reflectance does not depend much on the wavelength but the azimuth dependence is not exactly the same.

In contrast, the OFF state intrinsic reflectance is much more dependent on the wavelength as shown in figure 14. In the blue region, the amplitude of the intrinsic reflectance is more important at each angle and in particular along specific azimuths at ~0° and 20°. This behavior is probably resulting from the internal structure of the display itself. These measurements are important since they can be useful for optimizing such displays and improving their performances all along the wavelength range. In terms of intrinsic contrast the consequence can be different depending on the wavelength as shown in figure 15 in the case of our Ipod display.

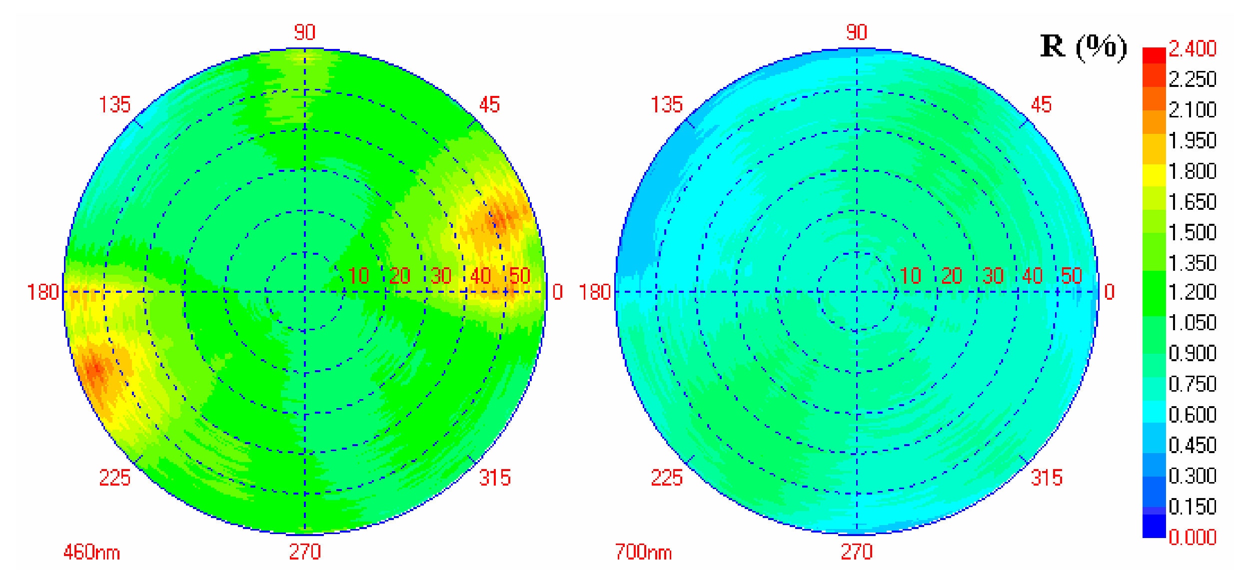


Figure 15. OFF state intrinsic reflection of an Ipod display: full angle of view is measured at 460 and 700nm.

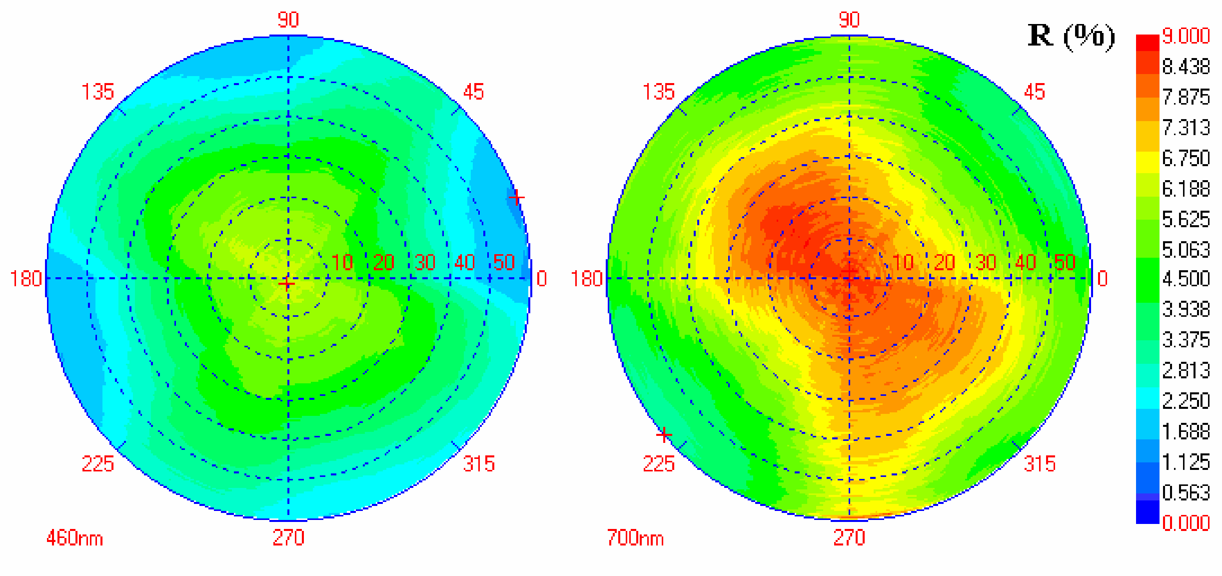


Figure 16. Contrast of an Ipod display measured at 460 and 700nm.

Conclusion

We have shown the interest to discriminate between front reflection and intrinsic reflection of a reflective display. This unique feature is only feasible using a Fourier optics instrument and provides full display characterization at all angles and wavelengths in reasonable measurement times. The ELDIM solution includes of all the hardware necessary to perform measurements easily and efficiently and an automated software capable of performing measurements, rotating the display, computing the different results and generating automatic reports. The results are provided at any incidence angle for a given azimuth or for any azimuth by reconstruction using the different display positions. These complete viewing angle diagrams can be especially useful to identify the different imperfections and to optimize displays specifications.

References

1. T. Leroux, “Modern methods for electro-optical characterization of displays”, SID Conference, 2001
2. T. Bignon, T. Leroux and P. Boher, “Angle of view measurements of reflective displays”, IMID Conference, 32-4, 2006