A Comparison of Optical Properties between High Density and Low Density Sintered PTFE

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ABSTRACT

Materials with similar chemical compositions often exhibit different optical properties due to their structural composition. PTFE is widely used in many applications for both its mechanical and optical properties. Low density sintered PTFE has optical properties that make it desirable for use as a white diffuser in applications such as remote sensing. The contrast between the commonly available high density material and the low density material may be useful for those interested in optical modeling of scattered light. Additionally, some applications may find high density PTFE suitable for some optical applications. This paper describes measurements of BRDF, 8°/hemispherical reflectance, and directional hemispherical transmittance for both high density (HD) and low density (LD) sintered PTFE.

Keywords: BRDF, diffuser, optical properties, PTFE, reflectance, low density sintered PTFE, transmittance, Teflon

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1. BACKGROUND

1.1 Description of high density PTFE and low density PTFE

Polytetrafluoroethylene (PTFE) is a synthetic fluoropolymer, which is made either by the emulsion polymerization of tetrafluoroethylene or by the direct substitution of hydrogen atoms on polyethylene with fluorine. It is most well known by its trademark, Teflon. PTFE has many desirable properties, because it is hydrophobic, non-reactive, chemically inert, is a good lubricant, and has a high melting point, low coefficient of friction, and excellent dielectric properties.

Sintering is a method for making PTFE from powder by heating it below its melting point until its particles adhere to each other. The result is a porous plastic fused together as a cohesive mass of resin particles. Particle size and shape of resin powders can be manipulated to optimize pore size, void volume, surface texture, and strength. Some advantages of sintering include: the possibility of very high purity, great uniformity, the preservation of purity from the strict fabrication process, and the stabilization of the details of repetitive operations by control of grain size in the input stages.

1.2 Applications

Since water-containing substances do not wet PTFE, PTFE is often used as a non-stick coating for pans and cooking utensils. Also, because it is very non-reactive, it is used in containers and pipework for reactive and corrosive chemicals. Due to its excellent dielectric properties, PTFE is used as an insulator in cables and printed circuit boards. Its extremely high bulk resistivity makes it an ideal material for fabricating long life electrets, useful devices that are the electrostatic analogues of magnets. Due to its low friction, PTFE is used to make computer mice feet and in applications involving bearings, bushings, and gears. PTFE has also been used in body piercings, machinery lubricant, armor-piercing bullets, thread seal tape, grafts to bypass stenotic arteries in peripheral vascular disease, and painted surfaces to prevent insects from climbing. PTFE's high corrosion resistance makes it ideal for laboratory environments as containers, magnetic stirrers and tubing for highly corrosive chemicals such as hydrofluoric acid, which will dissolve glass containers.

In the field of radiometry, the ability of PTFE sheets to diffuse light make it useful as measuring heads for spectroradiometers and broadband radiometers. In addition, the constant properties of LD sintered PTFE from the ultraviolet (UV) to the near infrared (NIR) make it attractive in many radiometric applications. In this spectral region,

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light transmitted through LD PTFE behaves like a Lambertian diffuser. This makes LD PTFE perfect for detectors measuring the power of optical radiation at a surface, such as in solar irradiance measurements.

1.3 Literature review

Most of the papers reviewed focused on the visible and infrared spectra. One study measured the bidirectional reflectance distribution function (BRDF) and directional hemispherical reflectance (DHR) of pressed and LD PTFE in the UV. [1] Five other studies measured BRDF of LD PTFE in the UV. [2-8] Another study investigated BRDF in the extreme ultraviolet (EUV) for white and black LD PTFE along with other black coatings. [9] BRDF was the sole measurement of most of the papers, while DHR was the next most popular measurement. Other quantities measured included the bidirectional transmittance distribution function (BTDF), absorption and scattering coefficients, and the phase function [10]; hemispherical transmittance, normal DHR, and solar transmittance [11]; and normal DHR [12]. A majority of the papers measured LD PTFE samples only. Other materials measured included bark, soil, and leaves [13]; zircon and silicate fibers [10]; aluminum, steel, and sandpaper [14]; Teflon, Tedlar, and acrylic [11, 12]; black paints [15]; and roof tile and roof paper [16]. Measurements on HD PTFE were not found in the literature, while most of the references found investigated the BRDF and DHR of LD PTFE in the visible and infrared regions [10, 13-15, 17-29].

