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Polarimetric multispectral bidirectional reflectance distribution function measurements using a Fourier transform instrument

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Abstract

Fourier optics system have already been recognized as an efficient solution to measure rapidly multispectral bidirectional reflectance distribution function (BRDF) of any kind of surface with very high angular resolution. This capacity is useful to study complex BRDF behaviors in particular for anisotropic surfaces. Measurement of the BRDF polarization dependence is useful to understand better the scattering processes involved in the different types of samples. In the proposed paper we show that polarimetric spectral BRDF (pBRDF) measurements are also possible using such instruments. We evaluate the accuracy of the system using black glass surface. Examples of pBRDF measurements on different types of samples (color shifting paints, car paints and gloss reference samples) are presented.

Introduction

The spectral bidirectional reflectance distribution function (BRDF) is generally used to characterize the scattering properties of surfaces. Due to the development of spectral ray tracing simulation software, the demand for rapid and accurate spectral BRDF measurements is increasing. Presently, most of the spectral 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. Measurement time is always an issue in particular for glossy or anisotropic surface were high angular resolution measurements are needed.

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]. The instrument is based on 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. This instrument has been used to characterize complex anisotropic metallic surfaces and OLED displays [2]. Even if the polarization state of light cannot be directly detected by the human visual system, it can play a role in many partical configurations. It is clear that full characterization of the reflective properties of a surface must include the polarization dependence [3]. In addition the polarization dependence can give a good insight and a better understanding of the scattering processes involved in the different samples.

In this paper we investigate the capacity of the new Fourier optics viewing angle system reported previously to measure polarimetric spectral BRDF accurately. The instrument is already capable to measure the polarization state of the light of emissive displays thanks to polarizers and wave-plates with different orientations. This option was for example useful to characterize polarized stereoscopic 3D displays [4]. In the present study we investigate the possibility to fix the polarization state of the illumination beam and we use the standard polarization option to analyze the polarization state of the light after reflection on the sample surface. Example of measurements on different types of surfaces are presented.

Experimental method

Optical setup

Spectral BRDF measurements are made with the EZContrastMS system which 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. 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 that reimage the first Fourier plane (cf. figure 1). Collimated illumination is obtained using a small optical fiber on the illumination Fourier plane. Light detection is made simultaneously at all angular locations including the illumination direction. The measurements are normalized using a near Lambertian spectralon sample.

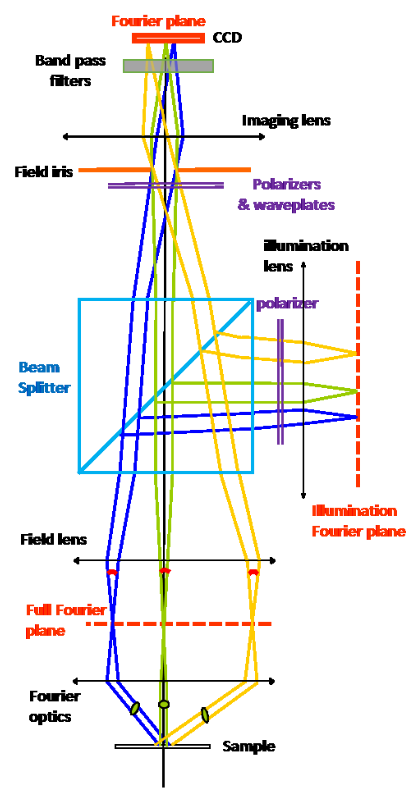

Figure 1. Schematic diagram of a Fourier system with beam splitter for internal illumination and the different polarizers and wave-plates for the polarimetry

Polarization analysis before the detector

The polarization analysis of the light collected by the Fourier optics is made with three polarizers and two wave-plates located near the field iris (cf. figure 1). The system makes automatically seven measurements with different polarization configurations and computes the Stokes vector components automatically. Three measurements with three polarizer orientations M(0),M(45) and M(90) are necessary to deduce the first three Stokes components:

$$S_0 = \frac{M(0) + M(90)}{2}$$

$$\frac{S_1}{S_0} = \frac{M(0) - M(90)}{M(0) + M(90)}$$

$$\frac{S_2}{S_0} = \frac{M(45) - M(0) - M(90)}{M(0) + M(90)}$$

Three additional measurements combining polarizer and wave-plate of phase shift φ are necessary to get the last Stokes component:

