Solar Energy Materials & Solar Cells 75 (2003) 387–395
Solar Energy Materials & Solar Cells
www.elsevier.com/locate/solmat

Transmittance from photovoltaic materials under diffuse light

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Abstract

The optical transmittance properties, under diffuse light, of semitransparent materials used to fabricate photovoltaic devices have been investigated by using an apparatus provided with two "coupled" integrating spheres, one for producing the incident diffuse light and the other for collecting the transmitted light. A detailed analysis of the measurement conditions has been performed taking into account the perturbing effect each sphere produces on the other, and a final expression for the correct transmittance of the sample is derived. © 2002 Published by Elsevier Science B.V.

Keywords: Transmittance; Diffuse light; PV modules; Integrating spheres; Texture; Encapsulants; TCO/glass.

1. Introduction

The semitransparent materials used as cover sheets in photovoltaic devices are generally characterized by measuring their transmittance under collimated light at normal incidence. In order to improve the knowledge of the optical behaviour of PV devices under outdoor illumination conditions, it is particularly useful to characterize the window materials also under diffused illumination, simulating the distributed light from the sky or from the albedo.

For this purpose, an optical apparatus has been realized, called hemispherical/hemispherical reflectometer (HERE), provided with two "coupled" integrating spheres, a main sphere for producing the incident diffuse light and a satellite sphere for collecting the light transmitted by the sample. The apparatus HERE can be used

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PII: S0927-0248(02)00186-1

also for reflectance measurements under diffuse light, when only one of the two spheres is employed, hence the name [1].

Measurements of transmittance have been carried out on semitransparent TCO/glass structures, with different "haze", used in the fabrication of thin-film amorphous or microcrystalline silicon modules. The results indicate that the transmittance under diffuse light of these samples is quite insensitive to the haze of the TCO and equal to 75–78%.

A theoretical analysis of the measurement conditions shows that the perturbing effect each sphere produces on the other has to be taken into account in order to get a correct expression for the measured transmittance. The experimental conditions which favour more accurate measurements correspond to small test area with respect to the satellite sphere area, and satellite sphere with high optical losses.

2. The method

The transmittance under diffuse light is a measure of the total light transmitted by the sample, illuminated by an isotropic diffused irradiation extending to 2π steradians, with respect to the total incident light. It is here indicated as hemispherical/hemispherical (h/h) transmittance, T^{hh}, and defined by the integration, over incidence angle θ and azimuth angle ϕ. of the directional/hemispherical (d/h) transmittance, $T^{\mathrm{dh}}(\theta, \phi)$. For isotropic samples, the quantity T^{hh} is expressed by

$$T^{\mathrm{hh}}(\lambda) = 2 \int_0^{\pi/2} \mathrm{d}\vartheta \sin\vartheta \cos\vartheta T^{\mathrm{dh}}(\lambda, \vartheta) \tag{1}$$

for monochromatic light of wavelength λ, or by an equivalent expression for light with spectrum "*s*".

The method here presented allows to obtain T^{hh} in a direct and simple way, avoiding the numerous measurements of T^{dh} (θ, ϕ), particularly when the sample is not isotropic. It requires, at first, a source of diffuse light which can be obtained by illuminating an integrating sphere (is1) and by holding the sample under test (*c*) against one of its windows (see Fig. 1) [1].

The integrating sphere (is1) of Fig. 1 is illuminated by a light beam striking the diffuser (d), placed near the centre of the sphere and acting both as diffuser and as baffle, to hide the test sample surface from the intense light spot of the main beam. The sphere acts as a Lambertian source of diffuse light (constant radiance) for a sample faced to one of its windows. This configuration is sufficient to carry out reflectance measurements [1]. For transmittance measurements, it is further necessary to couple the sphere (is1) with the new sphere (is2), to collect the light transmitted by the sample and to measure it by a photodetector (r) (see Fig. 1). In the sphere (is1), the indicatrix of the internal wall of the sphere, coated by a $BaSO_4$ layer is also drawn. The indicatrix describes the way in which the light is diffused inside the sphere, and in the case of an ideal behaviour from the coating, it takes a spherical shape [2].

