Solar Energy Materials & Solar Cells 145 (2016) 248–254

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Spectral characterization of specular reflectance of solar mirrors

Florian Sutter [a,*], Stephanie Meyen [a], Aranzazu Fernández-García [b], Peter Heller [a]

[a] DLR German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 44, 04200 Tabernas, Almería, Spain
[b] CIEMAT, Plataforma Solar de Almería, Ctra. Senés Km. 4, P.O. Box 44, 04200 Tabernas, Almería, Spain

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
21 August 2015
Accepted 22 October 2015
Available online 11 November 2015

Keywords:
Reflectometer
Specular reflectance
Acceptance angle
Solar reflector
Scattering
Spectrophotometer

ABSTRACT

Solar reflectors for concentrating solar power (CSP) concentrators require a high specular reflectance over the whole solar spectrum. A preliminary procedure to measure the reflectance of solar mirror materials has been proposed in the SolarPaces reflectance measurement guideline [1]. However, the guideline clearly states that the currently available measurement instruments need further improvement in order to be able to fully characterize the reflectance properties of solar reflectors. In this work a high precision spectral reflectometer has been developed that permits the measurement of the solar weighted specular reflectance at different incidence and acceptance angles and thus provides all relevant reflectance data of solar mirrors. Four typical reflector materials have been measured and the solar weighted reflectance as a function of the acceptance angle has been modeled.

1. Introduction and state of the art

The reflectance of a mirror is a function of wavelength λ, incidence angle θ, and acceptance angle φ. The acceptance angle φ defines the angular area around the perfect specular reflection (see Fig. 1) which is captured during a measurement and typically defines the degree of near specular reflectance. The dimensions of the solar absorber and its distance to the collector define the relevant acceptance angle of the different solar technologies. Specular reflectance is usually measured at an acceptance angle of 12.5 mrad when the mirror is to be employed in parabolic trough concentrators. In power tower applications, for heliostats far away from the tower, it is usually suited to measure reflectance at smaller acceptance angles (depending on the absorber dimensions). Any light that is reflected outside of the relevant acceptance angle is lost to the energy conversion process.

At the current state of the art, hemispherical reflectance is measured with a spectrophotometer equipped with an integrating sphere in the full solar wavelength range of 250–2500 nm in 5 nm steps. For hemispherical measurements the acceptance angle φ includes the complete half-space. The values are weighted with a standard solar spectrum and the solar weighted hemispherical reflectance $\rho(\text{SW},\theta,h)$ is calculated using Eq. (1). $E_\lambda(\lambda_i)$ denotes the spectral irradiance at the wavelengths λ_i, according to the standard solar spectrum ([2] or [3]).

$$\rho(\text{SW},\theta,h)=\frac{\sum_{i=250}^{2500}\rho(\lambda_i,\theta,\varphi)\cdot E_\lambda(\lambda_i)}{\sum_{i=250}^{2500}E_\lambda(\lambda_i)} \tag{1}$$

However, hemispherical reflectance is not a suited parameter to characterize mirrors for CSP applications because it includes the diffuse reflectance in addition to the specular component. Depending on the collector geometry, reflectance needs to be measured at acceptance angles in the range of 6–45 mrad in order to determine the scattering of the employed mirror materials.

Currently, specular reflectance is measured with commercially available instruments at only one single wavelength (the most common one measures at 660 nm). It has been proposed by Pettit [4] to approximate the solar weighted specular reflectance $\rho(\text{SW},\theta,\varphi)$ by Eq. 2:

$$\rho(\text{SW},\theta,\varphi)=\frac{\rho(660\text{ nm},\theta,\varphi)}{\rho(660\text{ nm},\theta,h)}\rho(\text{SW},\theta,h) \tag{2}$$

The SolarPaces Task III reflectance work group concluded that the measurement of specular reflectance at only one single wavelength is not appropriate for materials which show scattering, since the scattering phenomena is wavelength dependent. Usage of Eq. [2] may penalize products of certain manufacturers which employ thin film technology and therefore Pettit's approximation is not recommended [1].

* Corresponding author. Tel.: +34 950 277 684; fax: +34 950 260 315.
E-mail addresses: Florian.Sutter@dlr.de (F. Sutter), Stephanie.Meyen@dlr.de (S. Meyen), Peter.Heller@dlr.de (P. Heller).

http://dx.doi.org/10.1016/j.solmat.2015.10.030
0927-0248/

Nomenclature

a_1	distance between collimator and sample [mm]
a_2	distance between sample and parabolic mirror [mm]
d_f	diameter of fiber cable [μm]
EFL	focal length of the parabolic 90° off axis mirror [mm]
K	specular model coefficient [dimensionless]
θ	incidence angle [°]
λ	wavelength [nm]
$\rho(SW,\theta,\varphi)$	solar weighted specular reflectance at incidence angle θ and acceptance angle φ [%]
$\rho(\lambda,\theta,\varphi)$	specular reflectance at wavelength λ, incidence angle θ and acceptance angle φ [%]
$\rho(\lambda,\theta,h)$	hemispherical reflectance at wavelength λ and incidence angle θ [%]
φ	acceptance angle [mrad]
σ_1	half-width standard deviation (specular peak) [mrad]
σ_2	half-width standard deviation (broader peak) [mrad]