1.4 Outline

Section 2 describes each of the three facilities that were required in making the measurements for the HD and LD PTFE samples. In addition, the procedures for data acquisition using these facilities are also outlined in Section 2. The data are described, displayed, and discussed in Section 3. A discussion of the uncertainty analysis for each of the measurements is included in Section 4. Finally, the paper and its conclusions are summarized in Section 5.

2. FACILITIES AND PROCEDURES

Two sets of PTFE samples were procured: one HD PTFE set and the other LD PTFE set. The HD PTFE is commonly available for a variety of consumer products, while the LD is typically produced for optical use. In this study the HD PTFE has a density of approximately 2.17 g/ml while the LD PTFE has a density of 1.55 g/ml. All of the samples were approximately 5 cm square. Both sets have samples of the following nominal thicknesses: 19.05 mm (0.75 in), 12.70 mm (0.5 in), 6.35 mm (0.25 in), 4.76 mm (0.1875 in), 3.18 mm (0.125 in), and 1.59 mm (0.0625 in). The LD PTFE samples are Fluorilon^{TM} made by Avian Technologies LLC. [30] (DISCLAIMER: Any mention of commercial products in this paper does not imply recommendation or endorsement by NIST.) Measurements taken for both sets of samples were: BRDF, DHR, and directional hemispherical transmittance (DHT). Two instruments were used for the DHR and DHT measurements to cover the entire wavelength range. The HD PTFE samples were prepared by sanding both the front and back surfaces with 220 grit silicon carbide wet/dry sand paper. This was done to reduce the specular component and to approximate the same surface roughness as the Flourilon^{TM} samples.

BRDF was taken with the NIST Spectral Tri-function Automated Reference Reflectometer (STARR) [31]. The measurements were made using the quartz-tungsten-halogen (QTH) lamp in combination with the UV enhanced Si detector. The spot size on the sample was 17 mm. The spectral band width was 14 nm. The results are the average of both the S and P polarization states.

DHR and DHT were measured using the LAMBDA 950 spectrophotometer [32]. The measurements were made with both the deuterium lamp and the QTH lamp with a cross over at 319.2 nm. The detectors used were the photomultiplier tube and the PbS detector with a cross over at 860.8 nm. The spot size was approximately 5 mm by 15 mm. The spectral band width was 3 nm for the PMT and variable (less than 20 nm) for the PbS. The beam was depolarized prior to being incident on the sample. The integrating sphere used was a 150 mm with the specular reflection included.

DHR and DHT were also measured in the NIR at the Fourier Transform Infrared Spectrophotometry (FTIS) facility using the Infrared Reference Integrating Sphere (IRIS) coupled to a Digilab FTS-7000 Fourier transform infrared (FTIR) spectrometer. [33-35] The FTIR was set up in its NIR configuration using a coated quartz beamsplitter and a quartz halogen lamp source. Measurements were made from 2950 cm^{-1} to 10000 cm^{-1} (1000 nm to 3400 nm), with a spectral resolution of 8 cm^{-1}, and data spaced at 4 cm^{-1} intervals. The longer wavelength data are used in the results. The IRIS is a rough-gold coated sphere used with a HgCdTe detector. Samples are mounted on a port on the outside of the sphere, so that light is incident at 8°. The illuminated spot size is 1 cm in diameter. The sphere has an entrance port and is mounted on rotation stages, which enable measurement of both DHR and DHT for 8°.

