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Geometric optimisation of an accurate cosine correcting optic fibre coupler for solar spectral measurement

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Making accurate and reliable measurements of solar irradiance is important for understanding performance in the photovoltaic energy sector. In this paper, we present design details and performance of a number of fibre optic couplers for use in irradiance measurement systems employing remote light sensors applicable for either spectrally resolved or broadband measurement. The angular and spectral characteristics of different coupler designs are characterised and compared with existing state-of-the-art commercial technology. The new coupler designs are fabricated from polytetrafluorethylene (PTFE) rods and operate through forward scattering of incident sunlight on the front surfaces of the structure into an optic fibre located in a cavity to the rear of the structure. The PTFE couplers exhibit up to 4.8% variation in scattered transmission intensity between 425 nm and 700 nm and show minimal specular reflection, making the designs accurate and reliable over the visible region. Through careful geometric optimization near perfect cosine dependence on the angular response of the coupler can be achieved. The PTFE designs represent a significant improvement over the state of the art with less than 0.01% error compared with ideal cosine response for angles of incidence up to 50°. *Published by AIP Publishing.* https://doi.org/10.1063/1.5003040

I. INTRODUCTION

Critical to the ongoing implementation of Photovoltaic (PV) technologies is a necessity to accurately measure solar irradiance. Such measurements are typically made using a broadband pyranometer with thermopile sensors. However, these tools are expensive, and finding lower cost measurement solutions is important to help reduce the overall costs of solar energy. Besides the cost constraints of pyranometers, there is also little information that they can provide about the solar spectrum. A common solution for spectroscopic measurements is to couple the light with a spectrometer via an optic fibre (OF). This configuration is convenient because there can be a controlled environment for the spectrometer, where it is protected from outdoor influences such as humidity and heat as well as optic fibres offering reliable optical coupling. However, the OF is only able to capture light within a field view angle of typically 25°. By employing a scattering surface in front of the fibre, the limited angular acceptance can be increased (Fig. 1).

This correction is referred to as cosine correction because the ideal angular sensitivity should be proportional to the cosine of the incidence angle. The obstacles preventing the use of existing commercial cosine correctors in field irradiance measurements are their limited performance, both in terms of accurate reproduction of the cosine response and their physical fragility. Our motivation is to overcome these obstacles and design a robust, accurate coupler that can be used for extended periods in the field.

A typical state-of-the-art (SoA) cosine corrector available in the market is constructed from a hollow opaque metallic tube in which a 150 μm thick disc made of polytetrafluorethylene (PTFE) inserted at one end of the tube and clamped about 200 µm from the end, while at the other end there is a female 1/4 in. screw-type coupling mechanism to allow the standard optic fibre SubMiniature version A (SMA) adapter to be screwed into the coupler.

We find that the design is not suitable for extended field use as the thin PTFE disc becomes distorted by a combination of rain and wind. In an ideal case, the incident light received on the thin PTFE disc would be diffusely and isotropically scattered forwards towards the OF cable behind the disc. The cosine corrector would provide an accurate reproduction of a cosine response of a nude planar detector in cases where the scattering follows Lambert's law,[1] as seen in Eq. (1),

$$\boldsymbol{I_\theta} = \boldsymbol{I}_0 \cos \boldsymbol{\theta}, \tag{1}$$

where $\boldsymbol{I_\theta}$ is light intensity in angle $\boldsymbol{\theta}$, which is subtended between the light source and the normal of the reflective surface and $\boldsymbol{I}_0$ stands for the input light intensity delivered on the reflective surface. Results relating to the SoA coupler are presented in Sec. II.

As well as the commercial state of the art, we also review the performance of research couplers from the literature as a performance benchmark. Bartlett *et al.*[2] detailed the performance of a spectral measurement system with six sensors arranged on a horizontal plane using cosine correctors. Each sensor had a bandpass of about 10 nm with center wavelengths of 411.4, 442.9, 489.9, 555.2, 683.8, and 699.5. The error was under 7% only for incidence angles under 70°. In the study of Blackburn and Vignola,[3] it was found that the cosine error was 45% for angles above 72° due to the self-shading generated by the geometry of the cosine correcting coupler.

