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Optical loss of photovoltaic modules under diffuse light

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Abstract

The optical behaviour of photovoltaic (PV) modules from different fabrication technologies was investigated under diffuse light by a novel characterization method. The optical apparatus, hemispherical/hemispherical reflectometer, allows both reflectance and transmittance measurements under an incident diffuse light which simulates the distributed outdoor irradiation from the sky or from the albedo. This paper presents only the configuration for reflectance measurements. The apparatus is provided with a single integrating sphere of 40 cm diameter, which acts as a lambertian source of diffuse light and spontaneously collects the diffuse light reflected by the sample in the front hemisphere. The hemispherical/hemispherical reflectance, R^{hh}, expresses the optical loss of the PV device under diffuse light, and is obtained by measurements of light irradiance inside the sphere in correspondence with the sample and with a selected number of standards of diffuse reflectance. The best optical performances, in terms of optical loss, were achieved by modules realized with blue mono-Si cells and having textured front surfaces in the cover sheets.

Keywords: Optical losses; Reflectance; PV modules; Diffuse light; Integrating spheres

1. Introduction

Five effects influencing the true rating of a photovoltaic (PV) module outdoor performance are: optical loss, low irradiation level, spectrum, polarization of light, and temperature. In practice, the rating calculated from the total irradiance incident

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on a module and the nominal (STC) efficiency does not correspond to the actual rating of the module, but is generally lower.

This has to be attributed to the fact that one or more operating conditions of the module are different from those established as standard: perpendicular light, temperature of 25°C, illumination level equal to $1000\,\mathrm{W\,m^{-2}}$, unpolarized incident light and spectrum of light equal to the AM1.5G [1].

The standard optical loss test had module illumination by a parallel light beam with incident light almost perpendicular to the device surface. Hence, it simulates only the effect of the direct component of the solar irradiation on a sun-tracked device. The optical loss of a PV module under diffuse light irradiation has not been adequately investigated before. Neglecting the absorption of light into the cover sheet, it can be estimated by the hemispherical/hemispherical (h/h) reflectance, R^{hh}, it being a measure of the total light reflected by the device in the front hemisphere, when it is illuminated by an isotropic diffuse irradiation, extending to 2π steradians. The R^{hh}(s) reflectance at the specific spectrum of light, "s", could be taken as a useful parameter for comparison of PV modules of different fabrication technology, with a view to establish those conditions of a high diffuse light component which are most suitable for working in (i.e. high |latitudes| values, generally cloud-covered sky, unfavourable installation conditions of the module).

The purpose of this work is to present a practical method, and to describe the corresponding apparatus, for measuring the h/h reflectance of a PV module and to show the results obtained by characterizing mono-Si, multi-Si and a-Si modules. The apparatus hemispherical/hemispherical reflectometer (HERE) can be used for both reflectance and transmittance measurements under diffuse light. In this work we present the apparatus HERE only for reflectance measurements, while the transmittance measurements are discussed in a separate paper [2].

The HERE apparatus is provided with a 40 cm diameter main integrating sphere which, adequately illuminated, becomes a lambertian source of diffuse light. The reflectance measurements are based on the fact that the level of illumination inside the sphere depends, besides the input light power and the reflectance of the surface where the source light beam strikes over, also on the average reflectance of its internal surface and then on the reflectance of any sample held against one of its apertures. Measurements were performed under white light (Xe arc lamp) and under a laser beam (He–Ne, $\lambda = 633\,\mathrm{nm}$).

The quantity R^{hh}, when measured for very heterogeneous samples, such as multi-Si or poly Si solar cells, could be taken to represent the optical loss of the PV device operating outdoors, in the absence of sun tracking. This method, and the corresponding apparatus, can be extended to the optical characterization of PV samples of any dimension and, in general, to any plane surface sample.

2. Samples

Measurements were carried out on Eurosolare (ES) prototype modules with encapsulated blue mono-Si and coloured multi-Si cells electrically unconnected. Two prototype modules were made, both containing 18 cells: ES18G with normal cells and ES18GL with "gridless" cells. Both modules had textured glass surfaces. The cells without grids allow the reflectance measurement only on the optically active (o.a.) region of the device. The comparison between measurements on normal and gridless cells allows to investigate the effect of the grid.

