Development of a Scatterometer for Spatial Distribution Measurements of Reflected and Transmitted Light from Diffuse Surfaces

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Abstract. *A new device is comprised of two ellipsoidal mirrors of revolution and an optical detection system. It enables the absolute measurements of the reflectance and transmittance and the spatial distribution measurements of light scattering from almost all materials. The optical detection system is developed to measure total photo-intensity using a photodiode and to capture the imaging data using a CCD camera. This results in faster, more complete and often more accurate measurements than can be achieved with traditional goniometric methods and integrated sphere methods. The absolute total integrated reflectance and transmittance of well-known samples were measured and the spatial distribution of light scattering from a diffraction grating was captured and evaluated.*

Keywords: STAR GEM, CCD Camera, Fish-Eye Lens, Absolute Diffuse Reflectance

1. Introduction

Scattering measurements provide us with material characterization based on scatter for metals, plastics, paper, textiles and also with surface treatment characterization based on scatter for cleaners, polishes, paints, coatings. Not only TIR/TIT (Total Integrated Reflectance/ Transmittance) but also BRDF/BTDF (Bi-directional Reflection/Transmission Distribution Function) are mainly measured in the scattering measurements. Traditionally BRDF/BTDF measurements are performed using goniometric systems, which involve tilting and rotating a sample or detector about the sample center in order to measure the BRDF/BTDF at selected points on the sphere around the sample, but these systems are relatively slow, potentially requiring hours to measure the sample.[1] Nominally TIR/TIT measurements are made by integrating the BRDF/BTDF over a portion of the sphere around the sample, but actually they are measured using an integrating sphere. Although the measurement using the integrating sphere is fast, it is made only at a designed angle of incidence and the measurement of the spatial distribution can't be made.

Almost all devices for the measurements of reflectance and transmittance have not been designed to scrutinize spectra measured by the devices themselves. A way of the scrutinization of the spectra is to measure both reflectance and transmittance spectra with the same accuracy at the same time and to compare the spectra with the law of energy conversation. Thus the accuracy of the measured spectra can be estimated. We have already completed this scrutinization method for the measurements of reflectance and transmittance of specular samples using a STAR GEM® (Scatter, Transmission and Absolute Reflection measurements using a Geminated Ellipsoid Mirror) and the method is called a self-diagnosis [2] of measured spectra.

Because reflection and transmission around us are diffusive with a few exceptions like mirrors and windows, the spatial distribution of the scattered light as well as absolute reflectance (transmittance) is important. Our goal is to develop a STAR GEM type 3, which allows high-precise absolute reflectance (transmittance) measurements based on the spatial distribution measurements of the scattered light using a CCD camera.

2. Structure of a STAR GEM type 3

Until the early 1980s a hemi-ellipsoidal mirror had been studied as a scatterometer.[1] A fatal flaw is inter-reflections between a sample and a detector, which are located at two focuses, through the intermediation of the ellipsoidal mirror. When the reflectance of a sample becomes higher, this inter-reflection becomes larger. For example, Sullivan and Allen [1] estimated the size of the inter-reflection error by employing an averaging sphere at the detector focus. For an actual sample reflectance of 0.70, inter-reflections would cause the reflectance to be measured as 0.77.

A STAR GEM is comprised of two ellipsoidal mirrors of revolution and an optical detection system. The previous STAR GEM intended to measure both reflectance and transmittance of specular samples is composed of two belt-shape ellipsoidal mirrors. The belt-shape ellipsoidal mirror in Fig. 1(a) was fabricated by cutting an ellipsoid along two planes at the same distance from an equatorial plane and also along a plane perpendicular a rotation axis through one focus. A sample is placed at a common focus and two rotating mirrors are placed at two remaining focuses. Because the light source and detector are placed outside the ellipsoidal mirrors, the inter-reflection becomes negligible.

