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Spectral reflectance, transmittance, and angular scattering of materials for solar concentrators

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ABSTRACT

The narrow-angle spectral specular reflectance and angular scattering of conventional and novel reflective materials for solar concentrators are measured over the wavelength range 300–2500 nm at incidence angles ranging from 15° to 60° using a spectroscopic goniometry system. The solar-weighted specular reflectance at near normal incidence and an acceptance half-angle of 17.5 mrad is 0.941 for back-silvered glass, 0.908–0.926 for silvered polymer films, 0.895 for aluminized polyester film, 0.939–0.954 for silvered aluminum sheets, and 0.860 for aluminized aluminum sheet. The angular scattering, quantified in terms of the standard deviation of a Gaussian distribution, is found to be negligible for aluminized polyester (<0.05 mrad) and back-silvered glass (<0.07 mrad), and noticeable for silvered polymer films (0.27–1.12 mrad) and silvered aluminum sheets (0.12–1.66 mrad). In addition, the spectral transmittance of semi-transparent materials suitable for protective covers is measured, yielding solar-weighted normal transmittance values of 0.913 and 0.946 for 100 μm thin films of ETFE (ethylene-tetrafluoroethylene) and FEP (fluorinated ethylene propylene), respectively. The measured optical properties are incorporated in a Monte Carlo ray-tracing program and applied to analyze the optical performance of solar concentrators.

1. Introduction

Knowledge of the optical properties of reflective materials is of paramount importance for the design of solar concentrating systems. Of interest is the reflectance weighted by the solar irradiance spectrum, which strongly affects the attainable solar concentration ratio. The spectral directional-hemispherical reflectance $R_{h,\lambda}$ at near normal incidence, with ASTM G173-03 for direct normal irradiance (DNI) at AM1.5 [1], is employed as standard for concentrating solar collectors [2]. Absolute reflectometers such as the one by NIST was developed to measure bi-directional reflectance in the range 200–2500 nm [3]. Measurements of specular reflectance were reported for several reflective materials, including back-silvered glass, metallized polymer films, and polished aluminum [4,5]. However, measured spectral data over the solar spectrum and at various incidence angles are generally not available for defined acceptance angles suited for solar applications. In addition to the reflectance, measurement of the narrow-angle surface scattering is needed for characterizing the imperfections of the solar concentrator, as these strongly influence the solar flux distributions. Surface scattering is generally understood to be a wave phenomenon of phase differences caused by surface roughness, and it is often treated as diffraction for optically smooth surfaces [6–8]. For solar concentrators, the aim is to find a convenient description of the specular reflected beam shape that can then be further applied for design purposes and performance predictions, e.g. by Monte Carlo (MC) ray-tracing. The angular scattering distribution may be accurately described by Gaussian probability density functions [4], which are straightforward to integrate into MC simulations. In addition, the standard deviation σ is a quantitative indicator of the severity of scattering and can be compared to that derived from other sources of beam spreading such as surface slope and tracking errors [4]. Reflected beam profiles of silvered polymer films applied to different substrates were measured at various incidence angles using adjustable source and detector slits combined with Fourier transform analysis [5]. More recently, angle-resolved reflectance was measured using quasi-monochromatic LEDs (455, 533, 631 nm) as light source and a CCD detector [9] and the bi-directional reflectance was measured using the principle of a Coblentz sphere [10]. In this work, we employ a spectroscopic goniometry system that enables the spectral and directional measurement of reflectance, transmittance, and scattering with high accuracy over the wide range of wavelengths and incidence angles relevant for solar concentrating applications.