$$\frac{S_3}{S_0} sin\varphi = \frac{M(0,135) - M(0,45)}{M(0,45) + M(90,45)}$$

Polarization of the illumination

In addition, different polarizers can be added inside the illumination path near the beam splitter to fix the polarization state of the illumination (cf. figure 1). Since the different optics (Fourier, field, imaging and illumination lenses) are designed to avoid parasitic polarization, the main source of parasitic light should be the beam splitter. In order to quantify the amount of parasitic polarization in the illumination beam we have made measurements on a black glass surface illuminating all the angles together at the same time. It is made in practice using an integration sphere whose exit is located on the illumination Fourier plane. The black glass surface is quasi free of diffusion and only the specular reflections are obtained on the measurements made with two polarizer orientations on the illumination (0° and 90°) (cf. figure 2). The minimum of reflection obtained at the Brewster angle around 57° along the azimuth corresponding to the p-polarization is useful to quantify the amount of parasitic polarization (cf. figure 3). The adjustment provides this quantity for different wavelengths along the 0° and 90° directions (cf. figure 3). The parasitic polarization is acceptable in most of the visible range and particularly good in the red region with the system used in this study.

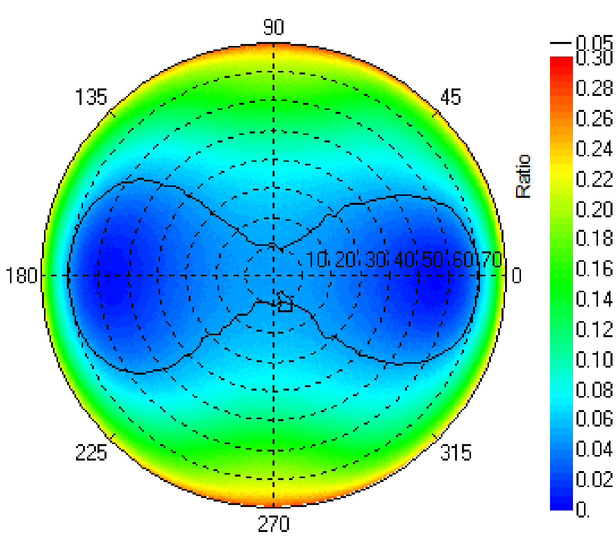

Figure 2. BRDF measured at 689nm on a black glass with p-polarized illumination along azimuth zero.

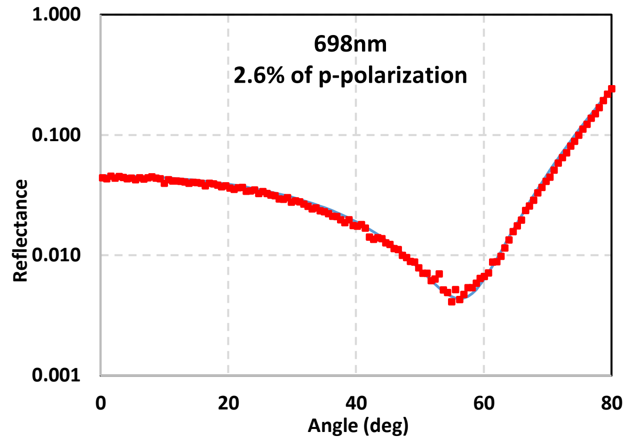

Figure 3. Adjustment of degree of parasitic polarization on the reflectance measured at 698nm along azimuth 0° for p-polarizer illumination.

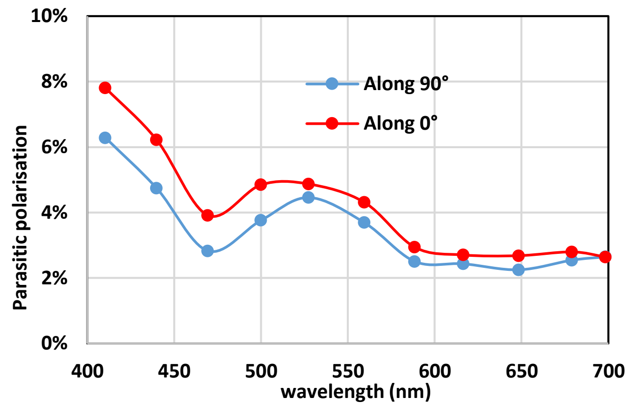

Figure 4. Percentage of parasitic polarization measured versus wavelength on the Fourier optics system.

