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Improved Diffusers for Solar UV Spectroradiometers

Tomi Pulli[a], Petri Kärhä[a,b], Joop Mes[c], Josef Schreder[d], Priit Jaanson[a] and Farshid Manoocheri[a,b]

[a]*Metrology Research Institute, Aalto University School of Electrical Engineering, Espoo, Finland*
[b]*Centre for Metrology and Accreditation MIKES, Espoo, Finland*
[c]*Kipp & Zonen, Delft, The Netherlands*
[d]*CMS - Ing. Dr. Schreder GmbH, Kirchbichl, Austria*

Abstract. Diffuser heads whose angular response is proportional to the cosine of the zenith angle are needed for global irradiance measurements. Various material samples were measured for their transmission properties to find out the most promising material candidate for use in an improved solar UV diffuser. Novel bubbled quartz materials were found to be attractive alternatives to the traditional PTFE materials for this purpose. A 3D Monte Carlo particle tracing software was constructed and used to optimize the diffuser design. Integrated cosine error of 2.3 % was measured with a raised flat diffuser on a prototype detector. The preliminary simulation results indicate that integrated cosine error can be lowered to 1.7 % or below simply by adjusting the dimensions of a flat diffuser. Integrated cosine error of 0.8 % or below can be reached with shaped diffusers.

Keywords: Radiometry, Solar UV, Diffusers, Monte Carlo analysis.
PACS: 07.60.Rd, 42.15.Dp, 42.25.Bs

INTRODUCTION

Solar UV radiation scatters heavily in the atmosphere. Therefore, global irradiance measurements are necessary to determine the total amount of UV radiation that reaches the surface of the Earth. High quality entrance optics are needed for these measurements. The angular response of an ideal device is proportional to the cosine of the zenith angle. Deviations from the cosine response cause errors in global radiation measurements that can be corrected afterwards but only to an extent [1].

Typically, the cosine response is achieved either by using an integrating sphere or a sheet of diffusing material. Polytetrafluoroethylene (PTFE, brand name Teflon) is the most common diffuser material used in solar UV spectroradiometers. However, novel quartz based materials with small gas bubbles that act as scattering centers have proved to be interesting candidates as base materials for new detector heads [2]. Apart from the diffuser material itself, the angular response of a detector head also depends on factors such as the thickness, the diameter and the height of the diffuser, the shape of the diffuser surface, as well as the shadow ring, the protective quartz dome and the detector geometry. Optimizing the various parameters by trial-and-error can be very time consuming and expensive, especially if complex diffuser shapes are required. Therefore, it is beneficial to optimize the diffuser design through modeling before actually producing the detector head.

We have studied the possibility of designing improved solar UV diffusers by characterizing various materials and simulating their operation before manufacturing. In the first step, 6 PTFE samples and 7 quartz samples were measured for their angular responses. Based on these results, the most promising material candidate was selected and the relevant material parameters were deduced. Next, a 3D Monte Carlo particle tracing software was constructed to simulate the light propagation inside the diffusers. Finally, the software was used to optimize the diffuser shape in order to reach an angular response that was as close to the ideal cosine response as possible.

ANGULAR CHARACTERIZATION OF THE MATERIAL SAMPLES

The measurement setup for the angular characterization of the materials is presented schematically in FIGURE 1. Helium cadmium (HeCd) laser was used as the light source throughout the measurements. The device produces two laser lines, one at UV region (325 nm) and the other at blue region (442 nm). A beam expander was placed between the source and the sample in order to overfill the diffuser. A photodetector was used to monitor the long term stability and the short term fluctuations of the laser power. The diffuser materials were mounted, one at a time, on a

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prototype detector that consisted of a diffuser holder, an aperture and a photodetector. The prototype detector was attached to a rotary stage. The measurements were carried out in the incident angle range of −90° to 90° with a step size of 1°.