BRDF measurements at 1550 nm and 2130 nm were taken with the Infrared Laser-based Gonio-Reflectometer Instrument (ILGRI). The ILGRI performs BRDF measurements up to 11000 nm, using a number of laser sources including a diode laser operating at 1550 nm and a PPLN (periodically poled $LiNbO_3$) laser tunable from 1000 nm to 5000 nm. [36]

3. MEASUREMENTS

BRDF data for the thickest samples, 19.05 mm, were measured at viewing angles of -70º to 70º in increments of 10º. Data points at 0º incidence were excluded for 400 nm, 550 nm, and 1000 nm. Measurements for both the HD PTFE and the LD PTFE samples were acquired at wavelengths of 400 nm, 550 nm, and 1000 nm. The results in Fig. 1 plainly show that the BRDF data for the LD PTFE sample is fairly independent of wavelength, while the results in Fig. 2 reveal that the BRDF for the HD PTFE sample varies significantly with wavelength. For the HD PTFE sample data, it is evident that BRDF decreases with wavelength for the HD PTFE sample. Also, there is a possibility of a small peak at normal incidence due to the flattening out of the BRDF curve around ±20º and the slight increase from the normal curve at ±10º. All data appears to be fairly symmetrical. Although it is not evident in the plots, normalized results show that the BRDF becomes broader with wavelength for the HD PTFE sample, while the BRDF become slightly narrower with wavelength for the LD PTFE sample. BRDF, DHR, and DHT are a function of many factors, including particle and pore size and bulk density of the starting resin. In addition, the BRDF is also a function of the surface finish, how the materials were machined, and final density of the material.

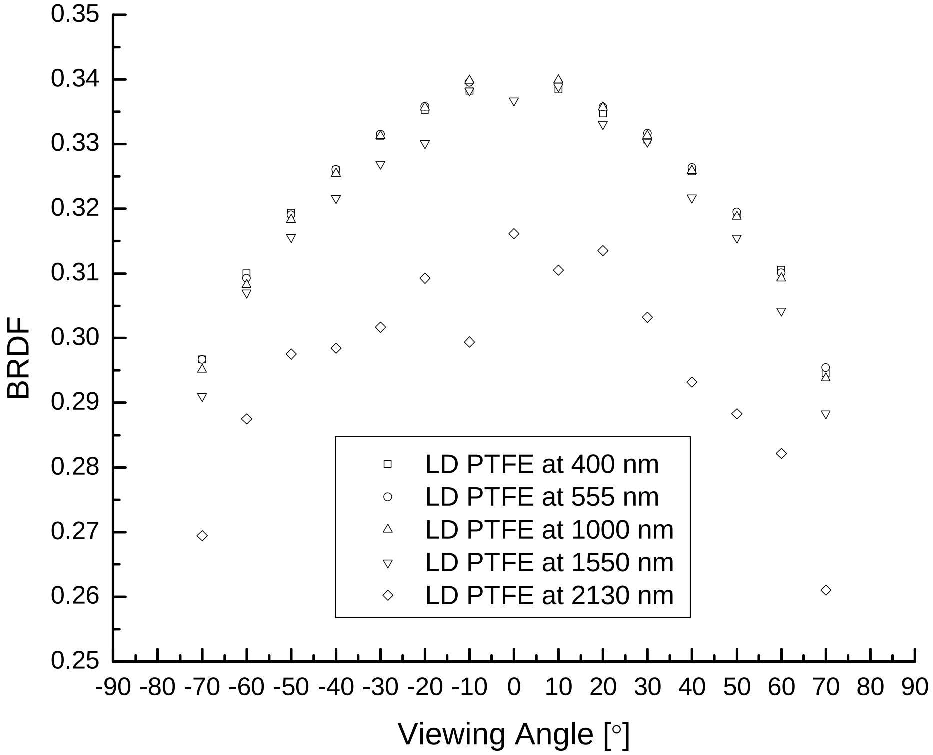

Figure 1. Plot of BRDF for a LD PTFE sample as a function of viewing angle for wavelengths of 400 nm, 555 nm, and 1000 nm.