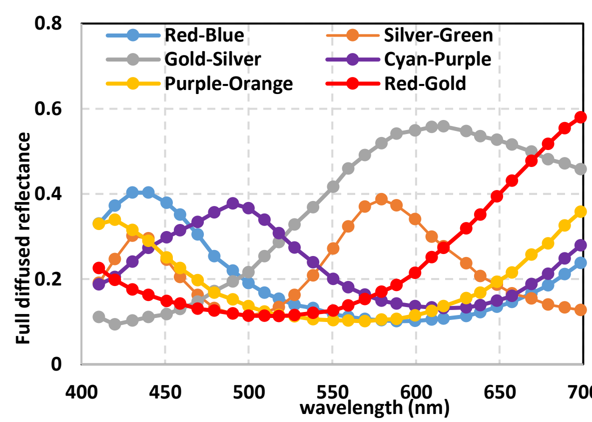

Figure 5: Full diffused reflectance measured at normal incidence on six color shifting paints.

Experimental results

Color shifting paints

Full diffused spectral reflectance

ChromaFlair pigment consist in an ultra-thin, multi-layer interference film that forms micron size flakes. The color is the result of a thin-film interference phenomenon inside the flakes. Precise control of the thickness of the multi-layers in the pigment's flake structure produces different colors. To get an overall idea of the color behavior of such coatings we have first performed full diffused reflectance measurements. Normal incidence values versus wavelength of six color shifting paints are reported in figure 5. Well defined interference fringes with different periodicities are measured on all the samples. When observed versus incident angle and wavelength the pattern of fringes becomes more complex as shown in figure 6 for Cyan-Purple sample.

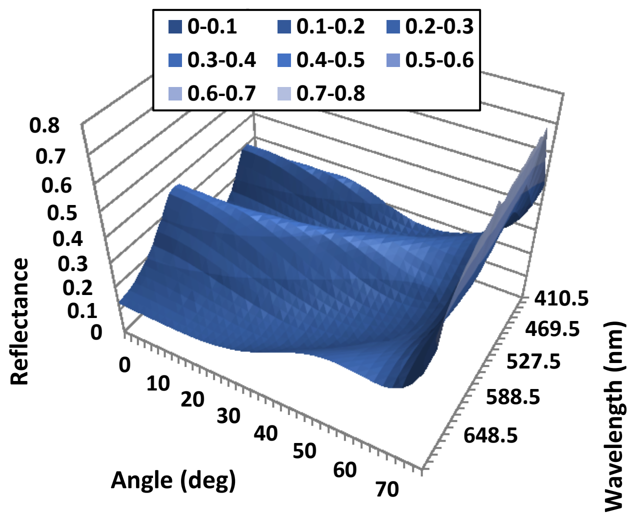

Figure 6 Full diffused reflectance measurements on Silver-Green sample versus incidence and wavelength.

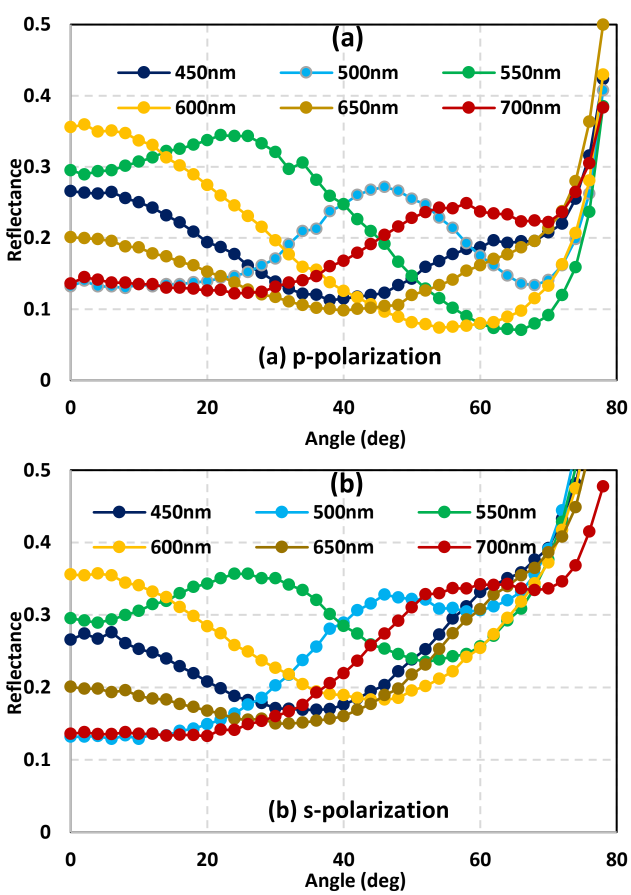

Figure 7 Polarized Full diffused reflectance measurements on Silver-Green sample versus incidence at different wavelengths.