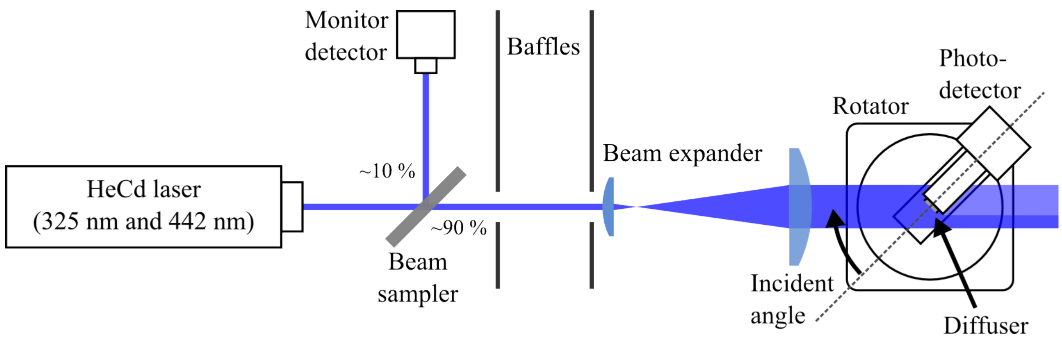

FIGURE 1. Measurement setup for diffuser material characterization.

To compare the light diffusing properties of the materials, the integrated cosine error was calculated for each sample as

$$f_{2,85^\circ} = \int_{0^\circ}^{85^\circ} \sin(2\theta) \left| \frac{T(\theta)}{T(0^\circ)\cos(\theta)} - 1 \right| \cdot 100\,\%\, d\theta \tag{1}$$

where $T(\theta)$ is the measured signal as a function of the incident angle θ. To rank the samples according to the amount of transmitted light, the integrated photocurrent over the measured angular range was calculated for each sample. This value was then divided by the average monitor detector current to account for the possible laser power fluctuations between the measurements. Finally, the average of the integrated signals over all samples was calculated, and the values were normalized to this average. In Figure 2, the diffuser materials are ranked according to their integrated cosine error and the integrated signal level.

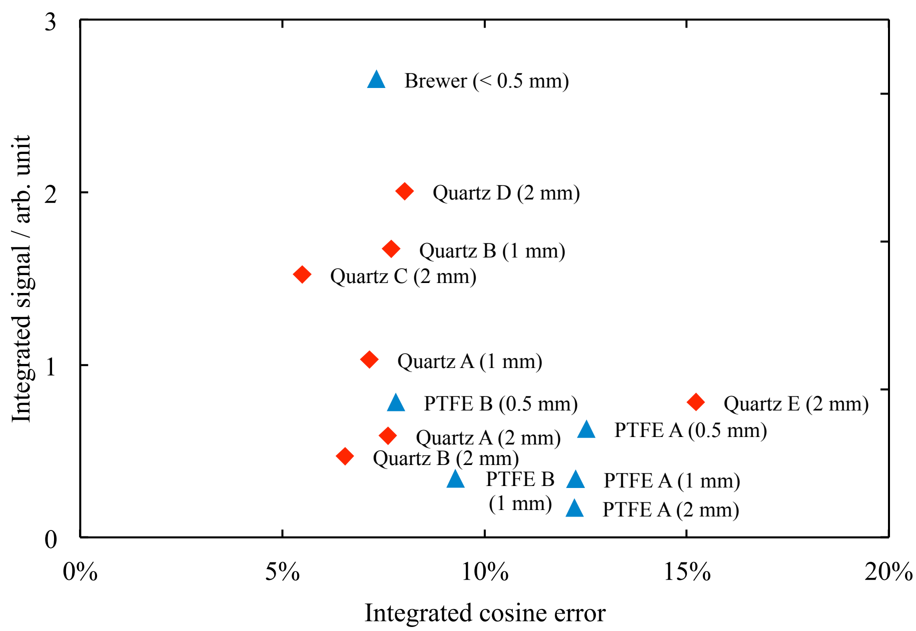

FIGURE 2. Level of transmission versus integrated cosine error for the measured samples at the wavelength of 325 nm. Red and blue markers indicate quartz and PTFE samples, respectively. The thickness of the samples is in parenthesis.