In the scatterometer the sample and optical detection system must be placed at the common focus and third focus, respectively, and are facing toward the ellipsoidal mirror. These setups are the same as those in the previous scatterometer with the hemi-ellipsoidal mirror. In order to reduce the inter-reflection, two kinds of ellipsoids were prepared, a quarter ellipsoid in Fig. 1(b) and an octantal ellipsoid in Fig. 1(c). The quarter was fabricated by cutting an ellipsoid along the equatorial plane and also along a plane perpendicular the axis through one focus, so that a volume ratio of the quarter to a whole ellipsoid is larger than quarter but a solid angle of the quarter looked by the sample is π steradians. The octant was cut the quarter in half and a solid angle is π/2 steradians.

An example of a scatterometer using the belt-shape (E1) and quarter (E2) ellipsoidal mirrors is shown in Fig. 2 and Fig. 3, where a common focus (F0), a focus (F1) of the E1 mirror and a focus (F2) of the E2 mirror are aligned. A sample is placed at F0, a plane rotation mirror (RM1) is placed at F1 and the optical detection system is placed at F2. The reason why the belt-shape was chosen as an incoming ellipsoid is to make the absolute measurements of both reflectance and transmittance using a modified symmetry X method. The second reason is to reduce the inter-reflection with decreasing the E1 mirror area. The third is to change an incident angle to the sample by the rotation of the RM1 mirror.

The symmetry X method [3] was invented to measure absolute reflectance of a specular sample. When two optical paths measuring reflection from the sample agree everywhere with two optical paths measuring background without the sample, the optical loss at all optical components is completely compensated by the calculation of the geometric means of four light intensities. Consequently, the absolute reflectance of the sample can be obtained.

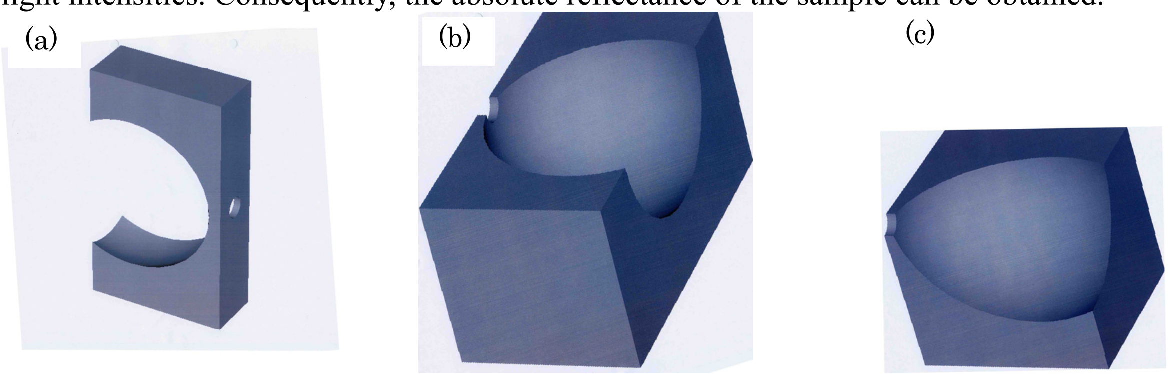

Fig. 1(a), (b), (c) A belt-shape, a quarter, and an octantal ellipsoidal mirrors, respectively.