Polarized spectral reflectance

In order to check the polarization influence we have repeated the full diffused reflectance measurements with a polarizer inside the illumination path. Along azimuth 0° the collected reflectance is p-polarized (cf. figure 7.a) and along azimuth 90° it is s-polarized (cf. figure 7.b). A pseudo Brewster is detected around 60° for most of the samples which is mainly due to the optical index of the binder.

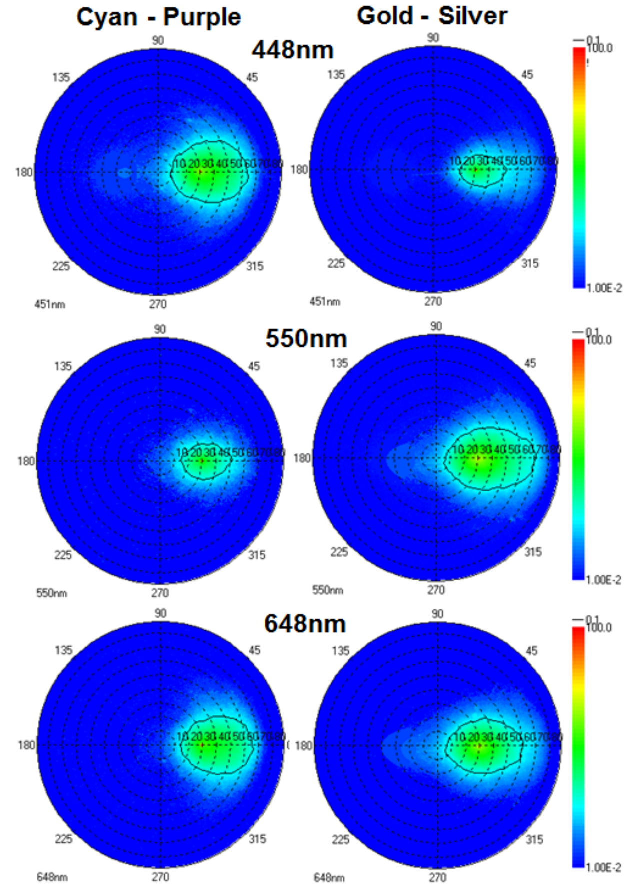

Figure 8 BRDF measurements on cyan-purple sample (left) and gold–silver sample (right) at 30° of incidence and three wavelengths.

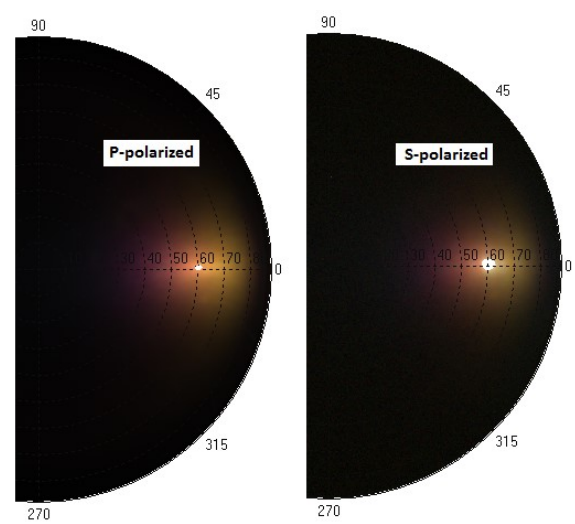

Figure 9 Color simulation using polarized BRDF measurements on cyan-purple sample: Incidence 60°, D65 illuminant.

Unpolarized and polarized spectral BRDF

Spectral BRDF is useful to check the behavior of the diffused light near the specular contribution. On color shifting paint, the strong specular peak is always surrounded by light diffusion that is clearly modulated by the interferences already noticed in full diffused measurements (cf. figure 8). When the polarization of the illumination beam is fixed, the diffused contribution is reduced when the specular one is increased for s-polarized beam compared to p-polarized beam. At 60° the impact on the color can be judged making a simple color simulation as shown in figure 9.