The quartz samples transmitted significantly more light and, on average, had better angular responses than the PTFE samples of similar thickness. Moreover, it is known that the transmittance of PTFE changes abruptly by 1 − 3 % at around 19 °C due to a phase shift of the crystal structure [3]. Quartz does not exhibit similar behavior. For these reasons, synthetic quartz, specifically Quartz C of Figure 2, was selected as a base material for the improved diffuser. The sample was also measured in a fluorescence spectrometer. No fluorescence peaks were discovered in the excitation and emission scans.

DIFFUSER SIMULATIONS

The simulation program – constructed specifically for the purpose of this study – used 3D Monte Carlo path tracing to describe light propagation inside the diffusing material. To increase the simulation efficiency, the traced particles emanated from the detector or fiber head instead of the sky. Furthermore, instead of individual particles, large groups of particles were considered in order to permit the partial absorption and reflection/refraction.

In the model, the scattering of light was governed by Henyey-Greenstein phase function [4] where one parameter g determines the anisotropy of scattering. Isotropic scattering (g = 0) turned out to yield the best fit with the measured angular responses of the studied diffuser materials. The average path lengths between the scattering and absorption events were determined by the scattering parameter μ_s and absorption parameter μ_a, respectively. For the materials studied, scattering greatly dominated absorption ($\mu_s \gg \mu_a$). Reflection and refraction from the diffuser sidewalls and facets was taken into account. The refractive index of the material was found to have a significant effect on the angular response of the diffuser at large incident angles. The mechanical construction of the detector head – including the photodetector/fiber, the shadow ring and the protective quartz dome – was also accounted for in the software.

Figure 3 shows the measured and simulated angular responses of Quartz sample C with three different heights h as shown in the inset of Figure 3. In each case, the shadow ring was aligned with the front surface of the detector in order to prevent any light from reaching the diffuser at incident angles higher than 90°. The simulated and measured responses were matched when the diffuser was in level with the detector surface (h = 0 mm) by adjusting the scattering parameter μ_s. The measurement – simulation pairs with raised diffusers confirmed that the model can be used to optimize the diffuser design. The optimal height of the diffuser, in terms of angular response, was approximately 1 mm in the prototype detector configuration. The integrated cosine error calculated as (1) at this height was 2.3 %.

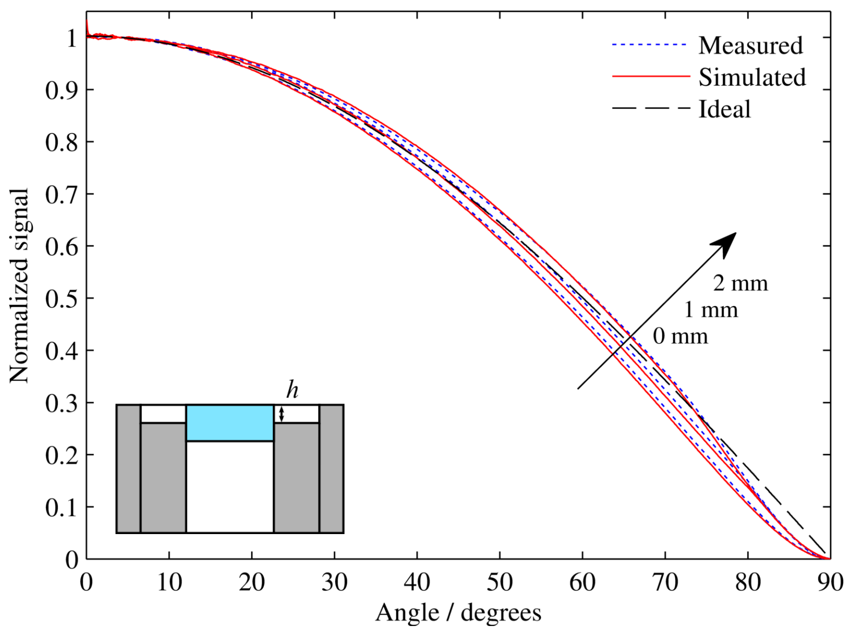

FIGURE 3. Measured (dotted blue lines) and simulated (red solid lines) angular responses with three different diffuser heights 0 mm, 1 mm and 2 mm. Also plotted is the ideal cosine response (black dashed line).

