Multispectral BRDF measurements on anisotropic samples: application to metallic surfaces and OLED displays

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Abstract

We use a Fourier optics multispectral instrument to measure the BRDF of isotropic and anisotropic samples. The capacity to measure rapidly high angular BRDF patterns is useful to study complex BRDF behaviors in particular for anisotropic surfaces. Metallic two dimensional structured surfaces exhibit different diffusion properties along particular directions. Brushed metallic samples coated with transparent protective layer show complex BRDF patterns modulated by interference fringes due to the coating. The color of the surface is driven by the anisotropic diffusion and the coating thickness. The surface of OLED displays shows also complex scattering patterns due to the periodic pixel structure. We examine how to use spectral BRDF measurements to simulate the aspect of the surfaces and how to take into account the anisotropy in practice. Results are compared in some cases to aspect measurements made with multispectral imaging and punctual illumination source. Optical properties of curved OLED TV under parasitic illuminations are also presented.

Introduction

The spectral bidirectional reflectance distribution function (BRDF) characterizes the scattering properties of a material for any angle of illumination and any viewing position and offers a complete description of the spectral and spatial optical characteristics. Most of the BRDF measurements are made with goniometric systems based on a scanning process, i.e., the sample, detector, or source perform relative individual movements to cover all incoming and outgoing light flux directions for which BRDF data are needed. Nevertheless, the measurement time is always an issue when medium or high angular resolution is needed. For anisotropic materials it is especially true since series of measurements at various azimuth illumination angles are needed.

In this paper we use a Fourier optics viewing angle system reported previously [1] to measure different anisotropic surfaces and to make photo-realistic simulations. 2D structured metallic surfaces, coated brushed metallic surfaces and OLED displays are measured as examples. The spectral BRDF is then used to simulate what will be seen by an observer in different illumination conditions. For the OLED display the emissive properties measured under dark conditions are also taken into account. The simulations are compared to imaging measurement taken with a multispectral imager using controlled illumination conditions.

One of the main applications of the study is the physico-realistic simulation of displays under parasitic illumination on which we have already made different contributions [2-5]. In this paper we present new results on OLED displays which can present strong anisotropic reflective properties due their periodic structure. Under parasitic illumination, these types of diffraction effects can produce very annoying parasitic contributions for the display user in particular in the case of large size curved TVs.

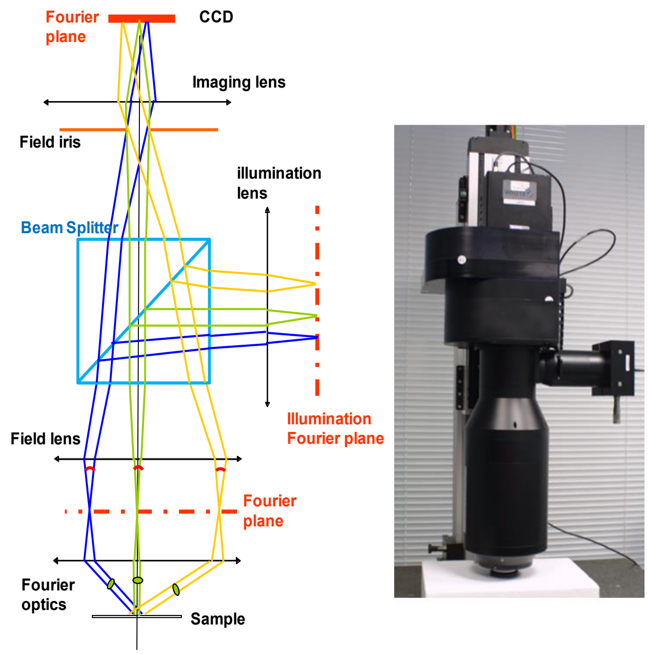

Figure 1. Schematic diagram and photograph of a Fourier system with beam splitter for internal illumination

Experimental techniques

Spectral BRDF measurements:

At SPIE imaging 2015, we have presented a new generation of Fourier optics multispectral instruments that allow rapid full diffused or collimated beam spectral BRDF measurements [1] (cf. figure 1). It uses a specific optic that converts angular field map into a planar one allowing very rapid measurements of the full viewing cone with an imaging camera. Main features are the patented optical configuration which allows controlling the angular aperture of the system independently of the measurement spot size, and the high collection efficiency. The light rays are collected by ultra-large angular aperture Fourier optics (up to ±88°) and refocused on a primary Fourier plane. This plane is reimaged on a CCD detector via field optics and imaging optics. The spot size is defined by a diaphragm at a location where we have a direct image of the measurement spot. The system has a spot size of 2mm and a maximum angular aperture of 80°. The spectral information is obtained using different automated wheels with 31 band pass filters regularly distributed in the visible range near the imaging sensor. Illumination is realized across the same optics using a beam splitter and an additional lens (cf. figure 1). Collimated illumination is obtained using a white LED on the illumination Fourier plane. Light detection is made simultaneously at all angular locations including the illumination direction.