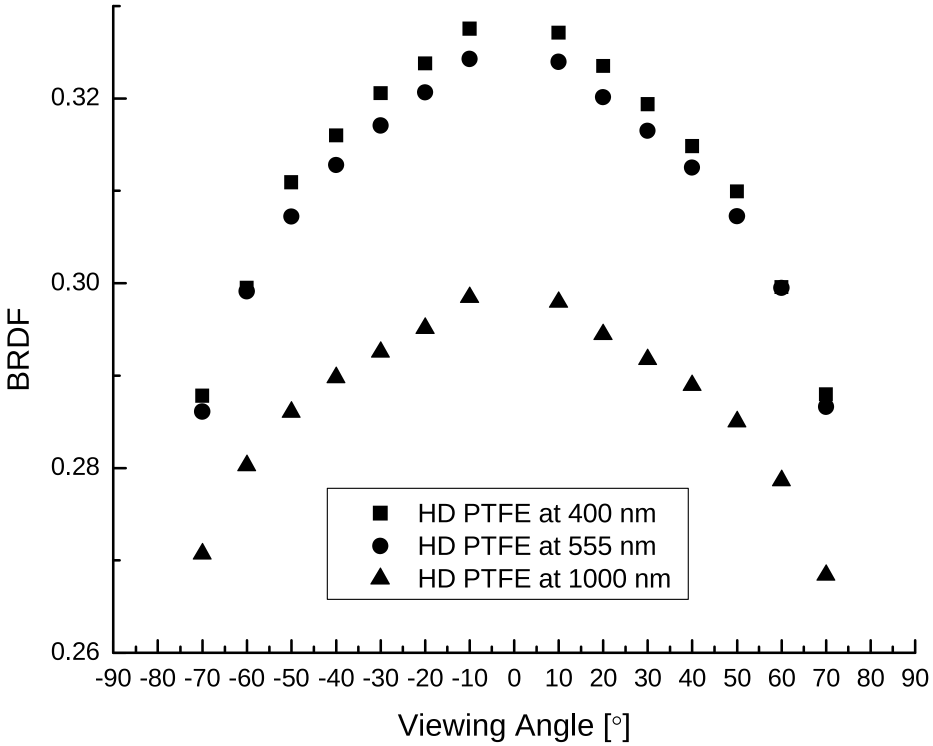

Figure 2. Plot of BRDF for a HD PTFE sample as a function of viewing angle for wavelengths of 400 nm, 555 nm, and 1000 nm.

Directional hemispherical transmittance data were measured for each of the six thicknesses at wavelengths of 400 nm, 550 nm, and 1000 nm. Measurements for the LD PTFE samples in Fig. 3 show as expected that the directional hemispherical transmittance decreased exponentially as a function of thickness. Furthermore, the directional hemispherical transmittance increases with wavelength. The same data for the set of HD PTFE samples are shown in Fig. 4. Trends for the HD PTFE sample are similar to those for the LD PTFE sample. The directional hemispherical transmittance decreased exponentially as a function of thickness, but it is not known why the three data points at 3.18 mm, 4.76 mm, and 6.35 mm appear to be collinear for all wavelengths. The lower reflectance of the HD PTFE samples is primarily a function of radiation losses due to transmittance of the material.