Measurements were also carried out on record efficiency, prototype modules (PERL modules) fabricated at UNSW with a shingling assembling technique with record efficiency mono-Si cells (PERL cells) of $38 \times 62\,mm^2$ area [3]. One of these modules had a planar glass surface and MgF_2 antireflection coating (ps-PERL module), and the other was provided with a polymeric surface textured by upright pyramids of 5 μm average base dimension (ts-PERL module). For comparison, the R^{hh} reflectance of 1-ft square, single junction, a-Si module realized at ENEA is also reported. It was realized by using a flat glass sheet cover.

Eight standards of diffuse reflectance were used, from Labsphere, with nominal reflectance values of 2%, 5%, 10%, 20%, 40%, 60%, 80% and 99%. These samples are furnished as standards for the 8°/hemispherical reflectance, but it is immediate to demonstrate that, in the hypothesis of constant reflectance vs. angle of incidence, they are also standards of diffuse reflectance with the same value [4].

3. The R^{hh} method

The method used for measuring the R^{hh} reflectance of a PV module is relatively simple and non-destructive [4]. It requires, as a first step, the production of an isotropic diffuse light, to be used as incidence light on the test sample. The lambertian character of the source is verified by measuring its radiance, L ($W\,m^{-2}\,sr^{-1}$), which has to be constant. This can be done by orienting the photodetector (ph) (see Fig. 1), collecting light within the solid angle $\Delta\Omega$, towards the

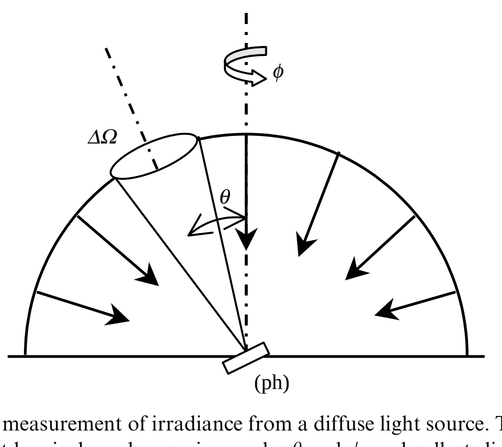

Fig. 1. Illustration of the measurement of irradiance from a diffuse light source. The photodetector (ph) is oriented towards the front hemisphere, by varying angles θ and ϕ, and collects light within the solid angle $\Delta\Omega$. If the measured irradiance is constant, also the radiance of the source is constant.

source. If the photodetector measures an irradiance independent of the angles θ and ϕ, the radiance of the source is constant and the source is lambertian. Fig. 2 shows the example of a diffuse radiation incident on a lambertian diffuser. This diffuser is characterized by the fact that the reflected light is diffused towards its front hemisphere with an intensity described by a spherical indicatrix [5]. This means that, if θ is the angle from which the diffuse light is observed, the measured intensity follows a $\cos\theta$ law and is independent of the azimuth angle ϕ. The lambertian diffuser of Fig. 2 is the ideal counterpart of the standards of reflectance used in this work to perform the calibration of the R^{hh} measurements.

One way to produce a lambertian source of diffuse light is to illuminate a reflecting wall surrounding the sample under test. Fig. 3 shows this wall, illuminated in some way. $I_0(\theta, \phi)$ is the intensity of light diffused by the wall. It is easy to demonstrate that, if $I_0(\theta, \phi)$ is a constant with respect to θ and ϕ, then the wall behaves as a lambertian source of light, independent of its shape [4]. The condition to fulfil is that the wall completely surrounds the sample (m).

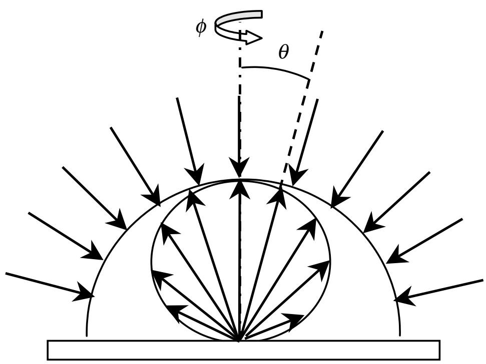

Fig. 2. A source of diffuse light is irradiating the surface of an ideal diffuser (lambertian diffuser). The reflected light is diffused towards the front hemisphere in such a way that its intensity decreases with angle θ following a $\cos\theta$ law, and is independent on the azimuth ϕ (spherical indicatrix).