Automotive paintings

Full diffused spectral reflectance

Automotive paintings produce generally extremely specular surfaces where the color is completely defined by the light diffused by the different components diluted inside the binder. We have characterized four different paintings with quite different components resulting in various visual aspects:

- Grey Aluminum: aluminum flakes in polymer matrix, diffusing and reflective aspect
- Yellow: mineral & organic pigments, opaque effect with Lambertian diffusion
- Blue: pigment & flakes, intermediate painting with high chromaticity
- Violet: organic pigments & nacres: low diffusion and low coloring power.

To get an overall idea of the color behavior of the four paintings we have first performed full diffused reflectance measurements. Normal incidence values versus wavelength are reported in figure 10. As expected, grey aluminum is strongly reflecting at all wavelengths. Blue and yellow painting are reflecting preferentially in the blue and in the yellow. Violet painting has clearly a low reflection power in particular in the green region.

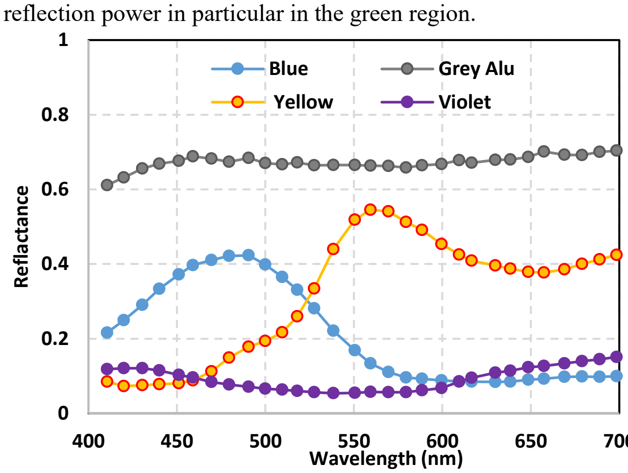

Figure 10: Full diffused reflectance measured at normal incidence on four automotive paintings.

Spectral BRDF

Full diffused reflection data do not predict the aspect of the surface. Only an averaged color value can be deduced. On the contrary, spectral BRDF quantify the proportion of specular and diffusion which is essential for the painting aspect. As shown in figure 11 the four paintings exhibit a strong specular reflection component and much lower diffused components (2 or 3 order of magnitude lower). Only the diffused component is depending on the wavelength and so it is driving the color of the painting. The angular dependence of the diffused component is quite comparable for the blue, grey aluminum and violet paintings and near Lambertian for the yellow painting. A simple cross section is not sufficient to judge of the aspect of the painting. The full angular pattern at all incidence and azimuth angles presents in some cases several fluctuations due to the flakes or the nacres inside the painting. Using the measured spectral BRDF we have performed a simple color simulation of the four samples for a 40° incidence beam. The results reported in figure 12 are useful to judge of this aspect. Some sparkling effect is in particular visible for the grey aluminum painting.