In terms of understanding the influence of the solar spectrum on photovoltaic energy production, Cornaro and Andreotti[4] evaluated the influence of the solar spectrum upon amorphous-silicon PV cells, used spectroradiometers with an optical diffuser integrated and protected by a glass dome and reported a cosine error ≤5% for all wavelengths. This work

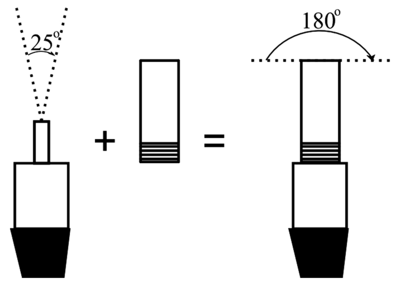

FIG. 1. Visualisation of the necessity for a cosine correcting coupler when attached to the optic fibre allows for a wider field view angle.

did not detail the diffuser's geometry, yet it is inferred that it was a simple flat PTFE surface as seen in most of devices available in the market. Pohl *et al.*[5] prepared multiple low-cost stations to measure, among others, solar irradiance for weather monitoring. For the irradiance measurement, a simple flat scattering PTFE surface was employed. Guerra, Faez, and Fuentealba[6] describe the manufacturing of a low cost pyranometer but did not address cosine correction. They used a PTFE layer of 1.05 mm of thickness for attenuation. Medugu, Burari, and Abdulazeez[7] and Martínez, Andújar, and Enrique[8] describe the design and test of different low-cost pyranometers. It is interesting to see a similar approach to ours, testing alternative geometries for the cosine correction of a photodiode-based pyranometer. The designs were the frustum of a cone with different angles. Bevel edges of 45° gave the best results. PTFE was used as a diffusing material due to its optimal optical characteristics referred to by Lowry, Mendlowitz, and Subramanian,[9] describing the near perfect diffusion of transmitted light for a wavelength range from the ultraviolet (UV) to near infrared (NIR).

In summary, PTFE is typically used as a diffusing material in cosine correctors—both for fibre optic coupling and for correction of planar sensors. The accuracy of the couplers reported in the literature varies from a respectable 5% to a rather poor 45% absolute error depending on the angle of incidence.

In the present work, we report the design and fabrication of several different fibre optic couplers using PTFE as a scattering material. We systematically characterise the designs in terms of spectral transmission, cosine response, and specular reflection. Our best performing design (G2) has a mean absolute error of less than 3% averaged over all angles of incidence and an excellent error of 0.01% for angles less than 50°.

II. EXPERIMENTS AND RESULTS

A. Assessment of PTFE empirical light attenuation

PTFE is widely used as a light scattering material within the optics industry with the transmission of low and high density materials being reported for UV, visible, and near infrared wavelengths.[10,11] For this research, high density PTFE, 2.5 g/ml, was chosen.[12] Of importance to the use of PTFE as a scattering material for an optic coupler in an irradiation instrument is the relative attenuation of different spectral components. The ideal scatterer would have equal attenuation so as not to contribute to systematic errors in the irradiance measurement during changes to spectral intensity. To assess the impact of differential attenuation in our PTFE coupler, we measured the empirical transmission of stock material of different thickness ranging from 1 to 10 mm. The empirical attenuation was calculated using Eq. (2),

$$\boldsymbol{T}_{\lambda} = \frac{\phi_{T,\lambda}}{\phi_{0,\lambda}}, \tag{2}$$

where $\boldsymbol{\Phi}_{0,\lambda}$ is light intensity by wavelength incident on the surface, $\boldsymbol{\Phi}_{T,\lambda}$ stands for the transmitted light intensity by wavelength, and $\boldsymbol{T}_{\lambda}$ is the fraction of transmitted light at a given thickness. Results can be seen in Fig. 2.

This result shows that the attenuation of PTFE is spectrally void of features and shows approximately 20% of difference between 500 nm and 700 nm or 10% per 100 nm. Since the mean wavelength of sunlight changes less than 50 nm[13] between fully diffuse and fully scattered light, the inferred maximum error due to differential attenuation by wavelength is estimated to be less than 5%.

B. Cosine response of SoA coupler

As a benchmark for the assessment of the newly designed couplers, we initially characterised the cosine response of a commercial coupler. A goniometer was set up with a stabilised white LED aligned along the rotating arm and the coupler device under test aligned in the plane of the reference axis. The light source was moved on the circular path around the coupler under test. The angle of incidence was measured in degrees subtended between the normal of the coupler surface and the position of the light source, this angle was varied from 0° to 90° with an increment of 5°. For each step 15 independent readings were made. The measurements were taken using an Ocean Optics spectrometer. As the main purpose was to measure the change of intensity in the function of the angle of incidence, the units used in these readings were only raw spectrally integrated counts rather than a radiometrically calibrated value. The experimental layout can be seen in Fig. 3.

The light intensity was normalized to the value at 0°. For the SoA, it is seen that at 25°, a fractional error of 5% is reached and the error became higher with wider angles reaching 94% by 85°, as seen in Fig. 4.

