Diffuse Reflectance and Transmittance Measurements Using a STAR GEM® Optical Accessory

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Abstract. *Four methods, a goniometer, integrating sphere, conical mirror and biconical mirror methods, for the measurement of the diffuse reflectance and transmittance are described and compared. These have been in use for a number of years. A STAR GEM, which has been recently developed in AIST, belongs to the category of the biconical mirror. The disadvantage of the biconical mirror is that it does not collect scatter at all angles, so anisotropic materials are not measured accurately. This disadvantage may be solved by such an improvement of the STAR GEM as the second ellipsoidal mirror can rotate around a GEM axis.*

Keywords: STAR GEM, biconical mirror, absolute reflectance, diffuse reflectance, BRDF, THR, absolute transmittance, diffuse transmittance, BTDF, THT

1. Introduction

Whether materials are almost purely diffusive, as in a lightly packed powder, predominately specular, as in an aluminum mirror, or something in between, such as a glossy paint sample, diffuse reflectance and transmittance spectroscopy tells us much about the physical and chemical characteristics that are not available by other analytical means. Four accessories to perform diffuse reflectance and transmittance measurements are based on the use of a goniometer, an integrating sphere, a conical mirror and a biconical mirror [1].

A STAR GEM accessory has been developed, at first, for the measurements of absolute reflectance and transmittance of specular materials in the wavelength region from 0.24 µm to 25 µm in AIST [2]. The STAR GEM is an acronym of Scatter, Transmission, and Absolute Reflection measurements using a Geminated Ellipsoid Mirror. This development succeeded beyond all expectations. Next step is to develop a STAR GEM as a scatterometer. It is ultimate that the scatterometer can measure absolute reflectance and absolute transmittance of a diffusive material as well as anisotropy of scatter from the diffuse material. Although the STAR GEM belongs to the category of the biconical mirror, it is expected that the STAR GEM may measure both the bidirectional transmittance/reflectance distribution function (BTDF/BRDF) and the total hemispherical transmittance/reflectance (THT/THR) by one accessory, because it carries two strong points of the goniometer and the integrating sphere. The first measurement about the BTDF using the STAR GEM was already published [3]. In this paper the possibility will be discussed to measure the THT/THR using the STAR GEM. Because there is not so much difference between diffuse reflectance and diffuse transmittance measurement methods, mainly the diffuse transmittance measurement method is described below.

Textiles, paper, and rough materials will show changes in the apparent reflectance just by rotation of the sample, which will not be observed using an integrating sphere. It is often said that the BRDF measurement is more a measurement of appearance than the THR. On the other hand, it is important to measure the THR of many materials in the R&D for the utilization of the solar energy in the wavelength region from 240 nm to 50 µm.

2. Comparison of four traditional accessories

Measurements by a goniometer involve tilting and rotating the sample or detector about the sample center in order to measure beam transmitted as a function of illumination and collection angles at selected point on the hemisphere above the sample. This function is called the bidirectional transmittance distribution function (BTDF). This function makes an anisotropy of the diffuse transmission clear. The time required to perform a goniometric measurements has decreased significantly due to advances in computer-controlled instrumentation. Nevertheless, the disadvantage is that goniometric measurements are still time consuming due to the large number of data points required, when people want to know not only the anisotropy (BTDF) but also the total hemispherical transmittance (THT). The THT can be obtained through the spatial integration of the BTDF all over the hemisphere.

Methods based on the integrating sphere are by far the most common in use today. A beam is focused onto the sample, which lies on a line tangent to the inside radius of the sphere. The transmitted radiation is collected by the sphere. The detector lies at another point on the inside tangent of the sphere and collects the diffusely transmitted radiation. As a result the THT can be measured, but the anisotropy can't be measured. Other disadvantages are that a sphere is by very nature an attenuating device and that the corrections of a sphere zero error and a substitution error are necessary and difficult [1].

In conical mirror accessories, the light source is placed at one focus of a highly specular hemiellipsoid and the sample is placed at the other focus. A reverse geometry also exists when the sample is illuminated by a directional beam with the detector lying at the other focus of the hemiellipsoid. The advantage is a great increase in efficiency of collection. The disadvantages are that the interreflections between the sample and detector or source and the position misalignments of the sample and detector or source become significant error sources. Another disadvantage is the cost required to produce such hemiellipsoid.