The full characterization of one surface requires different incidence angles if the surface is isotropic and different incidence and azimuth angles if the surface is anisotropic. For each angle the spectral BRDF is measured:

$$BRDF(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda) = \frac{dL_r(\theta_r, \varphi_r, \lambda)}{dE_i(\theta_i, \varphi_i, \lambda)} \quad (1)$$

(θ_i,φ_i) and (θ_r,φ_r) are the polar coordinates of the incidence light beam and detection direction respectively. The radiance dL_r diffused by the surface is directly given by the instrument. The irradiance of the sample dEi is obtained by the measurement of one spectralon sample using the same illumination conditions.

$$BRDF(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda) = \frac{dL_r(\theta_r, \varphi_r, \lambda)}{\iint_{2\pi} R_W(\theta_r, \lambda) L_W(\theta_r, \varphi_r, \lambda) \cos(\theta_r) d\Omega_r} \quad (2)$$

L_W is the radiance measured on the spectralon sample and R_W the reflection coefficient of the spectralon. The parasitic reflections inside the optics are corrected subtracting the measurement of a light trap illuminated in the same conditions.

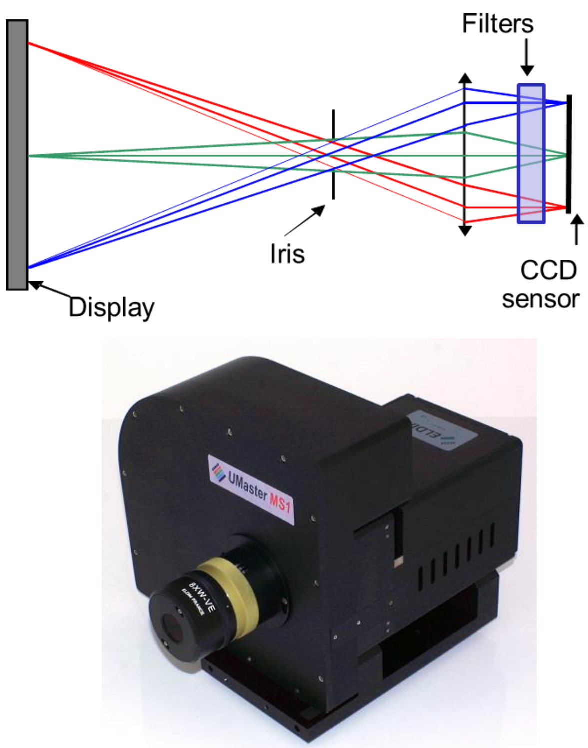

Figure 2. Principle of imaging videocolorimeter telecentric on sensor side and photograph of UMasterMS system

Spectral imaging measurements:

Multispectral imaging systems generate different images of the same object at different wavelength. Compared to color imaging, this technique is much more powerful avoiding metamerism problems and analyzing in depth the light emission properties of any object. Until now, this technology has been limited to selected military, medical and scientific applications. Indeed, absolute measurements are quite difficult to obtain using most of the spectral imaging techniques. The system used in this study allows absolute multispectral measurements in the visible range with excellent accuracy. UMaster-MS includes a true 16-bit Peltier cooled CCD camera, different filter wheels with band pass filters and imaging objective telecentric on sensor side (cf. figure 2.a). This feature ensures the same incidence for all the rays crossing the filters and therefore the same spectral response in all the field of view. In addition the flux is quasi-independent of the object distance while conventional optic can suffer from up to 20% reduction at short distance [6]. UMaster-MS uses 31 high quality band pass filters and offers a resolution of 10nm for all the visible range (400-700nm. Near infrared filters up to 950nm can be available on request. Different objectives with various angular apertures are available (±8°, ±16° and ±30°). In the following we use an objective of 8° aperture to restrict the incidence angle variations on the display. Additional optics can be added to make high spatial resolution imaging. For global approach, another important parameters is the size of the entrance iris of the optical system. In the system of figure 2.a, it can be adjusted to a value comparable to the human iris diameter without problem. With a conventional imaging objective the size of the first lens defines this parameter and is generally much larger than the human iris.

To compare aspect simulations to real measurements we have used the multispectral imaging system to measure what will be seen by the observer. The samples are illuminated by a quasi-punctual source (100µm fiber optic) fixed at a given distance and angle of the sample surface. The imaging is made with the multispectral imager adjusted at a position symmetric to the optical fiber (cf. figure 3). The inhomegeneities of the illumination are calibrated with a second measurement made on a white reference sample.

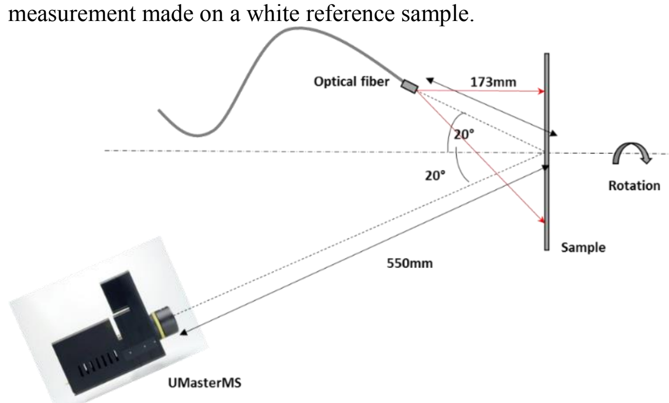

Figure 3. Schematic diagram of the imaging measurement setup with quasi punctual illumination.