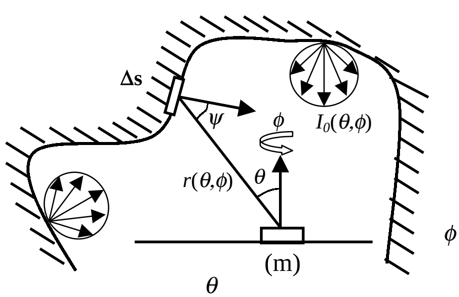

Fig. 3. Illuminated wall surrounding the sample (m). If the light intensity reflected by the wall is homogeneous, i.e. if $I_0(\theta, \phi) = \text{const.}$, then the wall behaves like an ideal (lambertian) source of diffuse light.

The simplest way to set up a lambertian source of diffuse light is to adequately illuminate an integrating sphere. Figs. 4A and B show two different ways by which an integrating sphere can be illuminated. In both cases the sample (m) is faced to one aperture (w) of the sphere. In Fig. 4A the beam of an external light source is striking the internal wall of the sphere. A baffle (b) is necessary in this case to hide the sample surface from the intense light spot produced on the wall. In Fig. 4B, on the contrary, the light beam strikes a diffuser (d) placed at the centre of the sphere. The diffuser (d) diffuses the light into the sphere and, at the same time, acts as the baffle of Fig. 4A.

The configuration of Fig. 4B assures a higher symmetry of light inside the sphere, with respect to the sample position. It was adopted, therefore, by us to produce the diffuse light. It has been already experimentally verified by us that the irradiation measured on the IS window (w), where the sample is placed, shows a constant radiance, and then is equivalent to an isotropic sky illumination. We will refer hereafter to Fig. 4B for the further discussions. The irradiation inside the sphere (is) can be measured by facing a photodetector to one of its apertures, avoiding that intense reflected beams directly strike the photodetector surface. The light intensity measured by the photodetector depends, besides on the power of the input beam and on the reflectance of the surface where the beam is striking, on the mean reflectance of the internal surface of the sphere, and then on the reflectance (R^{hh}) of any sample faced to the test window. By keeping constant the input light power, therefore, the illumination level inside the sphere depends on the reflectance, R^{hh}, of the test sample. The higher the R^{hh}, the higher the intensity of illumination of the sphere.

The correct procedure to follow consists in measuring the illumination intensity in correspondence of the exposure of a selected number of standards of diffuse reflectance, after which a calibration curve is obtained, specific for the spectrum of light or for the light wavelength used. The calibration curve correlates the irradiation level and the R^{hh} reflectance, hence allowing the derivation of the h/h reflectance for the unknown sample by a simple interpolation.

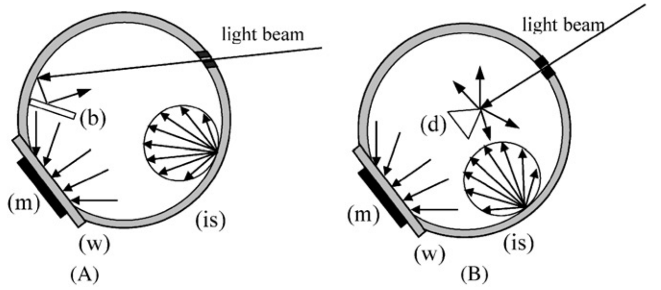

Fig. 4. (A) The sphere (is) is illuminated by a light beam striking its internal wall. (B) The sphere is illuminated by a light beam striking the central diffuser (d). The configuration (b) assures a better homogeneity of light inside the sphere and on the sample (m).

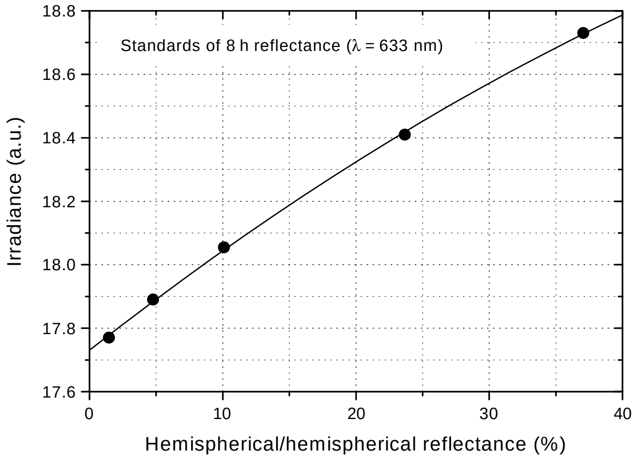

Fig. 5. Example of calibration curve for R^{hh} measurements. The irradiance measured inside the sphere is reported as function of the reflectance under diffuse light of a set of five standards.