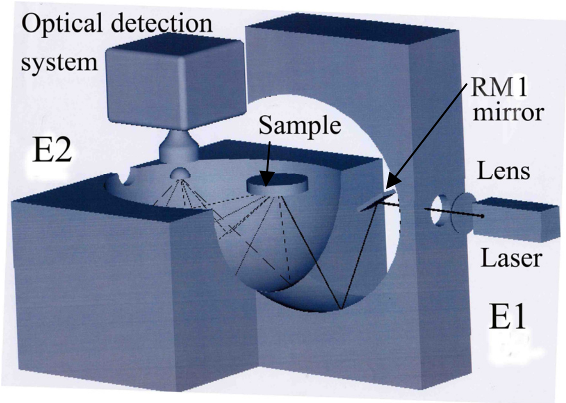

Fig. 2 STAR GEM type 3

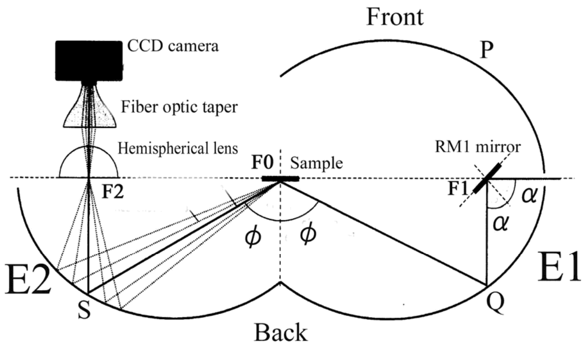

Fig. 3 Sectional drawing of STAR GEM type 3. Reflection measurement mode (RBB)

The modified symmetry X method is explained as follows. In Fig.3 the E1 mirror and RM1 mirror can be rotated independently around the axis of the ellipsoid and around the axis perpendicular the equatorial plane, respectively. Upper and lower sides of the scatterometer are named Front and Back, respectively. For the background measurement the RM1 mirror looks at the upper side, one optical path is a sequential line of F1-P-F0-S-F2 denoted by BFB. The other path is a sequential line of F1-Q-F0-S-F2 by BBB, when the E1 mirror is rotated by 180 degrees. For the reflection measurement the RM1 mirror looks at the lower side and the sample is placed at F0 and light reflected from the diffuse sample spreads around S, one optical path is a sequential line of F1-Q-F0-around S-F2 denoted by RBB. The other path is a sequential line of F1-P-F0-around S-F2 by RFB, when the E1 mirror is rotated by 180 degrees. Thus two reflection paths of RBB and RFB agree everywhere with two background paths of BFB and BBB, if the sample is specular. If the sample is diffuse, two paths of RBB and RFB agree partially with two paths of BFB and BBB.

The optical detection system at F2 is composed of a hemispherical lens, a fiber optic taper and a photo-detector such as a CCD camera and a photodiode. The hemispherical lens at F2 has a function of a fish-eye lens. The diameter and refractive index of the lens made of S-LAH79 (Ohara) are 10mm and 2.003, respectively. The focal plate obtained from the ray tracing is a curved surface and coincides with a large aperture of the fiber optic taper as shown in Fig.4. Its small aperture also coincides with an image sensor of the CCD camera. The angular resolution of the system is determined by the number of pixels on the image sensor and is about 0.5 degrees (0.0003 steradians). The weak point of the system is that the image at a surrounding area is compressed too much.

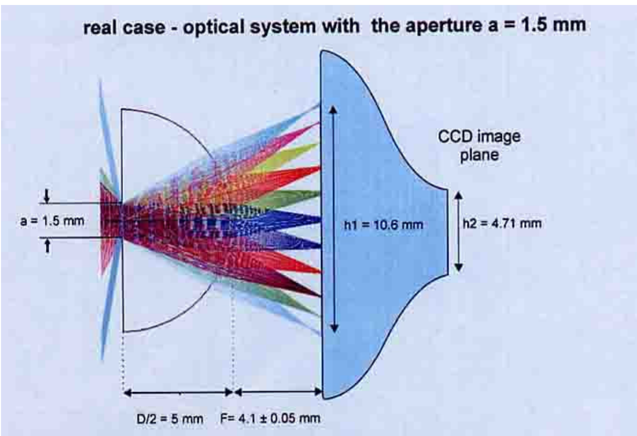

Fig. 4 Focal plate of a hemispherical lens

Red curve: with a hemispherical lens
Black curve: without a hemispherical lens

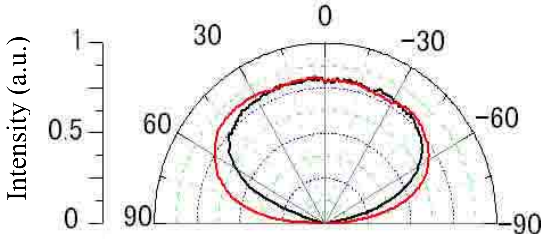

Fig. 5 Efficiency of a hemispherical lens

3. Results and Discussions

A light source was a He-Ne laser of 633 nm. The effect of the hemispherical lens was studied. The optical detection system was only a hemispherical lens and a Si photodiode, which is located at the focal plate. A beam was scanned along a semicircle of the quarter by rotating the E1 mirror with a fixed RM1 mirror. In Fig. 5 red curve was obtained with the hemispherical lens and black curve without it. Using the hemispherical lens the visual angle is larger by 30 degrees. Our optical detection system works well as a fish-eye lens.