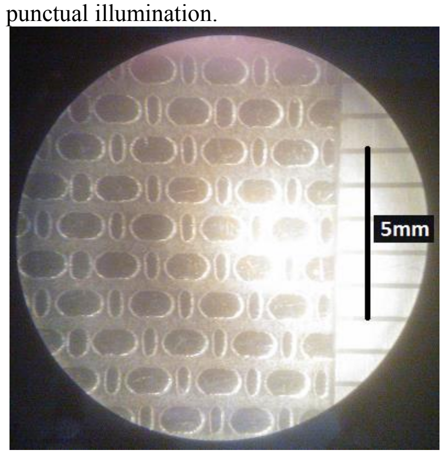

Figure 4. Photograph of the structured metallic surface.

Experimental results

Structured metallic surface

Spectral BRDF

A first example concerns an artificially structured metallic surface (cf. figure 4). Periodic elliptical bumps with two types of size are regularly distributed on the surface at millimetric scale. Examples of BRDF measurements are reported in figure 5. Elliptic patterns orientated along two orthogonal directions (cf. figure 4) produce a strong anisotropy of the BRDF properties and in particular on the shape of the lobe of diffusion near the specular contribution. The BRDF properties measured by the EZContrastMS instrument are averaged on several mm^2 and the sub-millimetric structure that can be visible by eye if the observer distance is sufficiently small is completely averaged in these data.

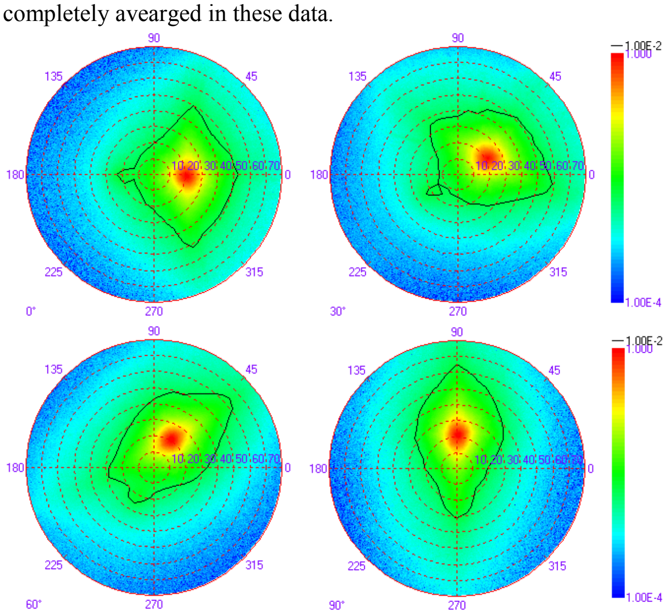

Figure 5. BRDF measured at 20° of incidence and azimuth 0°, 30°, 60° and 90°: wavelength is fixed at 600nm.

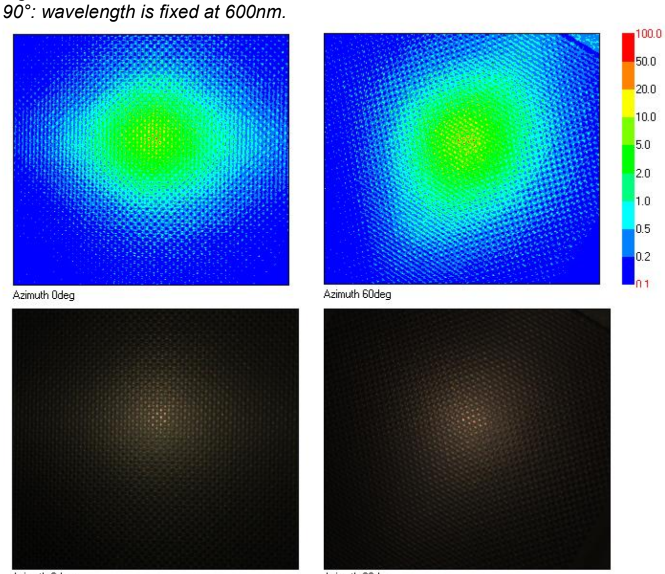

Figure 6. Computed luminance (top) and color (bottom) of the structured metallic sample around specular for a punctual illumination at 20° of incidence: illumination azimuth at 0° (left) and at 60° (right). illuminant D65.