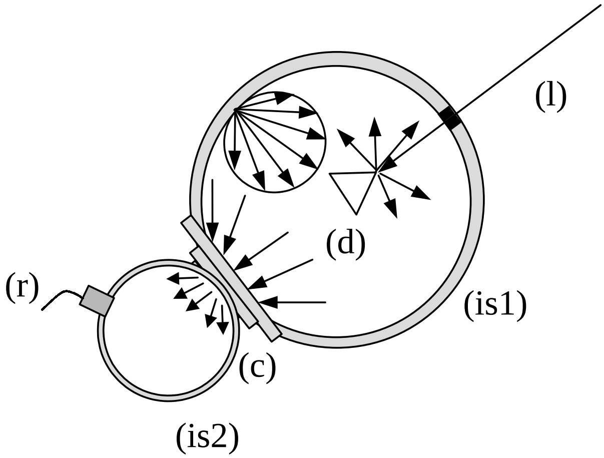


Fig. 1. Basic experimental set-up for measurements of T^{hh}. The sphere (is1) produces an isotropic diffuse light on the sample (c), and the sphere (is2) collects light transmitted by the sample. The photodetector (r) measures the transmitted light.

The h/h transmittance of the sample should be related to the ratio between the illumination intensity measured inside (is2) with the sample placed between the two spheres ($T^{hh} = x\%$), $S_2(x)$, and the illumination intensity measured inside (is2) with the test window open ($T^{hh} = 100\%$), $S_2(100)$. Further, to take into account variations of intensity in the source, that is on the illumination of sphere (is1), as a consequence of removing the sample, the above measurements should be normalized with respect to the correspondent (is1) illumination intensites, i.e. $S_1(x)$ and $S_1(100)$, respectively.

The h/h transmittance should be expressed, therefore, at a first approximation by

$$T^{hh}_{exp} = \frac{S_2(x)}{S_2(100)} \frac{S_1(100)}{S_1(x)}. \tag{2}$$

To take into account also the background signal of the detectors, the complete expression for the experimental h/h transmittance becomes

$$T^{hh}_{exp} = \frac{[S_2(x) - S_2(0)]}{[S_2(100) - S_2(0)]} \frac{[S_1(100) - S_1(0)]}{[S_1(x) - S_1(0)]}, \tag{3}$$

where the $S_1(0)$ is the radiation measured obscuring sphere (is1) that is closing the main beam input window; $S_2(0)$ is the radiation measured when an opaque sample is held on the test window.

As it will be shown in Section 6, the experimental transmittance obtained by Eq. (2) or (3) will be compared to the true h/h transmittance, T^{hh}. In that section, the experimental conditions which assure a good accuracy for the experimental transmittance will be discussed.

Eq. (2) or (3) implies the measurement of irradiance into both spheres, (is1) and (is2). Measurements could also be limited to only sphere (is2), but in this case the obtained transmittance is rougher than that derived by the above Eqs. (2) and (3)

$$T_{\exp}^{\mathrm{hh}} = \frac{S_2(x)}{S_2(100)}. \tag{4}$$

The intensities S_1 and S_2 in the above Eqs. (2)–(4) are all referred to the main beam intensity, S_3, i.e., to that of the collimated beam at the input of sphere (is1) (see Fig. 2). According to this, Eq. (2), for example, becomes

$$T_{\exp}^{\mathrm{hh}} = \frac{S_2(x)/S_3(x)}{S_2(100)/S_3(100)} \frac{S_1(100)/S_3(100)}{S_1(x)/S_3(x)}. \tag{2$'$}$$

3. The HERE apparatus

Fig. 2 shows the details of the HERE apparatus. The collimated beam from the source (l) enters the sphere (is1) through window (w1) and strikes the diffuser (d), placed near the centre of the sphere and faced opposite to the test window (w2). An isotropic diffuse light is produced on the test window (w2). The light intensity inside (is1) is measured by the photodetector (r1). The light transmitted by the sample (c) is collected by the sphere (is2), and measured by the photodetector (r2). The baffle (b) inside (is2) hides (r2) from direct light coming from the sample. The light source (l) can be a laser or a lamp. By using a lamp source, the apparatus is provided with collimating optics and filters to select the appropriate light wavelength or to modulate the light spectrum. The beamsplitter (bs) derives a reference beam to monitor source light fluctuations by the photodetector (r3). The collimated light beam is chopped and a reference signal from the chopper is sent to the multi-channel radiometer (ra), which collects the signals from the three detectors (r1)–(r3) and operates in the conventional lock-in configuration.