The absolute reflectance (*R*) and transmittance (*T*) measurements of several samples were made according to the modified symmetry X method. The samples were a specular quartz plate, a spectralon as a perfect diffuse material, and two kinds of a frosted quartz of #240 and #1,500 as a partial diffuse material. In Fig 6 open circles, open squares and open triangles are *T*, *R* and absorptance (A=1-R-T) of the specular quartz, respectively, and solid squares are *R* of the spectralon. In the range of a small angle of incidence *A* is almost zero, which is an expected value of the pure quartz and *R* of the spectralon is almost 0.5, which is also an expected value, because the quarter is looking at π steradians. In Fig. 7 *T*, *R*, and *A* of the frosted quartz are shown. In this case *A* is not zero but 0.1, because the spatial distribution of light scattering from the frosted samples is not isotropic.

Figures 8 (a) and (b) are the spatial distribution measurements of an irradiation beam and of light scattering from a diffraction grating, respectively. The full width at half maximum is 0.003 steradians from Fig. 8 (a). This value is the angular resolution of our STAR GEM type3.

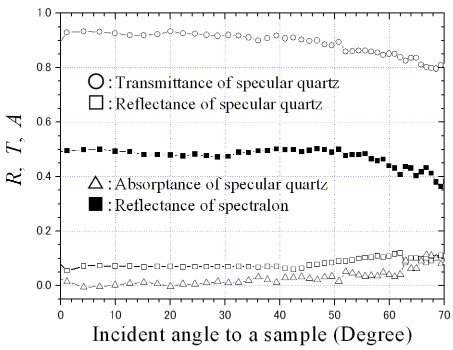

Fig. 6 *R*, *T* and *A* of a specular quartz and spectralon

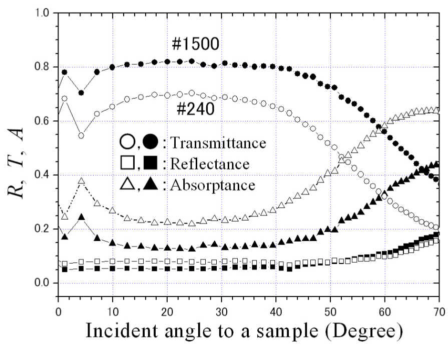

Fig. 7 *R*, *T* and *A* of a frosted quartz of #240 and #1,500

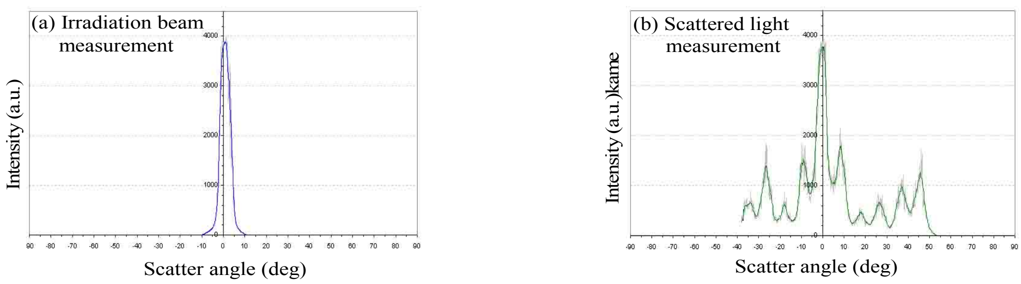

Fig. 8(a), (b) Spatial distributions of an irradiation beam and of light scattering from a grating, respectively

4. Conclusions

A new device, which is comprised of two ellipsoidal mirrors, a hemispherical lens, a fiber optic taper and a CCD camera, has been developed. Absolute reflectance and spatial distribution from diffuse surfaces were measured successfully.

References

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