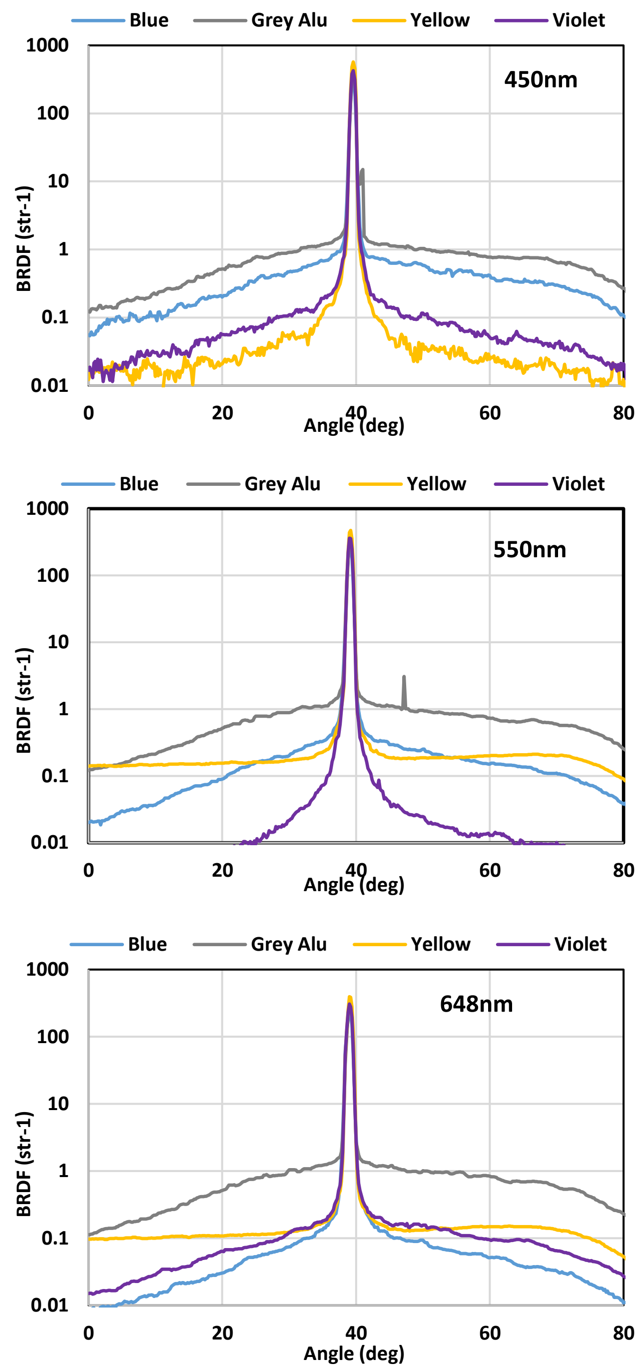

Figure 11: BRDF measured in the incident plane versus detection angle for the different painting: incidence angle 40° and 3 wavelengths 450nm (top), 550nm (center) and 648nm (bottom).

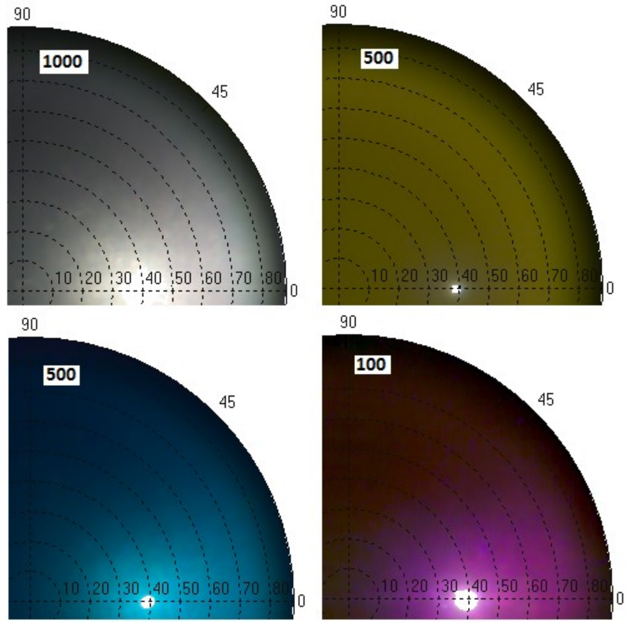

Figure 12: Color simulations using the BRDF measured for incidence 40°. The lightness level for saturation is indicated for each painting.

Polarized BRDF

In order to make physico-realistic ray tracing simulations it can be important to taken into account the polarization. It is particularly true for automotive applications. The polarization effect of a painting can be important in many cases. It is why we have measured the polarization state of the light after reflection on the four samples using a non-polarized illumination beam.

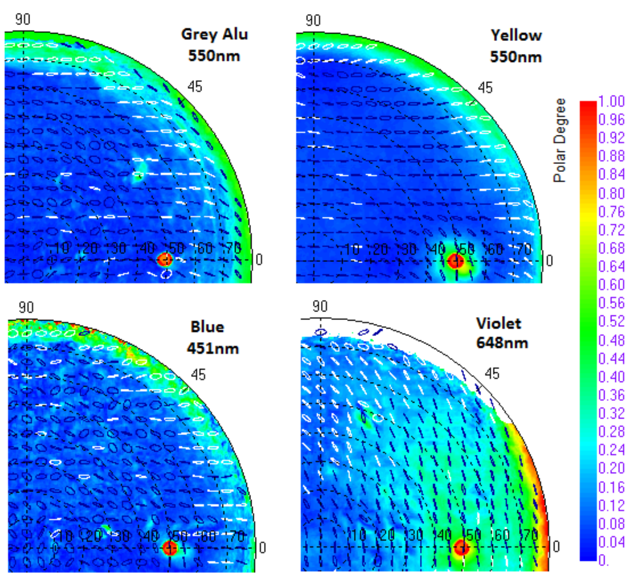

Figure 13: Polarization state of the light measured for incidence 50°. The color scale gives the polarization degree, the ellipticity is schematically reported in each graph. Wavelengths with high diffusion component have been selected.