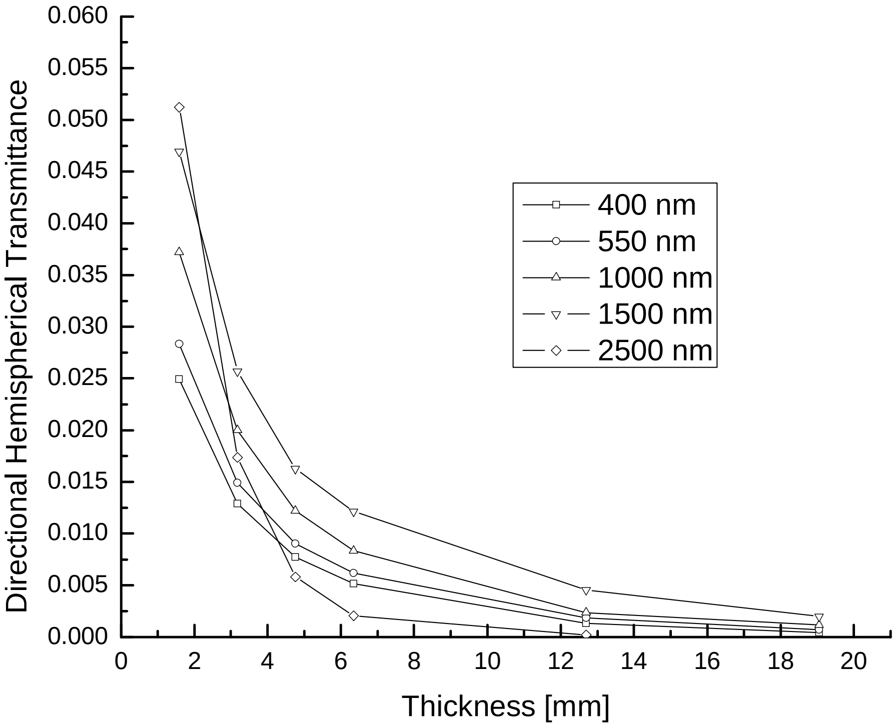

Figure 3. Plot of directional hemispherical transmittance for a LD PTFE sample as a function of thickness for wavelengths of 400 nm, 555 nm, and 1000 nm.

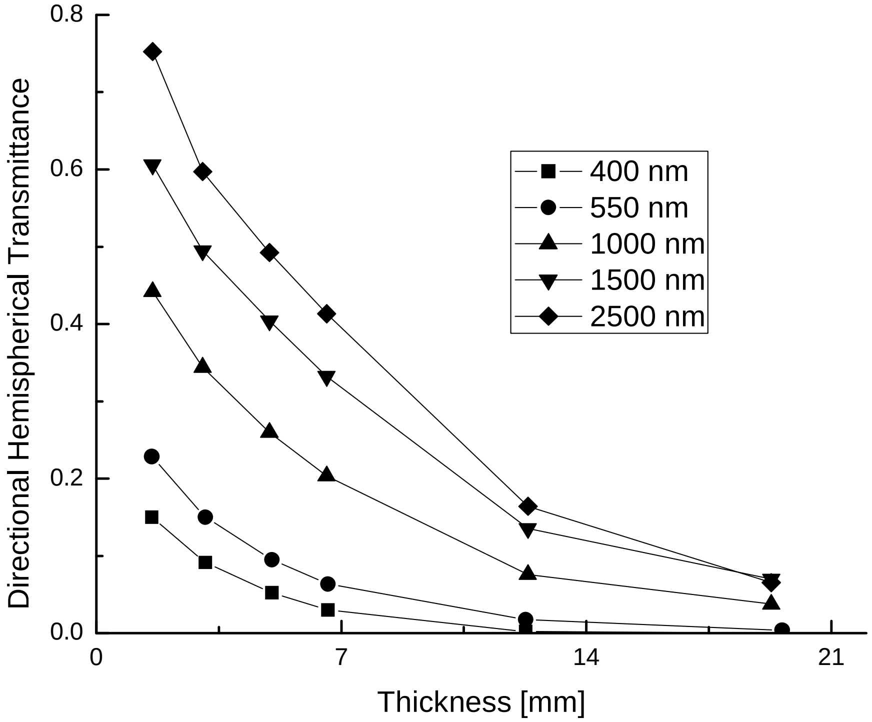

Figure 4. Plot of directional hemispherical transmittance for a HD PTFE sample as a function of thickness for wavelengths of 400 nm, 555 nm, and 1000 nm.

In Fig. 5, 8º/hemispherical reflectance (8º incidence and viewing throughout the whole hemisphere) results are shown for a HD PTFE sample and a LD PTFE sample. Measurements were taken as a function of wavelength from 250 nm to 2500 nm in increments of 10 nm. The results indicate clearly that the 8º/hemispherical reflectance is much higher and flatter for the LD PTFE sample than for the HD PTFE sample, especially in the infrared region. The 8º/hemispherical reflectance for the HD PTFE sample peaks at about 0.95 around 410 nm but quickly decreases to about 0.25 around 2500 nm. For the LD PTFE sample, the 8º/hemispherical reflectance is minimum at about 0.92 around 250 nm and around 2500 nm but stays above 0.98 between 320 nm and 1820 nm. Around 2225 nm, there is a small peak in the 8º/hemispherical reflectance for both the HD PTFE sample and the LD PTFE sample. Comparing the 8º/hemispherical reflectance to that measured by FTIR, for both the HD and the LD PTFE sample, the difference is less than 0.01 between 1000 nm and 2500 nm.

Similar results for DHT are displayed in Fig. 6 for both the HD and LD PTFE samples. The DHT increases up to 2500 nm because there is less scattering and thus higher transmittance at increasing wavelengths.