In biconical mirror accessories, an ellipsoidal mirror focuses an incident beam at a small point on a sample and the scattered transmitted light is caught by another ellipsoidal mirror that directs the beam to a detector. The advantage is that it allows one to get a spectrum on a far smaller sample that is required with an integrating sphere. The disadvantage is that it does not collect scatter at all angles, so anisotropic materials are not measured accurately. For this reason, biconical mirror accessories are generally thought of as qualitative.

3. Experimental details

An idea of a GEM is based on the fact that light emitted from a focus of the ellipsoidal mirror converges at the other focus [4]. The GEM consists of two ellipsoids of revolution (E1 and E2). A focus of the E1 coincides with that of the E2 and this common focus (F0) aligns with two remaining foci (F1 and F2). A sample is placed at F0 and two rotating plane mirrors (RM1 and RM2) are placed at F1 and F2, respectively. The RM1 and RM2 can rotate independently by each stepping motor.

We have already developed three types of the STAR GEM [3]. In a STAR GEM Type 3 in Fig. 1, a Ceiling was divided into two parts and each part was fastened on the E1 and E2 separately. The E1 was fixed on the Base in the previous manner. On the other hand, some part of the wall of a Base under the E2 was cut out and the E2 wasn't fixed on the Base, so the E2 was able to rotate around the GEM axis. A sample was placed vertically and incident light advanced along the GEM axis, as a result, the incident plane was a horizontal plane including the GEM axis. The STAR GEM Type 3 was an improved accessory to measure scattered radiation from a diffuse material not only in the incident plane but also out of the incident plane.

Fig. 1 STAR GEM Type 3 for scattered light measurements

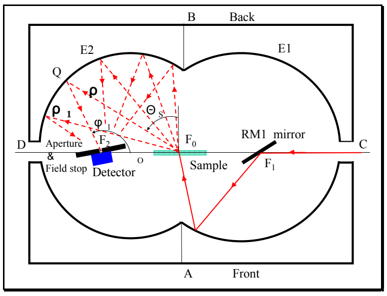

Fig. 2 Structure of GEM for BTDF measurements and beams

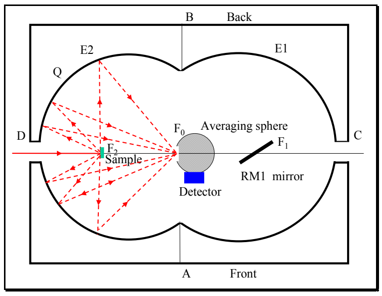

Fig. 3 Structure of GEM for THR measurements and beams

The STAR GEM Type 3 was used with a He-Ne laser and a silicon photodiode detector in Fig. 2. The laser was placed in the right hand outside the STAR GEM. The detector replaced the RM2 in Fig. 2. This configuration was to measure the BTDF of a transmissive diffuser. In order to measure the BTDF with high spatial (angular) resolution, a field stop and an aperture were attached in front of the detector. A laser beam was chopped to reduce both optical and electric noise. This was accomplished through the use of lock-in detection. A monitoring detector was also used to allow the computer to ratio out laser power fluctuations. The incident laser beam was focused onto the RM1 and also the sample surface and the detector following the nature of the ellipsoidal mirror. The source and the sample were fixed. The RM1 was rotated to a desired incident angle. The detector at F2 was also rotated to a desired collecting angle to collect scattered radiation from the sample.

Another configuration was to measure the THR of diffuse radiation using the STAR GEM Type 3. In Fig. 3 a sample, such as a reflective diffuser, replaced the detector in Fig. 2 and was settled to be perpendicular to the GEM axis at F2. A detector with an averaging sphere also replaced the sample in Fig. 2 and was settled at F0. The averaging sphere was used to eliminate the spatial anisotropy of the response of the detector. The laser beam entered into the STAR GEM along the GEM axis from the left side in Fig. 3. The ellipsoidal mirror of the E2 rotated around the GEM axis from χs= -65 degrees to χs= 65 degrees. It was impossible to rotate until ±90 degrees because of the existence of a rod to support the sample. In this configuration the detector received the total scatter field on the E2 due to a large aperture of the averaging sphere except for a specular component of reflection from the reflective diffuser because of an entrance hole for the laser beam on the E2, which is shown as D in Fig. 3. The sample diameter was limited within a solid angle, where the hole on the E2 was looked from F0. It was less than 10 mm. This configuration was like a conical mirror set up.