In figure 13, we have reported the results obtained for 50° incident beam. In each case, the specular beam is always polarized as waited for a binder of optical index around 1.3 but the diffused component is not polarized in the same way for the four paintings. The grey aluminim and blue paintings have unpolarized diffused components when it partially polarized for the violet and yellow paintings. This is an indication of the different diffusion mechanisms in the four paintings [5].

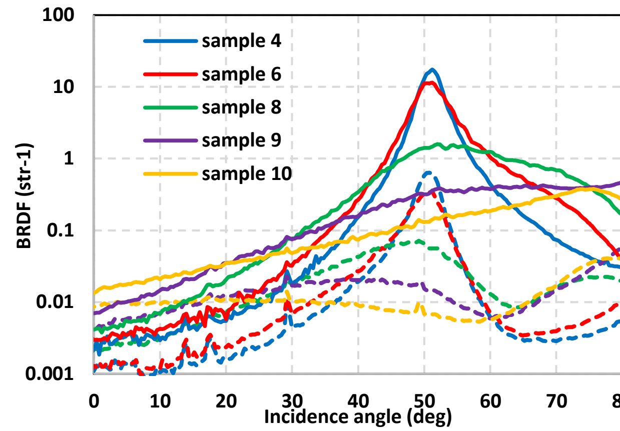

Figure 14: Stokes vector S_0 for s (full lines) and p-polarized (drash lines) illumination measured on five samples of a black coated papers at 550nm and 50° of incidence: the values are collected at 50° versus angle in the incidence plane.

Black coated samples

Polarized BRDF

We have used a gloss series composed of 10 black coated papers. This series of 10 samples with gloss values measured at 60° from 1 to 90 [6], is useful to obtained a large panel of scattering efficiencies on comparable samples. We have measured the Stokes vector of the light scattered by the samples for p-polarized and s-polarized beams at 550nm and 50° of incidence.

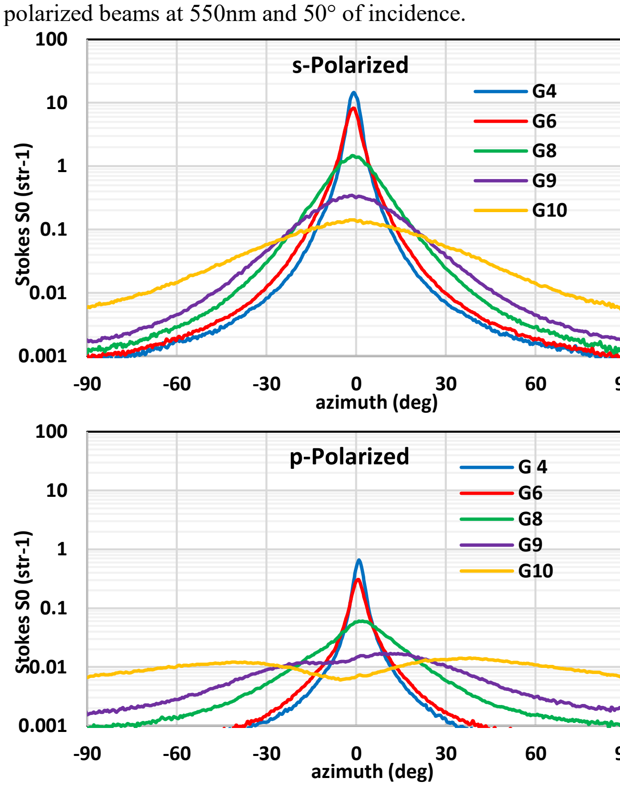

Figure 14: Stokes vector S_0 for s-polarized (top) or p-polarized (bottom) illumination measured on five samples of a black coated papers at 550nm and 50° of incidence: the values are collected at 50° versus the azimuth angle, 0° azimuth corresponds to the incidence plane.

The Stokes vectors S0 obtained for the two configurations on five samples are reported in figures 14 and 15. We have taken the data obtained in the incidence plane (figure 14) and out of the incidence plane (at 50° of incidence). For s-polarized beam, the Rs specular contribution is overriding for all samples. On the contrary for p-polarized beam the Rp specular contribution is minimized and the effect of the scattering is emphasized as shown in figure 14 and figure 15.b. The impact on the polarization degree is also very clear (cf. figures 16.a and 16.b). The proportion of non-polarized light is more important for p-polarized configuration and low gloss samples.