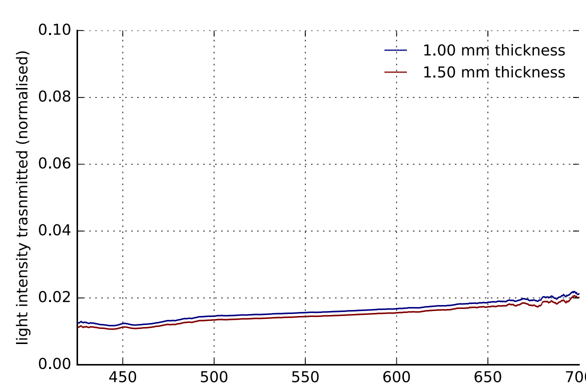

FIG. 2. PTFE's fraction of transmitted light through thicknesses of 1.0 mm and 1.5 mm of thickness.

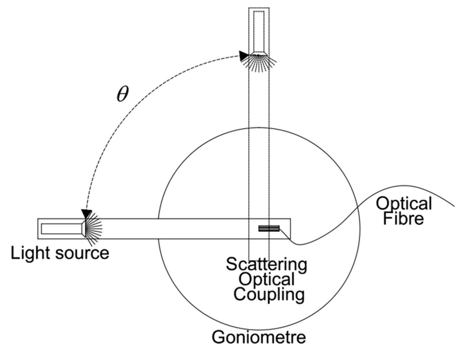

FIG. 3. Experimental setup for the assessment of the SoA cosine corrector and validation test for the couplers.

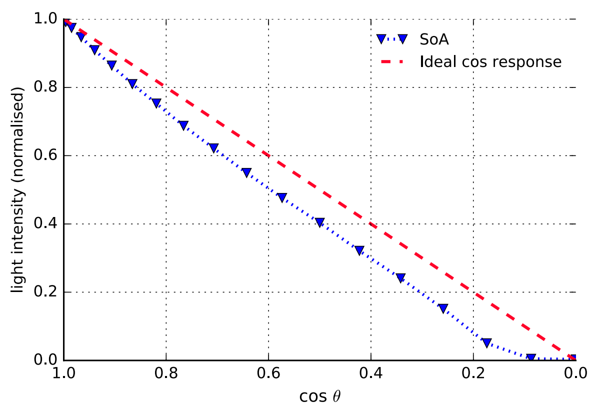

FIG. 4. Assessment of the cosine response for the State-of-Art (SoA) cosine corrector, compared with the ideal cosine response.

C. Design and characterisation method of CCOCs

The general geometry of the new designs was based on the SoA coupler, constructed as a hollow monolithic quasi-cylinder with a lateral wall of 1.2 mm thick. At one end, it is the diffusing surface and at the opposite end there is an opening with a female 1/4 in. SMA screw-type coupling mechanism for connection with the standard OF mounting. A comparison of the SoA and one of the experimental couplers can be seen in Fig. 5.

The monolithic shape was machined from a solid rod of PTFE to a diameter of 6.4 mm and from (20 to 20.55) mm high, depending on the design. All lateral sides of the coupler were covered with an opaque black tape to ensure that the only light received was from the scattering surface. There were 29 different designs fabricated and tested, but in this paper we only focus on the most relevant ones. The different geometries can be seen in Fig. 6.

FIG. 5. State-of-art cosine corrector (left) and experimental coupler design D1 (right).

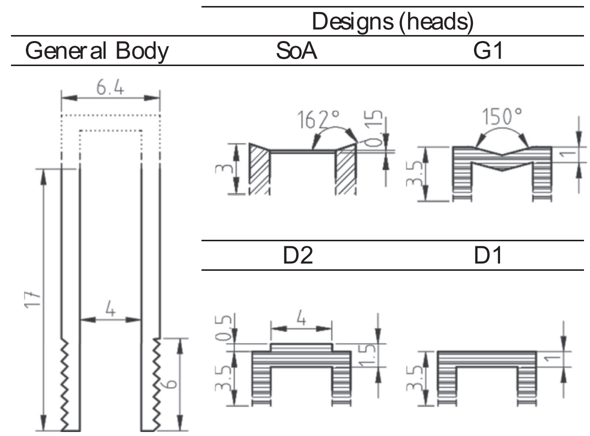

FIG. 6. SoA and coupler designs of interest. The present drawings are cross sections, the actual piece could be imagined as a solid produced by the revolution by the central axis of the general body plus head section. The bodies are made accordingly with the material of the head. Stainless steel for the SoA (represented by diagonal lines as metallic) and PTFE (represented by horizontal lines as plastic) for the rest of the designs. For the SoA, the diffuser is a PTFE disc of 150 μm of thickness, but the diffusing screen had a different thickness for the machined couplers. All presented units are in mm unless expressed otherwise. All designs were provided with opaque sheathes around their curved faces to permit only light absorption on the diffusing screen.