The source employed for the T^{hh} measurements of this work was a 20 mW He–Ne laser operating at $\lambda = 633$ nm. For these measurements, all the detectors were silicon photodetectors, like RKP-576RX from Laser Precision. For white light measurements, an Xe arc lamp can be used, whose spectrum matches that of the solar radiation. In this case, the T^{hh} transmittance directly gives the transmittance the window material manifests under outdoor illumination. For white light measurements, detectors (r1) and (r2) must be pyroelectric detectors, like RKP-575 from Laser Precision. The integrating spheres (is1), MACAM IS16 with 40 cm diameter, and (is2), MACAM IS6 with 15 cm diameter, were fabricated by MACAM Photometrics.

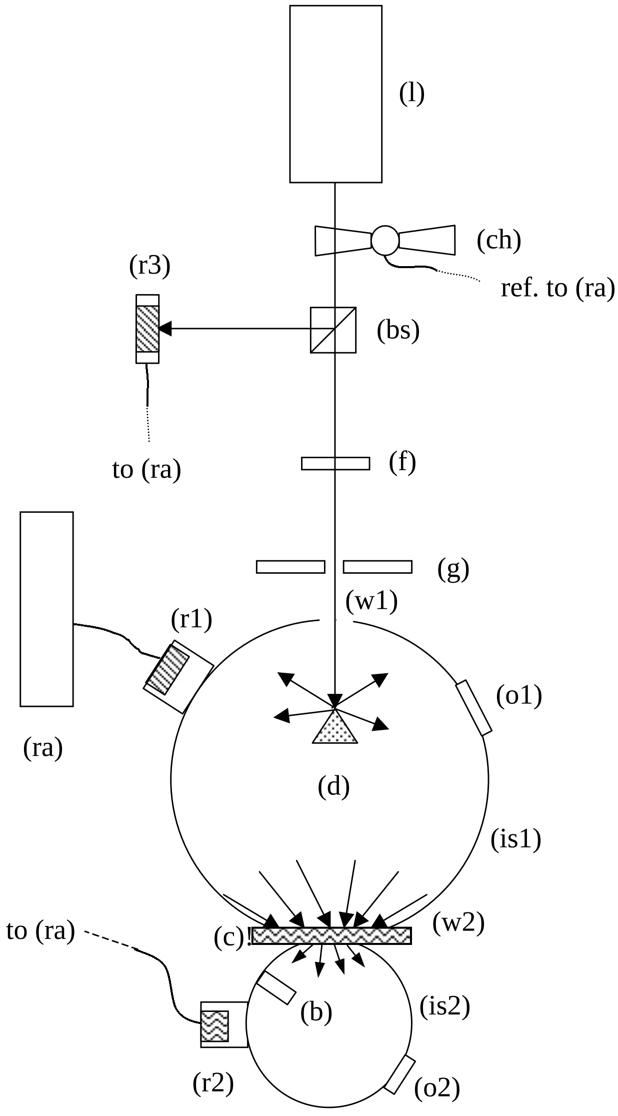


Fig. 2. Detailed schematics of the HERE apparatus.

4. Samples

The samples were TCO/glass sheets used in ENEA laboratories for fabricating a-Si modues. Samples with different "haze" of the TCO layer were examined: TCOG06, TCOG10 and TCOG20, with 6%, 10% and 20% nominal haze, respectively. The haze expresses the degree of surface texture of TCO layer and is defined as the ratio of diffuse (scattered) and total light transmitted [3].