The SolarPaces Task III reflectance work group was formed to satisfy the urgent demand to standardize the qualification procedures of solar mirrors and to provide reliable performance analysis tools, whose results are comparable. Only the shared consensus on parameters and methods allows concurrent industrial products available on the market to be equitably qualified and compared. As a consequence, a group of experts in the field of optical mirror reflectance characterization, involving participation of researchers and manufacturers, has been working together under the SolarPaces Task III framework to create a reflectance measurement guideline. The SolarPaces project “Development of guidelines for standards for CSP components”, was carried out during 2010 and 2011 to collect and prepare recommendations of procedures. As a result, a first guideline for reflectance characterization of solar reflectors, titled “Parameters and method to evaluate the solar reflectance properties of reflector materials for concentrating solar power technology” was published on the SolarPaces website [1]. Currently several standardization committees are transferring the updated guideline to national and international standards. The most advanced standardization committee in this topic is the Spanish one, AEN/CTN 206/SC 117 “Thermoelectric solar energy systems”, which is also linked at international level with the IEC Technical Committee TC 117 “Solar thermal electric plants”.

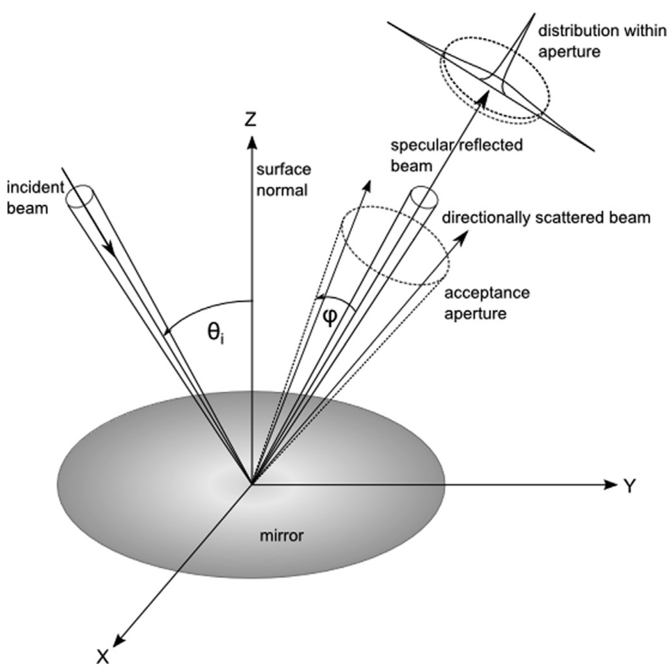

Fig. 1. Definition of parameters [1].

The SolarPaces work group is still active today to overcome the issue of specular reflectance characterization for innovative materials, which show scattering effects (e.g. due to the rolling process and the corresponding surface roughness of the substrate material, which is transferred to the reflective layers).

The actual version of the SolarPaces reflectance guideline (v. 2.5) proposes to use a simplified method for highly specular mirrors like glass reflectors, in which it is permitted to evaluate specular reflectance for only one single wavelength. On the other hand, the guideline states clearly that the simplified method is not suitable for innovative mirror materials like aluminum or silver polymer reflectors which display higher scattering. It concludes that the proper analysis of these materials requires the development of new instruments, which can

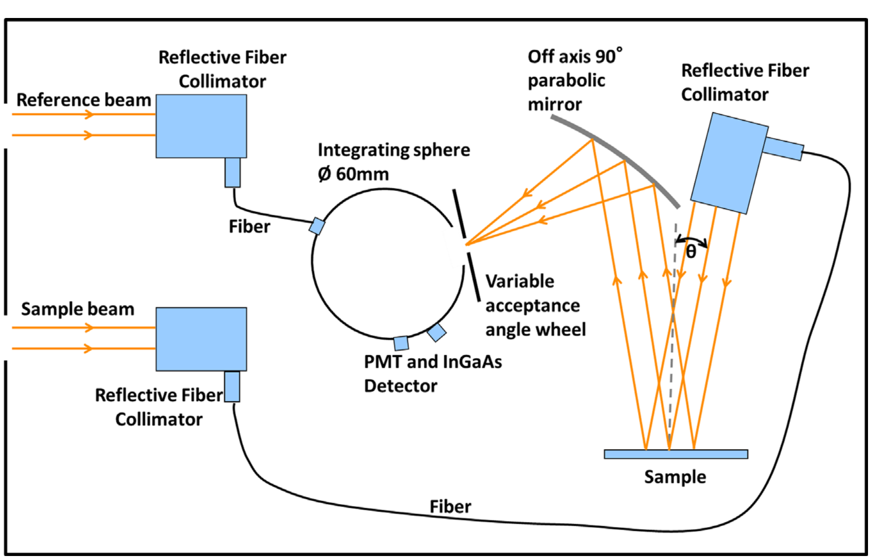

Fig. 2. Light path of *S2R*.