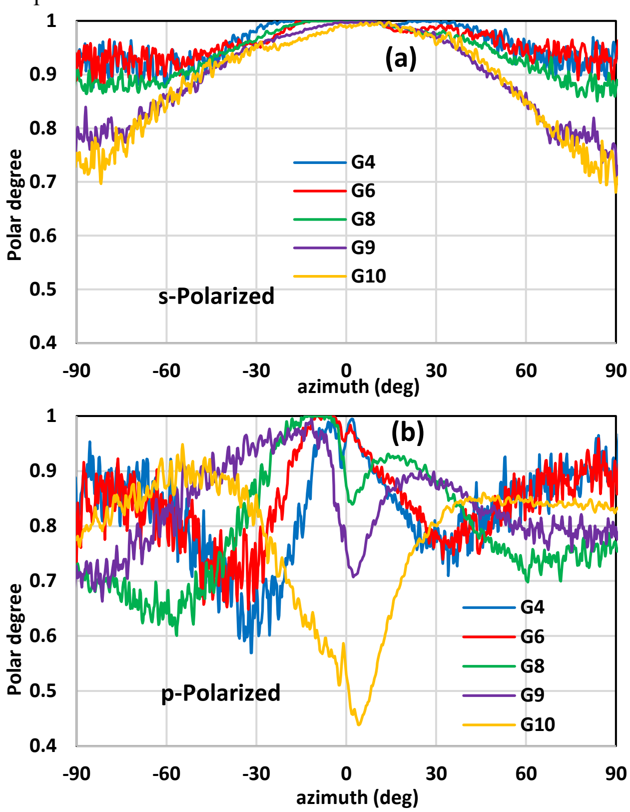

Figure 15: Polarization degree for s-polarized (top) or p-polarized (bottom) illumination measured on five samples of a black coated papers at 550nm and 50° of incidence: the values are collected at 50° versus the azimuth angle, 0° azimuth corresponds to the incidence plane.

Conclusions

The paper focus on a new way to measure polarized spectral BRDF using a Fourier optics instrument that provide high angular resolution measurements in reasonable measurement times. We have first studied the accuracy of the method using a black glass sample. Then different types of samples have been investigated. Color shifting paints have been measured in full diffused illumination and in collimated beam illumination. The interference produced in the flakes appear on both types of measurements. Nevertheless the diffused component is modulated in priority by the interferences which depends on the angle and the wavelength. Automotive color paintings have also been investigated. Their color and aspect is entirely driven by the diffused component and its origin plays also a role. In some cases, flakes or nacres produce random fluctuations on the diffused component resulting in some sparking effect for the viewer. Small differences in the polarization state of the diffused component have been also detected in relation with the different diffusion mechanisms taking place in this type of painting. The capacity to measure BRDF out of the incidence plane is in this case critical for a better understanding of the scattering mechanisms.

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Author Biography

Pierre Boher earned an Engineer degree at ECP, "École Centrale des Arts et Manufactures" in 1982, a Ph.D. in material sciences in 1984 and ability to research management 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.

Thierry Leroux earned an Engineer degree at ENSERG (École Nationale Supérieure d'Electronique et de Radioélectricité de Grenoble) in 1982. He obtained his Ph.D. in solid state physics in 1984 at University Joseph Fourier in Grenoble. He then worked during 10 years at CEA-LETI in Grenoble on various flat panel displays technologies before founding his company ELDIM in 1991. Since this date he is CEO of the company which is focusing on innovative photometric and colorimetric equipment for display characterization and other applications.

Ludivine Cavé earned a technical degree in engineering technologies and worked several years for Xerox and Compaq in Ireland. She joined ELDIM 10 years ago, as technical evangelist. She is international technical coordinator currently involved in scientific mediation to facilitate scientific-technological understanding of photonic technologies.

Thibault Bignon earned an Engineer degree at the École Centrale de Marseille in 2002. He joined ELDIM in 2004 as application engineer and R&D engineer to develop new metrology solutions and new instruments.

Véronique Collomb-Patton obtained her engineer degree in Instrumentation and her PhD in image processing in 2001 with a study on super-resolution applied to CCD defect detection. She then joined the R&D Team of ELDIM where she has worked on various themes: MURA defect, BRDF, 3D display characterization, radiotherapy, diffraction, color measurement accuracy, display rendering.