Fig. 5 shows, as an example, the calibration curve obtained by exposing to the sphere's light five standards, with nominal R^{hh} reflectance: 2%, 5%, 10%, 20% and 40%. The choice of the standards depends, naturally, on the expected value of the unknown sample. The irradiance vs. R^{hh} curve always shows an under-linear behaviour. By increasing the reflectance of the sample, in fact, a saturation limit is expected for the illumination intensity inside the sphere.

The reflectance of the unknown sample is obtained by measuring the corresponding irradiance, followed by a simple interpolation procedure.

4. Apparatus HERE

The apparatus HERE has been realized on the base of an original project [6], and is schematically shown in Fig. 6. It is provided with a source of light (l), an integrating sphere (is) and a detector system (r1) + (r2) + (ra). The light source is typically an arc xenon lamp, suitable for both white light and spectral measurements. For white light measurements, $R^{hh}(s)$, its spectrum "s" is adequately modulated to match that of a specific diffuse light which simulates the solar radiation. For spectral measurements, $R^{hh}(\lambda)$, a monochromator or a set of interferential filters are used. The integrating sphere, 40 cm in diameter, has been realized by MACAM Photometrics and has shown a reflectance for the internal wall >98%. A multichannel radiometer (ra), provided with the photodiode (r1) and with the pyroelectric detector (r2), has been used for light measurements. The beamsplitter (bs) derives a reference beam, measured by photodiode (r1), for monitoring the light intensity of the source. The main beam is also chopped by (ch) and the radiation is measured by the conventional lock-in system.

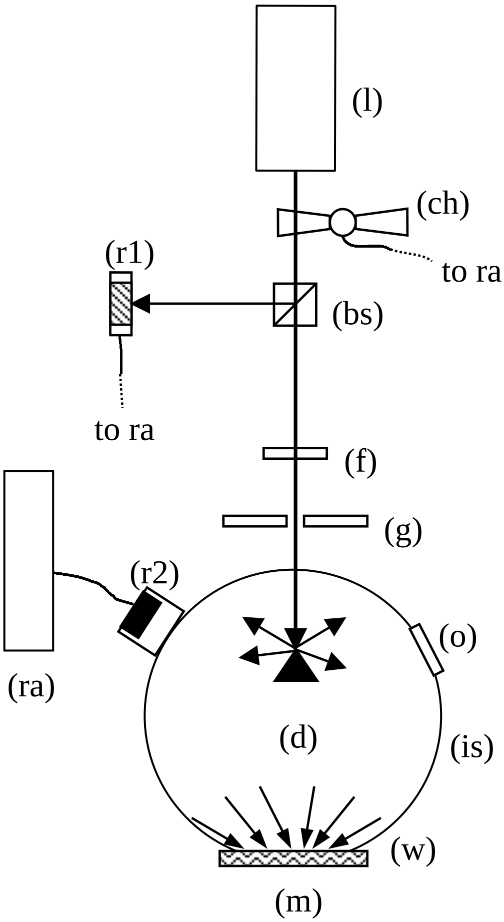

Fig. 6. Schematics of the apparatus HERE used for measurements of R^{hh} on the PV modules. Components: (l) light source; (ch) mechanical chopper; (bs) beamsplitter; (r1) diode photodetector; (ra) multi-channel radiometer (lock-in); (f) filter; (g) diaphragm; (r2) pyroelectric detector; (o) view port; (d) diffuser; (is) integrating sphere; (w) test window; (m) PV module.

5. Results

The results of R^{hh} (633 nm) and R^{hh} (white light) for the ES18GL module are shown in Fig. 7. Each datum represents the average optical behaviour of at least three cells. The blue mono-Si cells show the lowest R^{hh} values. The effect of cell colour on reflectance at the two different light sources is also observed. This effect is enhanced for red light, reduced for white light. Due to the strong anisotropy of the multi-Si cells, cells of this type, with the same colour, have shown significant discrepancies in reflectance values from the same cell and among different cells. This is the effect of the different crystallographic orientations of the crystals at the surface