The surface aspect can be simulated correctly under any type of illumination environment using the spectral BRDF. We can compared to the measure aspect in the specific conditions reported in figure 3. The results for two orientations of the samples are reported in figure 6. The diffusion lobe which is clearly visible on the imaging measurements corresponds to the light distribution observed on the BRDF measurements closed to the specular peak (-cf. figure 5). Since the imaging instrument is sufficiently closed to the sample, the microstructure is also visible in the imaging results. For the simulation it can be taken into account separately using a texture superposed to the BRDF properties on the surface.

Brushed & PVD coated metallic surfaces

The second example has been obtained using two Alanod test metallic samples. The metallic surfaces have been brushed along one direction and coated with a transparent PVD protection layer. Two samples have been investigated: one homogeneous aluminum sample and one inhomogeneous copper one.

Aluminum surface

BRDF patterns measured for two incidence angles (10° and 50°) along the brushing direction (azimuth 0°) and perpendicular to this direction (azimuth 90°) are reported in figure 7. The strong anisotropy of the sample is clearly evidenced and the stronger diffusion is always perpendicularly to the brushing direction. A cross section of the data of figure 7 in the plane of incidence is also reported in figure 8. It is clear that the reflection behavior is near mirror like along the brushing direction and becomes much more diffuser like perpendicular to this direction. The BRDF reported in figure 7 and 8 have been measured at 600nm. To check the wavelength behavior we have reported the BRDF measured at different reflective angles in the plane of incidence for the measurement realized for an incidence angle of 10° along the brushing direction (cf. figure 9.a) and perpendicular to this direction (cf. figure 9.b). We see that the spectral BRDF is modulated by interference fringes produced by the protection PVD coating on top of the metallic surface. The modulation is complex since the position of the interference peaks vary with the wavelength and the angles. There must be taken into account if one wants to simulate the aspect of the surface in particular when it is illuminated with fluorescence lighting.

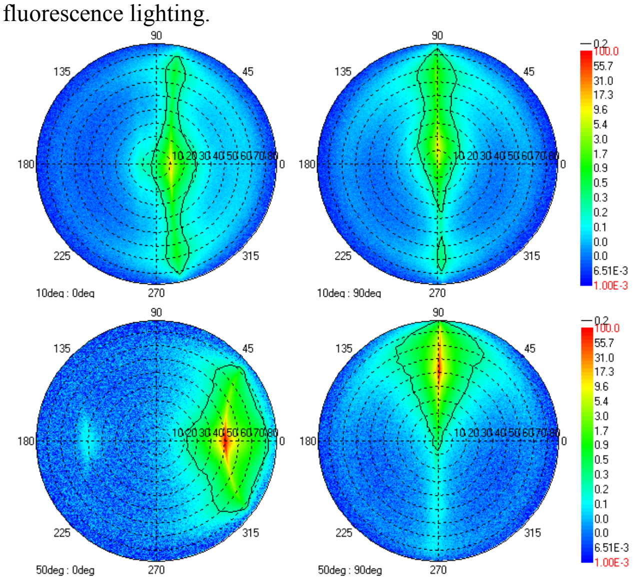

Figure 7. BRDF measured at 10° of incidence (top) and 50° of incidence (bottom) and along azimuth 0°(left) and azimuth 90°(right) : wavelength is fixed at 600nm.

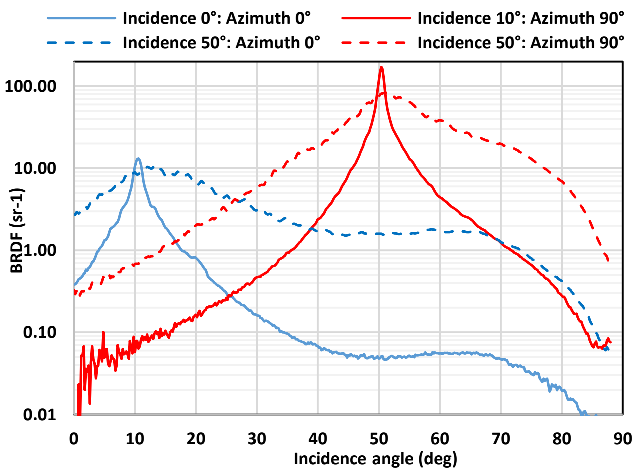

Figure 8. BRDF measured for 10° and 50° of incidence and along azimuths 0° or 90°: cross section in the incidence planes, wavelength is fixed at 600nm.