Cosine performance of the couplers was measured by calculating the average mean absolute error (MAE) of the different designs and the SoA measured with angles of incident light from 0° to 85°. The measured intensity was subtracted from the ideal light intensity of a perfect cosine response. The MAE was calculated using formula (3) for every angle and then averaged across all angles,

$$MAE = \frac{\sum_{i=1}^{N} |\Phi_{N,\theta} - \Phi_{\cos\theta}|}{N}, \tag{3}$$

where $\boldsymbol{N}$ is the number of measurements, $\boldsymbol{\Phi_{N,\theta}}$ is the light intensity measured normalised at angle $\boldsymbol{\theta}$, and $\boldsymbol{\Phi_{\cos\theta}}$ is the ideal light intensity proportional to cosine of angle $\boldsymbol{\theta}$. For the MAE readings at angle 90° that were ignored because the expected cosine response is 0 and such small values are very likely to be heavily influenced by the noise in the equipment, its calculation produced a misrepresentation of the observed validation.

D. Specular reflection measurement

Even if the detected forward scattered light obeys the cosine law, systematic errors can arise if light is reflected specularly from the front surface of the coupler, and as such the transmitted light intensity will depend on the angle of incidence. To quantify the effect of specular reflection on the cosine response of the coupler, the scattered and reflected light from a planar coupler design was measured. An ideal isotropic scatterer will have no specular reflection. The evaluation was made using a goniometer. On one arm, a 655 nm diode laser was aligned to the centre of rotation of the goniometer. On the second arm, a fibre coupled light detector was also aligned to the centre of rotation at a distance of 18 cm. The laser was fixed at a distance of 18 cm and an angle θ of 60° to the horizontal of the coupler surface.

The intensity of incident light was measured at the centre of the goniometer. Measurements of the scattered and reflected light were made relative to the incident intensity (both at the beginning and end of the experiment). 5 readings for every iteration were taken with the coupler at angle $\boldsymbol{\varphi}$, which was subtended from the plane of the diffusing surface on the opposite side to angle $\boldsymbol{\theta}$ to the coupler sensor within a range of 90°–0°, with progression of 10° for each step. A description of the experimental setup can be seen in Fig. 7.

For the calculation of the light intensity for angles φ, the readings were compensated for the dark noise signal and normalised to the intensity at $\varphi = 90°$. For the calculation of the ideal response, Lambert's law was used. The results can be seen in Fig. 8 where a small specular reflection leads to a doubling in the scattered intensity from the ideal isotropic value. However, the low intensity of the reflection measured at the given distance (4 orders of magnitude lower) leads us to estimate the systematic errors in the angular dependence of the intensity of the forward scattered light of less than 0.05%. We conclude that the influence of specular reflection on the performance of the coupler is negligible.

E. Results of CCOCs performance

Finally, we present the performance of the different coupler designs with reference to an ideal cosine response. The method described in Sec. II B is used. The angular response of the different designs is shown in Fig. 9. Surprisingly, the geometries with small concavities and convexities on their surface presented a response closer to the expected cosine relation. The strongest correlation to the ideal response was design G1. Designs D2 and D1 also have a good response, close to ideal for most angles, and in general they performed better than the SoA cosine corrector.

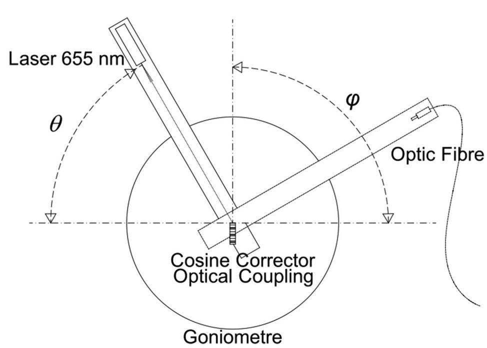

FIG. 7. Experiment setup to determine the fraction of light from specular reflection of PTFE. The laser was pointed to the scattering surface and the reflected light measured by the optic fibre at a given φ angle.