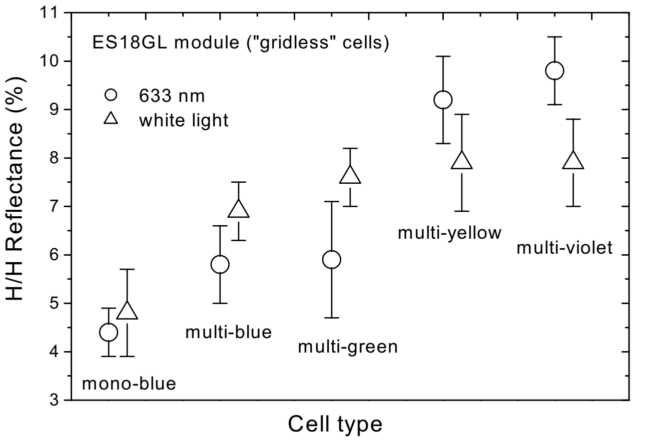

Fig. 7. Measured R^{hh} reflectance at $\lambda = 633\,\mathrm{nm}$ and at white light (Xe arc lamp) for the ES18GL Eurosolare module, realized with "gridless" c-Si cells.

of the cells, which manifest different reflection properties. This means that the reflectance of a multi-Si cell is strongly influenced by the crystalline substrate, even after the application of the same ARC process.

Comparing the R^{hh}(633 nm) values obtained for gridless and normal multi-Si cells, it was found only a slight increase, 1% at maximum, for the presence of the grid, well below the discrepancies in R^{hh} values themselves (2–3%). Grid effects could not be clearly detected between normal and gridless blue mono-Si cells.

The reflectance performances under diffuse light were also investigated for two prototype modules fabricated at UNSW. The superior quality of these modules was independently confirmed by outdoor testing at Sandia National Laboratories with 22.3% and 22.7% efficiencies for the ps-PERL and ts-PERL modules, respectively. Their optical behaviour under diffuse light has been investigated by exposing different regions of the two modules, both with a $\approx 780\,\mathrm{cm}^2$ aperture area, to the 3″ IS window. Several R^{hh} measurements were carried out on both modules and the final average values for R^{hh}(white light) were: $6.8 \pm 0.4\%$ for the ps-PERL module and $4.1 \pm 0.4\%$ for the ts-PERL module. The reduced optical loss of the textured module is explained by a better light collection capability assured by the texture, compared to the flat surface of the planar module, even if the later is coated by an ARC layer. The ARC layer, in fact, is generally optimized only for normal incidence.

A comparison between UNSW and Eurosolare normal mono-Si modules is made difficult by the different technology adopted for the two modules and by the unavailability of gridless PERL-cell modules. Nevertheless, the ts-PERL module has shown the lowest value of R^{hh} under white light, even in presence of grid and of optically passive areas between adjacent cells. Hence, this module is expected for the best performances in outdoor operation, where both direct (normal and inclined) and diffuse light is present. The highest optical loss at diffuse light was measured for the ENEA a-Si module with $R^{hh} \approx 15\%$ at white light.

6. Conclusions

In conclusion, a method has been developed for the characterization of PV materials and devices (solar cells, modules) under diffuse illumination. In this work we discuss the method applied to measurements of reflectance and we describe the apparatus developed for these measurements: hemispherical/hemispherical reflectometer (HERE). The same apparatus, adequately modified can be used also for measurements of transmittance under diffuse light. The method HERE allows to obtain the hemispherical/hemispherical reflectance, R^{hh}, of any planar surface sample, of whatever dimension, in a very simple and direct way. The HERE method has been used to characterize PV modules of different fabrication technology. Being intrinsically for "large areas", it has shown to be particularly useful for the characterization of multi-Si modules, highly heterogeneous from cell to cell and from point to point on the same cell. We suggest to adopt this method, in absence of alternative methods of characterization by collimated light, for the characterization of the optical loss of multi-Si PV modules. Prototype PV modules, to be used in buildings, and realized by Eurosolare by assembling gridless cells with different colorations of the ARC, have shown that the reflectance under diffuse light can be very low ($\sim$4–5%) for the blue coloured mono-Si cells modules. Higher values are obtained for green, gold-yellow and violet coloured multi-Si cells modules. The best optical performances under diffuse light were recorded, however, for prototype mono-Si modules realized assembling record efficient PERL cells by UNSW. UNSW modules realized with a textured polymeric cover have shown reflectance values as low as 4%, even if the cells were made with the grid.

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