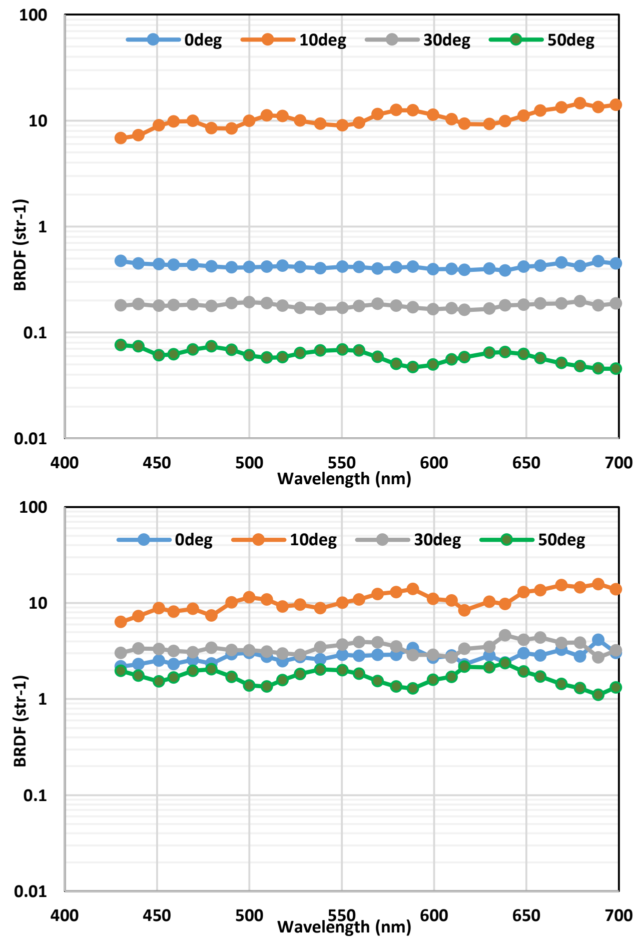

Figure 9. BRDF measured versus wavelength at different reflective angles in the incidence plane for an incidence beam at 10° along azimuth 0° (top) and along azimuth 90° (bottom).

Copper surface

The same type of measurements have been applied to the copper surface sample on two different areas where the color seems violet or yellow under fluorescence tube illumination (cf. figure 10).

Figure 10. Photograph of the copper sample illuminated with fluorescence tube

The BRDF patterns measured for an incidence beam at 30° along the brushing direction are reported in figure 11. Here also the sample exhibit a strong specular peak with diffusion quasi only perpendicular to the brushing direction. The diffusion is modulated differently depending on the area where the measurements has been performed (arrows in figure 11).

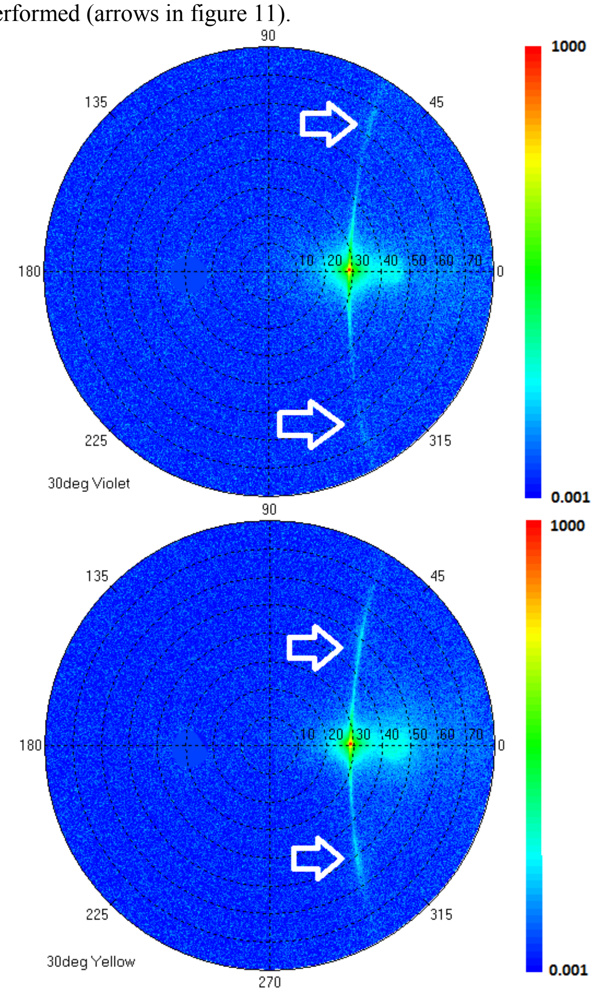

Figure 11. BRDF measured at 600nm for an incidence beam at 10° along the brushing direction on the violet area (top) and yellow area (bottom)

A better way to check the wavelength dependence is to report the BRDF measured at different reflective angles in the plane of incidence. This type of data is reported in figure 12 for the measurement made for an incidence beam at 10° and on the two different areas. As expected the PVD coating is not homogeneous in thickness and produces different modulations on the two areas that we have measured. Like for the previous sample, the simulation of such a surface requires to take into account the variable modulation of the protective coating and its inhomogeneity across the sample surface.