The angular response of the diffuser can be improved, to an extent, simply by tuning the diameter, the thickness and the height of the diffuser as well as the diameter of the shadow ring. The diameter of the shadow ring only affects the response at large angles, provided that the separation between the diffuser and the shadow ring is much larger than the diffuser height. By contrast, the diameter of the diffuser has a significant effect on the response at all angles, as it affects the surface-to-volume and the sidewall-to-facet ratio of the diffuser. By reducing the diameter of the diffuser from 15 mm (the diameter of Quartz C) to 10 mm, the angular response can be improved considerably, as shown by the dash-dotted line of Figure 4. The simulated integrated cosine error was 1.7 % in this configuration.

Drastic improvements in the angular response can be obtained by shaping the facets of the diffuser. The solid line of Figure 4 was obtained by replacing the flat front surface of the diffuser with a spherical surface of radius 13 mm. Integrated cosine error of 0.8 % was reached with this modification. It is expected that the angular response of both the flat and the non-flat diffuser designs can further be improved by fine-tuning the various diffuser parameters.

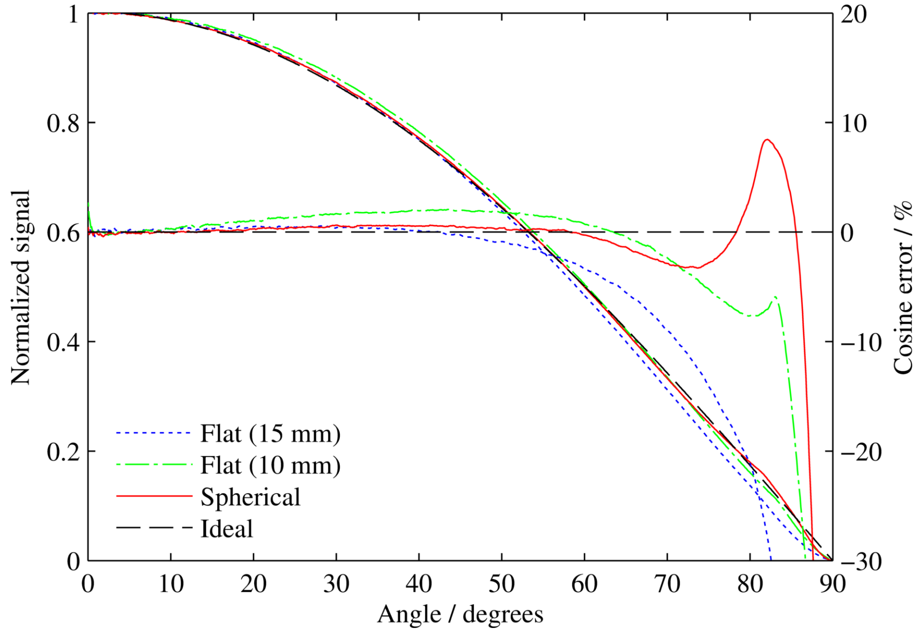

FIGURE 4. Simulated angular responses and the corresponding relative cosine errors of flat 15 mm (blue dotted line) and 10 mm (green dash-dotted line) diameter diffusers as well as of 10 mm diameter diffuser with a spherical surface of 13 mm radius (red solid line). All three diffusers were raised 1 mm relative to the detector front surface. Also plotted is the ideal cosine response (black dashed line.)

CONCLUSIONS

Various material samples were characterized for their angular responses. Quartz materials with small gas bubbles were found to be an attractive alternative to the traditional PTFE diffusers due to the high transmittance and good light diffusing properties. A Monte Carlo simulation software was constructed to describe the light propagation inside the diffuser structure. Good agreement between the measured and the simulated angular responses was discovered, indicating that the software can be used to optimize diffuser designs. By raising the diffuser in the prototype detector, integrated cosine error of 2.3 % was obtained. Initial simulation results indicate that with flat diffuser designs, integrated cosine errors of 1.7 % or below can be reached. With shaped diffusers, integrated cosine errors of 0.8 % or below can be obtained.

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