Table 1
Transmittance under diffuse light at $\lambda = 633\,\mathrm{nm}$ for TCO/glass samples

Sample	$T^{\mathrm{hh}}_{\mathrm{exp}}(633)$ (%)	$T^{\mathrm{hh}}_{calc}(633)$ (%)
TCOG06	77.5	73.1
TCOG10	74.9	69.5
TCOG20	76.8	72.0

5. Results

The results concerned the comparison between h/h transmittance, $T^{\mathrm{hh}}_{\mathrm{calc}}(\lambda)$, calculated by applying Eq. (1) for the isotropic TCO/glass samples, and experimental h/h transmittance, $T^{\mathrm{hh}}_{\mathrm{exp}}$, obtained from Eq. (2). The transmittance measurements at collimated light, $T^{\mathrm{dh}}(\lambda, \theta)$, with $\lambda = 633\,\mathrm{nm}$, were carried out by using the reflectometer for optical measurements in solar energy (ROSE), described by Parretta et al. [4], varying θ from 5° to 70° with steps of 5°. Before being integrated, the $T^{\mathrm{dh}}(\lambda, \theta)$ data were fitted by an eighth-degree polynomial. The calculated transmittance $T^{\mathrm{hh}}_{\mathrm{calc}}(\lambda)$ is reported in Table 1, together with the transmittance, $T^{\mathrm{hh}}_{\mathrm{exp}}$, measured by the proposed method.

The TCO/glass samples show total transmittance values quite insensitive to the "haze", with $T^{\mathrm{hh}}_{\mathrm{exp}} \approx 75 - 78\%$. This is an expected result, considering that, for these samples, haze is independent of TCO thickness, and of TCO absorbance. Considering further that absorbance of glass is negligible and absorbance of TCO is only few percents, the measured transmittance is mainly influenced by the reflectance of inclined light at the air/glass interface, which changes from about 4% at normal incidence to 100% at parallel incidence [5].

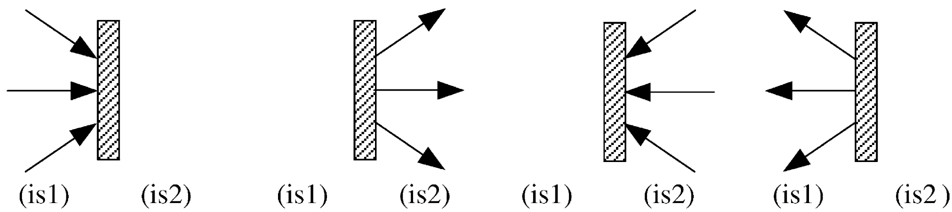
The components of the apparatus are: (l) light source; (ch) chopper; (bs) beam splitter; (r_3) detector; (f) filter; (g) diaphragm; (ra) multi-channel radiometer; (w1) input window; (r1) detector; (o1) view port; (d) diffuser; (is1) main sphere; (w2) test window; (c) sample; (is2) satellite sphere; (b) baffle; (o2) view port; (r2) detector.

The experimental and calculated values show, moreover, a systematic discrepancy, around 5%, which does not derive from the approximation introduced by Eq. (2), as the experiments were carried out by fulfilling the conditions outlined in the theoretical section to obtain accurate transmittance measurements (see later). It depends instead on the approximation introduced by the fitting curve of $T^{\mathrm{dh}}(\lambda, \theta)$ data from $\theta = 70°$ to 90°, which determines an underestimation of the transmittance in that interval.

6. Theoretical analysis

A detailed analysis of the measurement conditions requires the study of optical interaction between the two spheres. A step by step analysis of light exchanged between the two spheres has been carried out.