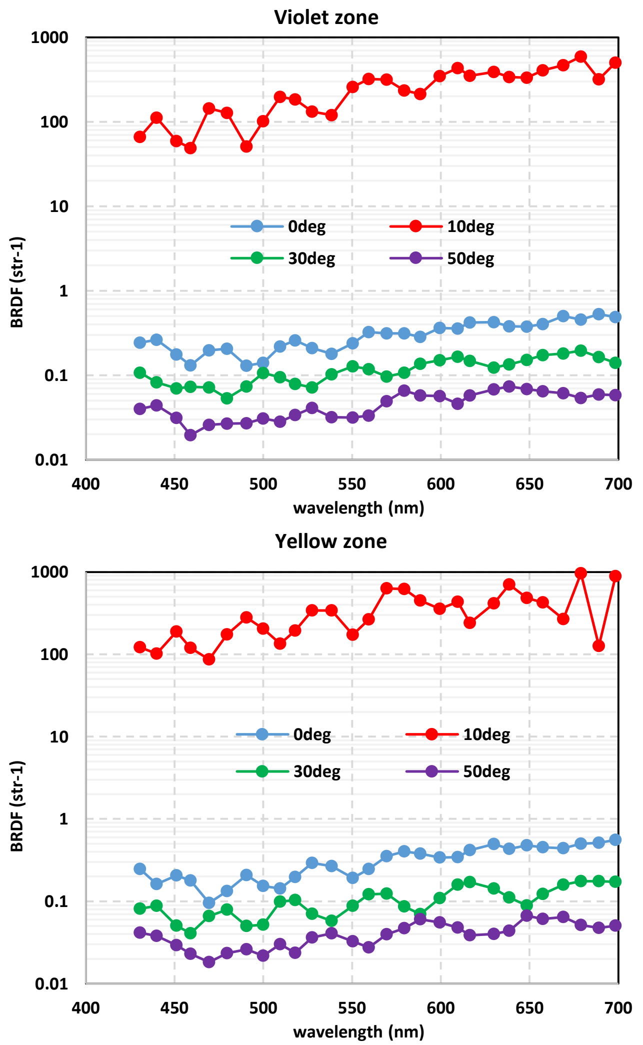

Figure 12. BRDF measured on the violet zone (top) and yellow zone (bottom) at different reflective angles for an incidence beam at incidence 10° along azimuth 0° versus wavelength.

Simulation strategy using BRDF space

The Fourier plane exhibit geometric distortions which change the shape of the diffusion pattern independently of the sample itself. One way to correct these distortions is to use a new BRDF space which avoids the geometrical deformations and in numerous cases which is more convenient for BRDF analysis and simulation [7]. To illustrate this effect we have reported the BRDF measurements obtained on Aluminum sample and already reported in figure 7 in the new BRDF space. The specular contribution is now always centered on the diagram and the geometric distortions due to the Fourier space are removed. The diffusion perpendicular to the brushing direction is in particular always vertical in the new BRDF space. To male aspect simulation the interpolation between two incidence angles becomes much easier.

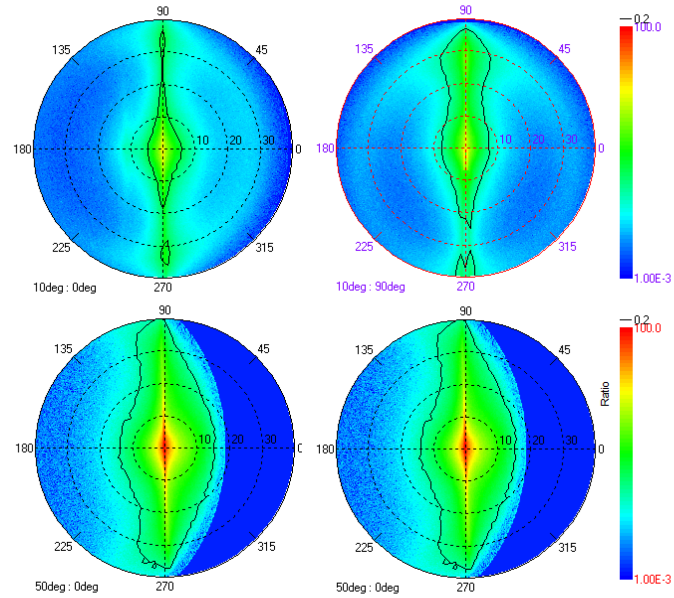

Figure 13. BRDF patterns of Aluminum sample of figure 7 reported in the BRDF space: 10° of incidence (top) and 50° of incidence (bottom) and along azimuth 0°(left) and azimuth 90°(right) : wavelength is fixed at 600nm.