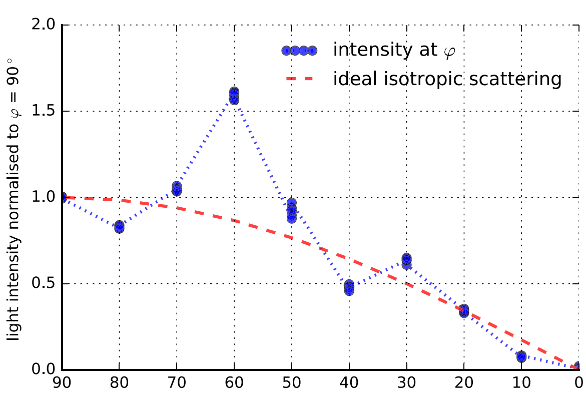

FIG. 8. Results of specular reflection fraction of PTFE material.

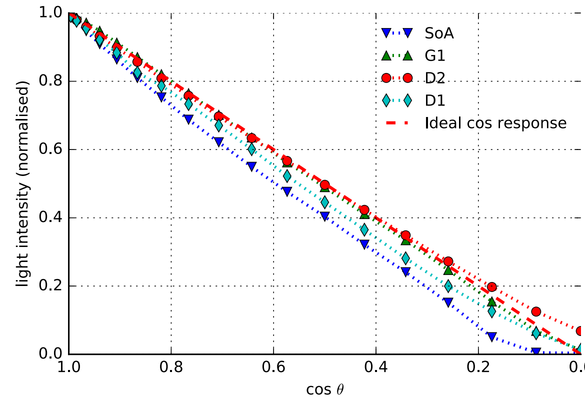

FIG. 9. Normalised cosine response for chosen CCOC designs and SoA cosine corrector in comparison with ideal cosine response.

The design that showed the near-to-ideal response was G1, with a MAE of 2.87% showing an error below 1% for every angle under 50°; for the range between 50° and 75°, the error stayed under 5%; over 75°, the error was between 4.52% and 21.16% (Fig. 10).

Design D2, with a MAE of 4.23%, presented an error up to 1% for angles below 25°. Between 25° and 70°, the error was under 1.50%; for greater angles, the error had a range from 1.97% to 43.55%. For design D1, the MAE was 9.03%, with an error minor to 1% for angles under 10°. Between 15° and 85°, the error was in the range from 1.13% to 29.21%. For the SoA coupler, the MAE was the lowest, with 20%. Errors were below 5% only below 25° reaching 30% by 70°, and by 85°, the error had reached 94%.

Results of the mean for all considered angles (as established in Sec. II C) are summarized in Table I.

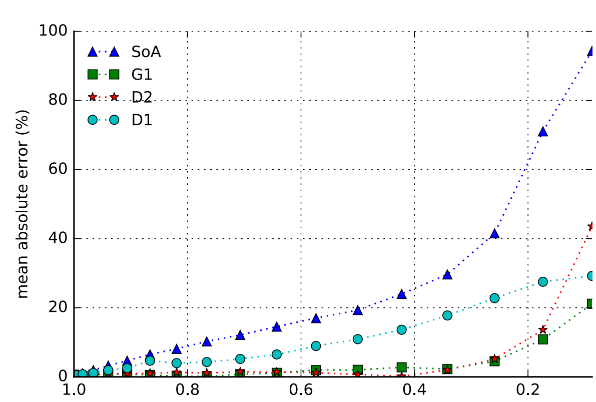

FIG. 10. Mean absolute error (%) for coupler designs G1, D1, and D2 and the SoA cosine corrector in comparison with ideal cosine response.

TABLE I. Results of the validation test for CCOC designs and SoA using the Mean Absolute Error (MAE) in comparison with ideal cosine response as an indicator.

Design	Mean absolute error (%)
SoA	20.00
G1	2.87
D2	4.23
D1	9.03

III. DISCUSSION AND CONCLUSIONS

Although further analysis should be conducted on the stability and light absorption of PTFE and its dependence on wavelength, overall due to the low-cost, physical, chemical, and optical properties this material stands as the best option for the manufacturing of couplers. We find that spectral dependence of attenuation varies approximately 5% per 50 nm over the range 450 nm–700 nm and that with a machined surface, specular reflection is minimised to a point where its impact on coupler performance is negligible.

The designs presented here have excellent agreement with the cosine response in comparison with the SoA coupler. Part of the poor performance of the SoA coupler is believed to be due to its geometry; thus the cylindrical frame for the PTFE diffuser disc shades the coupler and it is seen an under-measurement at a high angle of inclination. However, even for coupler D, with a flat surface, we see under-measurement for a range of angles of inclination; to correct this under-measurement of D1, G1 is concave and hence enhances measurements at all angles of inclination by approximately the level needed to generate perfect cosine response.

Our champion design G1 exhibits errors of less than 1% for angles under 50°—significantly outperforming the errors reported for the SoA coupler.

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