A schematic representation of this analysis is shown below



Step	A	B	C	D
1	I_1	$T^{hh}I_1$	$k_2T^{hh}I_1$	$k_2(T^{hh})^2I_1 = I_1^b$,
2	$k_1I_1^b = I_2$	$T^{hh}I_2$	$k_2T^{hh}I_2$	$k_2(T^{hh})^2I_2 = I_2^b$,
3	$k_1I_2^b = I_3$	$T^{hh}I_3$	$k_2T^{hh}I_3$	$k_2(T^{hh})^2I_3 = I_3^b$,
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
n	$k_1I_{n-1}^b = I_n$	$T^{hh}I_n$	$k_2T^{hh}I_n$	$k_2(T^{hh})^2I_n = I_n^b$,

where A is the incident irradiance on the sample from sphere (is1); B the transmitted irradiance to sphere (is2); C the incident irradiance on the sample from sphere (is2); D the transmitted irradiance to sphere (is1); k_1 the factor correlating light power at input of sphere (is1) with the irradiance produced at the sample location; k_2 the factor correlating light power at input of sphere (is2) with the irradiance produced at the sample location.

At step 1, light is stabilized inside sphere (is1), with sphere (is2) removed. I_1 in column A represents, therefore, the irradiance on the sample, without interference between the two spheres. Later, (is2) is connected to (is1) and light is transmitted to (is2) and back irradiates the sample. Light is then transmitted back to (is1) and, at step 2, an increment of radiation reaches the sample from the (is1) side. The phenomenon repeats indefinitely till it reaches a stationary state.

T^{hh} is here considered symmetric with respect to the sample orientation, as it should be in practice.Following the above outlined analysis, we obtain:

$$S_1(x) = \sum_i I_i(x) = \cdots = \frac{I_1(x)}{1 - k_1(x)k_2(x)(T^{hh})^2}, \tag{5}$$

$$S_1(100) = \sum_i I_i(100) = \cdots = \frac{I_1(100)}{1 - k_1(100)k_2(100)}, \tag{6}$$

$$\begin{aligned} S_2(x) &= \sum_i k_2(x)T^{hh}I_i(x) = k_2(x)T^{hh}\sum_i I_i(x) \\ &= \cdots = k_2(x)T^{hh}\frac{I_1(x)}{1 - k_1(x)k_2(x)(T^{hh})^2}, \end{aligned} \tag{7}$$

$$\begin{aligned} S_2(100) &= \sum_i k_2(100)I_i(100) = k_2(100)\sum_i I_i(100) \\ &= \cdots = k_2(100)\frac{I_1(100)}{1 - k_1(100)k_2(100)}. \end{aligned} \tag{8}$$

Eq. (2) for the experimental transmittance then becomes

$$T_{\mathrm{exp}}^{\mathrm{hh}} = \frac{S_2(x)}{S_2(100)}\frac{S_1(100)}{S_1(x)} = \cdots = \frac{k_2(x)}{k_2(100)}T^{\mathrm{hh}}. \tag{2''}$$

Eq. (2″) establishes the searched relation between experimental and theoretical transmittances: T_{exp}^{hh} better approaches the true transmittance, T^{hh}, when the factor k_2 is independent of which sample is placed on the test window. This means that removing the sample from the test window (w2) (see Fig. 2), the integration capability of sphere (is2), and then its optical properties remain unchanged.

The experimental conditions which favour a low dependence of factor k_2 from the sample under test are summarized here:

(i) size of test area or window (w2), little with respect to size of sphere (is2);
(ii) sphere (is2) with low reflective internal walls or with high optical losses.

Besides conditions (i) and (ii), which refer to the optical apparatus, also samples with high transmittance improve accuracy of measurements.

7. Conclusions

A method, and the corresponding apparatus, has been presented, which allow measurement of the optical transmittance, from diffuse light, of semitransparent materials used as windows in the front side of photovoltaic devices. The method HERE is simple, direct and non-destructive, and can be applied to any plane surface sample of whatever dimension. It is a practical alternative to the measurement of directional/hemispherical transmittance at different incident and azimuth angles, followed by a data fitting and integration procedure. The apparatus HERE can be realized by using a light source, two coupled integrating spheres and a detector/radiometer system. The experimental transmittance derived by simple measurements with the HERE apparatus is an approximation of true transmittance of the sample. This is the result of a theoretical analysis performed taking into account the reciprocal influence between the two integrating spheres. Conditions which assure a better accuracy for the experimental transmittance measurements have been investigated and presented.

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