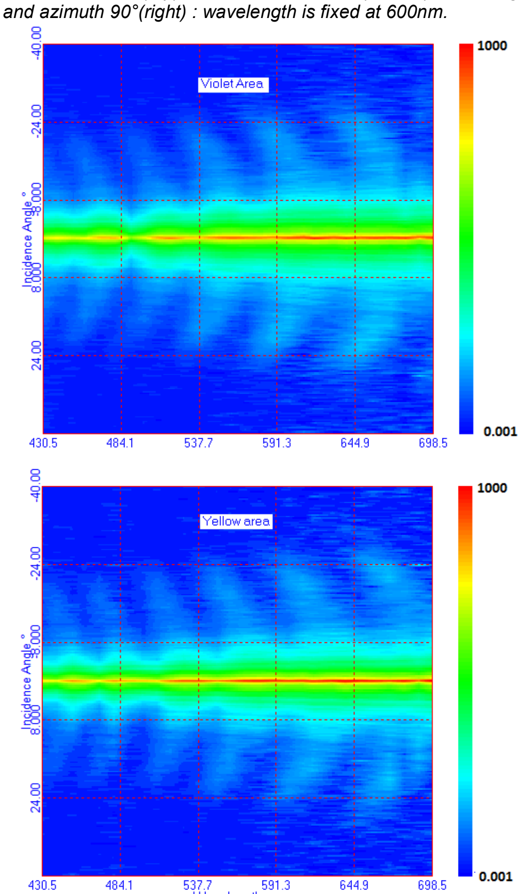

Figure 14. BRDF versus wavelength and emissive angle in the BRDF space and along vertical azimuth for an incidence angle of 10° and measured on the violet area (top) and yellow area (bottom).

The BRDF space is also useful to understand better the behavior of the measurements. If we use it to display the BRDF measurements made on the two areas of Copper sample we can understand better the wavelength dependence. One example using the measurements made for an incidence angle of 10° along the brushing direction (cf. figure 11) is reported versus wavelength and reflective angles in figure 14. The modulation of the diffusion appear much clearly and the different of thickness of the protective coating is obvious watching these data.

Curved OLED TV

Diffraction on the display periodic structure

The third example concerns the OLED displays. Even if the luminance contrast of any OLED is excellent due to the fact that the black state is really black, under realistic illumination conditions it is no more the case. OLEDs have long been recognized as highly specular and the ambient light plays generally a key role in the quality of such displays. We have measured the emissive and reflective properties of a 55" curved OLED TV from LG. The BRDF measured at 689nm for a collimated beam at 40° of incidence along the horizontal is reported in figure 15.a. The surface of the display is very glossy and additional anisotropic haze contributions can be detected. These haze contributions are probably due to some diffraction along the horizontal and vertical directions. One way to check the origin of these contributions is to shift to the BRDF space as reported above. As shown in figure 15.b, the same data in the new BRDF space exhibit very well defined horizontal and vertical contributions demonstrating that the origin is directly related to the horizontal and vertical alignment of the pixels on the display surface and so to an unexpected diffraction effect.

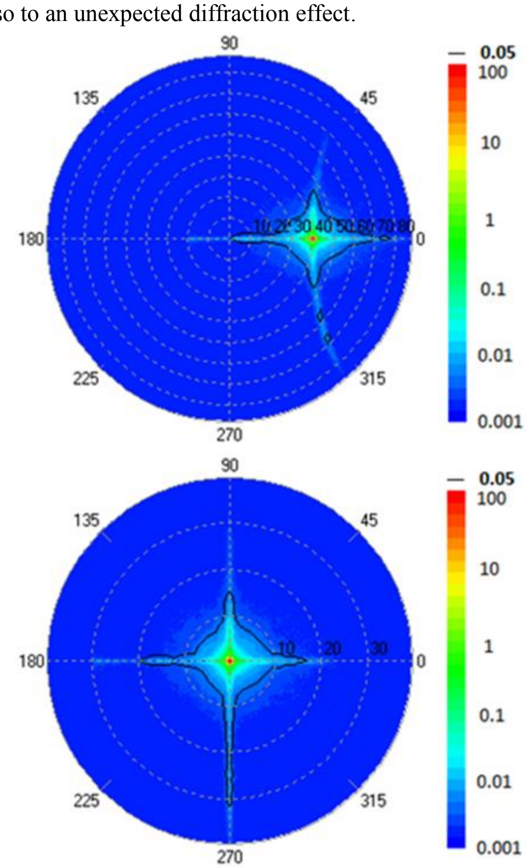

Figure 15. BRDF measured at 689nm on OLED TV for an incident beam 40° incidence and 0° azimuth (top) and same data in the BDRF space (bottom).

The spectral dependence of the BRDF is illustrated in figure 16. It is minimized in the green around 520nm. The haze contribution is about 1% of the specular contribution for all the wavelengths. The diffraction effect is not specific to this curved TV but observed with or more of less amplitude on most of the OLED displays that we have measured. Even if the amplitude of the effect is not very high the impact on the aspect of the display can be important.

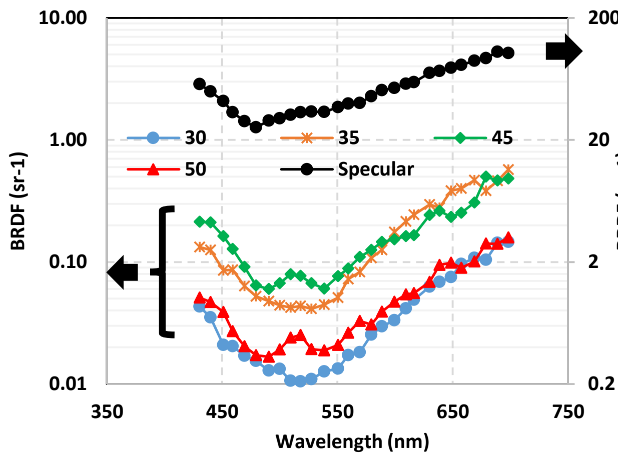

Figure 16. . Spectral BRDF measured on the OLED TV at 30°, 35°, 40°, 45° and 50° along horizontal for a incidence beam at 40°