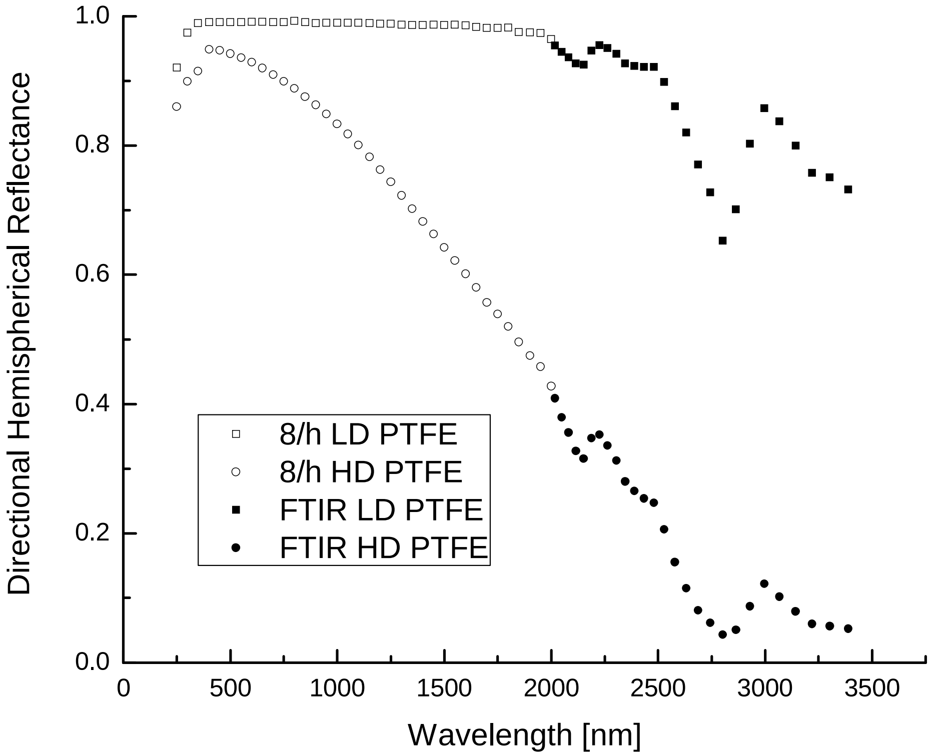

Figure 5. Plot of 8º/hemispherical and FTIR reflectance for a HD PTFE sample and a LD PTFE sample as a function of wavelength.