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Nomenclature

A	illuminated area, aperture area, m^2
a	power law constant, mrad; aperture width, m
BRDF	bi-directional reflectance distribution function, sr^{-1}
C	solar concentration ratio, suns
C_g	geometric concentration ratio
d_{pixel}	pixel size, µm
F	fraction
f	focal length, m; scattering function, mrad^{-1}
E	direct normal irradiance, W/m^2
E_λ	spectral direct normal irradiance, W/(m^2•nm)
M	half-width of reference beam profile, pixel
m	discrete convolution coordinate, pixel; number of internal reflections
N	half-width of sample beam profile, pixel
n	discrete coordinate (parallel to plane of incidence), pixel; refractive index
p	power law exponent
$\hat{\mathbf{n}}$	surface normal vector
R	reflectance
$R_{specular,solar}$	solar-weighted specular reflectance
$R_{specular,\lambda}$	spectral specular reflectance
r	reference beam profile, pixel^{-1}; receiver radius, m; radial coordinate, m
$\hat{\mathbf{s}}$	direction vector
s	sample beam profile (reflected/transmitted), pixel^{-1}
T_{solar}	solar-weighted narrow-angle transmittance
T_λ	spectral narrow-angle transmittance
U	voltage, V
x	x-coordinate (parallel to plane of incidence), m
y	y-coordinate (perpendicular to plane of incidence), m
z	z-coordinate (surface normal, optical axis), m
$\eta_{optical}$	optical efficiency
θ	incidence angle, deg; zenith angle, rad; cone half-angle, mrad
λ	wavelength, nm
ρ_λ	spectral surface reflectivity
σ	standard deviation of angular scattering, mrad
τ_λ	spectral internal transmissivity
Φ	radiant flux, W
Φ_{rim}	rim angle of solar concentrator, deg
ϕ	azimuth angle, rad
χ	convolution coordinate, m
ω	solid angle, sr

Subscripts

0	front surface, surrounding medium
1	first scattering distribution; back surface, material medium
2	second scattering distribution
acc	acceptance (angle)
exp	experiment
h	directional-hemispherical (reflectance)
i	incident; inlet
n	surface slope error
o	outlet
r	reflected; radial
s	scattering (angle)
src	source (divergence angle)
t	transmitted
x	in plane of incidence
y	perpendicular to plane of incidence
λ	spectral (per unit wavelength)
$\perp$	perpendicular polarization (s)
$\parallel$	parallel polarization (p)

Abbreviations

AM	air mass
AR	anti-reflection (coating)
DNI	direct normal irradiance
FWHM	full width at half maximum
MC	Monte Carlo

In this paper, we report the spectral specular reflectance of conventional and novel solar reflective materials measured over the solar spectrum (300–2500 nm) at incidence angles ranging from 15° to 60°. The angles of source divergence (6 mrad) and detector acceptance (17.5 mrad = 1°) in the plane of incidence are chosen to closely resemble the sun angle (4.65 mrad) and a typical solar receiver's acceptance angle for full interception (1°). In addition, the spectral narrow-angle transmittance of suitable semi-transparent materials for protective covers of solar concentrators is measured with the same experimental setup and characteristic angles. Furthermore, the narrow-angle surface scattering is measured over the wavelength range 350–1050 nm, which covers 75% of the DNI (ASTM G173-03 AM1.5) [1]. Finally, the measured optical properties are applied in MC ray-tracing simulations of two solar concentrators, namely a parabolic trough and a parabolic dish, to elucidate their effect on the solar flux distribution and solar concentration ratio at the focal plane, and draw conclusions for further development.

2. Materials

2.1. Reflective materials

Three types of solar reflective materials are investigated: (1) back-silvered glasses; (2) metallized polymer films; and (3) metallized aluminum sheets. An overview of the characterized materials is given in Table 1.

2.1.1. Back-silvered glass

This is a widely-used reflector material, fabricated by applying a reflective silver layer to the backside of the glass substrate by a wet chemical process and covered with a protective paint [11]. State-of-the-art parabolic trough concentrators are often constructed from 4 mm-thick back-silvered glasses. Attempts to decrease material use and cost while increasing the reflectance have triggered the development of thinner mirrors at the expense of reduced rigidity. In this study, three samples are tested with varying thickness (1–4 mm).

2.1.2. Metallized polymeric film

This lightweight alternative offers reduced material cost and weight. In this study, two samples for outdoor use are investigated: a silvered acrylic film featuring a protective copper layer at the backside, and a silvered film protected by multiple layers of semi-transparent polymers on both sides. The polymeric top layer should be highly transparent to solar radiation and resistant to abrasion and UV radiation [12]. A cost-effective alternative to silvered films are aluminized films. In contrast to silver, aluminum is highly reflective in the UV spectral range, enabling the use of inexpensive, non-UV-resistant substrate such as polyethylene