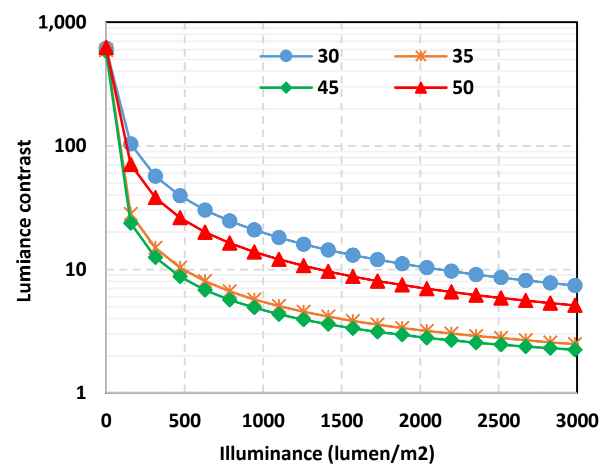

Figure 17. . Simulation of the luminance contrast I_{255}/I_{31} at 30°, 35°, 45° and 50° along horizontal for a incidence beam at 40°

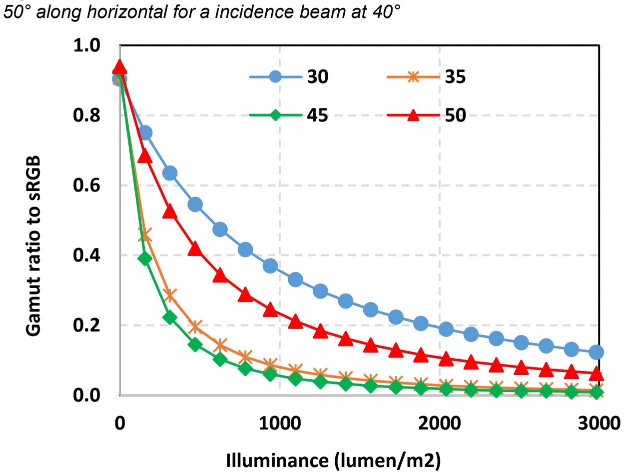

Figure 18. . Simulation of the gamut to rRGB ratio at 30°, 35°, 45° and 50° along horizontal for a incidence beam at 40°

Impact on luminance contrast & color gamut

To enlighten this point we have computed the impact of the anisotropic diffusion on the luminance contrast and the color gamu of the display. The behavior of the luminance contrast (between gray level 31 and gray level 223) in the incidence plane and versus illuminance for a collimated beam at 40° is reported in figure 17. The contrast reduction is important even for angles outside specular position of more than 10° along the two diffraction directions. The color gamut is also strongly affected by the same illumination conditions (cf. figure 18). In practice the user watching this TV with a bright punctual source in his back see bright reflections that extend along horizontal and vertical directions. On a curved display this is even more problematic due to the focusing effect of the surface when the user in front of the display at the required viewing distance.

Conclusions

In the present paper we have presented different examples of spectral BRDF measurements on anisotropic samples:

- The metallic structured surface exhibit a strong anisotropy that results in a strong dependence of the diffusion lobe to the direction of the incidence illumination beam. The aspect of the surface is derived from its variable diffusion properties and from the artificial microstructure if the observer is sufficiently closed to the surface.
- Brushed metallic surfaces with protective coatings show also strong anisotropic properties with strong diffusion perpendicular to the brushing direction. In addition, the transparent protective coating results in a complex pattern of interference fringes that modulate the BRDF data and drives the color of the surface when illuminated with fluorescence like illuminants.
- OLED surfaces a generally very glossy but the periodic structure of the display produces additional diffraction effects that produce important BRDF contributions along specific directions. Simulation of the optical properties under variable illumination conditions show that the luminance contrast and the color gamut can be strongly affected by this parasitic light. The focusing effect of curved TVs play also a role in this artefacts.

Thanks to the capacity of the instrument to measure this type of sample quite rapidly with high angular resolution and for illuminations at different incidence and azimuth angles, simulations using the measured BRDF data directly becomes possible. The spectral dependence is mandatory for that in order to be capable to use any type of illumination. We have shown that the used of the reduced BRDF space is interesting to remove the distortions due to the Fourier space and the interpolation of the measurements become much easier.

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Pierre Boher earned an Engineer degree at ECP, "Ecole Centrale des Arts et Manufactures" in 1982. He obtained his Ph.D. in material sciences in 1984 and his ability to research management at "University Pierre et Marie Curie" in 1991. He worked in the French Philips Laboratories during nine years on the deposition and characterization of very thin films and multilayers. R&D manager at SOPRA between 1995 and 2002, he developed different metrology tools for non-destructive characterization mainly for microelectronics. He joined ELDIM as R&D manager in 2003.

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