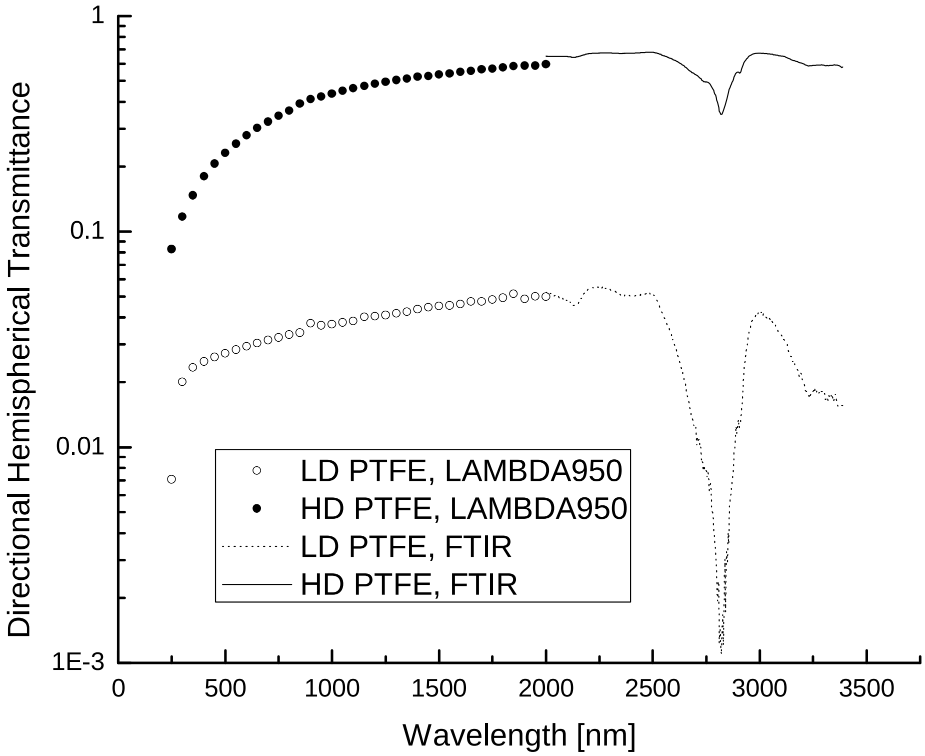

Figure 6. Plot of directional hemispherical transmittance for a HD PTFE sample as a function of wavelength.

4. UNCERTAINTIES

The uncertainties for the different measurements will be summarized here. The uncertainty in BRDF is a function of the uncertainties in the source stability, wavelength, stray light, the geometry (angles and distances), and the incident and reflected signals. The $k = 2$ relative combined expanded uncertainty for BRDF of a white PTFE plaque at 400 nm ranges from 0.32 % at 0º reflected angle to 1.09 % at 75º reflected angle. [31]

The DHR uncertainty depends on the uncertainties in the source stability, wavelength, and the incident and reflected signals, while the DHT uncertainty is influenced by uncertainties in the wavelength, accuracy, linearity, reproducibility, repeatability, noise, and stray light. Using Type B uncertainty values from the LAMBDA 950 manual, the $k = 2$ relative combined expanded uncertainty for both the DHR and DHT of PTFE samples is estimated to be about 0.5 %. [32]

FTIR reflectance uncertainties shorter than 2500 nm are 3.0 % to 3.1 % for all thicknesses of both the HD and the LD PTFE samples. For the 1.6 mm thickness of the HD PTFE sample, the FTIR transmittance uncertainties at 1000 nm, 1500 nm, and 2500 nm are all about 3.0 %. For the 19.65 mm thickness of the HD PTFE sample, the FTIR transmittance uncertainties at 1000 nm, 1500 nm, and 2500 nm are 5.4 %, 3.5 %, and 3.6 %. For the 1.6 mm thickness of the LD PTFE sample, the FTIR transmittance uncertainties at 1000 nm, 1500 nm, and 2500 nm are 6.4 %, 4.0 %, and 3.7 %. For the 18.9 mm thickness of the LD PTFE sample, the FTIR transmittance uncertainties at 1000 nm, 1500 nm, and 2500 nm are all above 40 %.

For the FTIR-IRIS system, for high level reflectance or transmittance, the expanded uncertainty for DHR and DHT measurements of unknown samples is 3% of the reflectance or transmittance value. For samples that behave in a near-Lambertian fashion, such is demonstrated in Figure 1 for the HD and LD PTFE samples, the uncertainty is reduced to 1.25% of the value.

5. CONCLUSIONS

Facilities at NIST allow accurate characterization of the DHR and DHT from 250 nm to 3390 nm using FTIR and monochromator-based instrumentation. BRDF characterization as a function of wavelength and various geometries is also available at NIST. BRDF measurements for PTFE samples in this study show a distinct wavelength dependence of the BRDF for HD PTFE samples but not for LD PTFE samples. The trend for the HD PTFE samples is a decrease in BRDF with increasing wavelength. The directional hemispherical transmittance decreases exponentially with the thickness for all the PTFE samples measured. For both the LD and HD PTFE samples, the directional hemispherical transmittance increases with increasing wavelength. The DHR for the LD PFTE samples is fairly constant with wavelength and is above 0.98 between 320 nm and 1820 nm. On the other hand, the DHR for the HD PTFE samples peaks at about 0.95 at 410 nm but decreases monotonically with wavelength. There is fairly good agreement between the FTIR and LAMBDA950 measurements; differences are less than 1%. As expected, the directional hemispherical transmittance for the LD PTFE sample is an order of magnitude less than that for the HD PTFE sample. Agreement between the FTIR and LAMBDA950 measurements is between 3% and 5%.

6. ACKNOWLEDGMENTS

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