A sample was a ground glass diffuser (DFSQ1-30C02-240) made by SIGUMA KOKI CO. and was a transmissive diffuser. A front surface was a frosted glass and a back surface was polished. Its diameter was 30 mm and its thickness was 2 mm. Another sample was a reflective diffuser. Its diameter was 10 mm and its thickness was 1 mm.

4. Results and Discussions

Attentions must be paid to the calculation of the BTDF measured by the STAR GEM [3]. In the goniometer, the detector rotates around the sample and the detector field of view (FOV) is always constant, because the distance between the sample and the detector is constant. On the other hand, in the STAR GEM the detector rotates around the F2. The sum of two distances from a point of Q, which is on the E2 in Fig.2, to F0 and to F2 is constant because of the ellipsoid. These two distances change simultaneously, when a collection angle, θs, changes in Fig. 2. As a result the field of view (FOV), where the detector looks at the sample in the ellipsoid mirror of the E2, also changes depending on the θs.

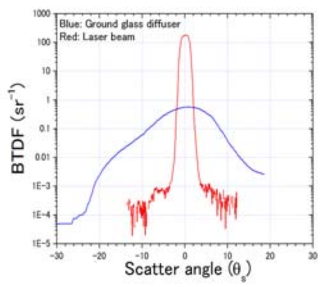

Fig. 4 BTDF and laser beam profile

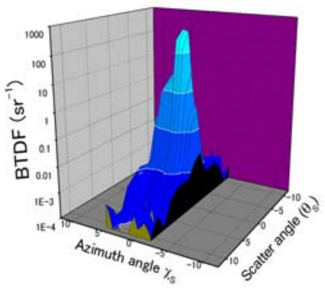

Fig. 5 Three dimensional profile of laser beam

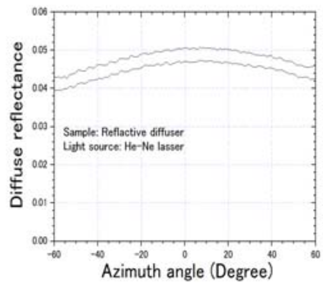

Fig. 6 Diffusive reflectance

In Fig. 2 a ground glass diffuser was illuminated using a 0.633 μm-He-Ne laser. In order to measure the angle dependence of scattered radiation from the transmissive diffuser, the detector was rotated around F2, so its FOV was swept through the scatter field on the E2. The BTDF is shown in Fig. 4. The spatial profile of the laser beam is also shown in Fig. 4. It is clear that the diffuser scatters the laser beam over a wide range of angles.

The STAR GEM Type 3 allowed the E2 also to rotate around the GEM axis. This rotation corresponded to the change of the azimuth angle, χs, from the incident plane. While the detector was simultaneously rotating around F2 and around the GEM axis, the intensity of the laser beam was measured. A three dimensional profile of laser beam is shown in Fig. 5. A full width at half maximum is 1.8º and its maximum value is 200 sr-1. The profile of the laser beam is not isotropic but is broad in the positive azimuth angle region. This result isn't found from the measurements only in the incident plane in Fig. 4. The STAR GEM Type 3 may measure the anisotropy of the diffuse transmittance as well as the spatial profile of a laser beam.

The diffuse reflectance of the reflective diffuser, which was measured using the setup of Fig.3, is shown in Fig.6. The χs= 0 degree means that the E2 is horizontal. There are two curves, because the diffuse reflectance was measured two times by rotation of the sample around the normal to the surface by 90 degrees. Although both signals are decreasing with increasing the azimuth angle, this is not due to anisotropy of the sample but due to the shadow of the rod. In this setup the signal intensity is sensitive of the sample position. The intensity of both signals doesn't correspond each other because of the shadow of the sample itself. In this configuration, it is difficult to measure a transmissive diffuser and there is another problem that the diffuse reflectance in Fig. 6 always includes the signal from the neighborhood of the D point in Fig. 3 independent of the azimuth angle.

When the configuration for the BTDF measurements in Fig. 2 compares with the configuration for the THR measurements in Fig.3, the configuration of Fig. 2 is superior because there is no shadow of the supporting rod and the sample itself and because not only diffuse reflectance/transmittance but also specular reflectance/transmittance can be measured. The disadvantage is a small aperture in Fig. 2. In the next step we will improve the field of view in Fig. 2 and find the method to obtain the THR/THT using the STAR GEM Type 3.

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