Field Guide to

Solar Optics

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Introduction to the Series

In 2004, SPIE launched a new book series under the editorship of Prof. John Greivenkamp, the *SPIE Field Guides*, focused on SPIE's core areas of Optics and Photonics. The idea of these *Field Guides* is to give concise presentations of the key subtopics of a subject area or discipline, typically covering each subtopic on a single page, using the figures, equations, and brief explanations that summarize the key concepts. The aim is to give readers a handy desk or portable reference that provides basic, essential information about principles, techniques, or phenomena, including definitions and descriptions, key equations, illustrations, application examples, design considerations, and additional resources.

The series has grown to an extensive collection that covers a range of topics from broad fundamental ones to more specialized areas. Community response to the SPIE Field Guides has been exceptional. The concise and easy-to-use format has made these small-format, spiral-bound books essential references for students and researchers. Many readers tell us that they take their favorite Field Guide with them wherever they go. The popularity of the *Field Guides* led to the expansion of the series into areas of general physics in 2019, with the launch of the sister series of *Field Guides to General Physics*.

The core series continues as the *SPIE Field Guides to Optical Sciences and Technologies*. The concept of these Field Guides is a format-intensive presentation based on figures and equations supplemented by concise explanations. In most cases, this modular approach places a single topic on a page and provides full coverage of that topic on that page. Highlights, insights, and rules of thumb are displayed in sidebars to the main text. The appendices at the end of each Field Guide provide additional information such as related material outside the main scope of the volume, key mathematical relationships, and alternative methods. While complete in their coverage, the concise presentation may be best as a supplement to traditional texts for those new to the field.

Introduction to the Series

The *SPIE Field Guides* are intended to be living documents. The modular page-based presentation format allows them to be updated and expanded. In the future, we will look to expand the use of interactive electronic resources to supplement the printed material. We are interested in your suggestions for new Field Guide topics as well as what material should be added to an individual volume to make these Field Guides more useful to you. Please contact us at **fieldguides@SPIE.org**.

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Field Guide to Solar Optics

The *Field Guide to Solar Optics* consolidates and summarizes optical topics in solar technologies and engineering that are dispersed throughout literature. It also attempts to clarify topics and terms that could be confusing or at times misused.

As with any technology area, optics related to solar technologies can be a wide-ranging field. The topics selected for this field guide are those frequently encountered in solar engineering and research for energy harvesting, particularly for electricity generation. Therefore, the selected topics are slanted toward solar thermal power, or as it is commonly called, concentrating solar power.

The first section provides background on energy needs and usage, and explains where solar technologies fit into the energy mix. Section 2 covers properties of the sun and presents our basic understanding of solar energy collection. The third section introduces optical properties, concepts, and basic components. In Section 4, the various optical systems used in solar engineering are described. Optical systems used for solar energy collection are commonly referred to as collectors (e.g., a collector field)—a term that is frequently used in this field guide. Another term commonly applied in solar collectors is nonimaging optics. The fifth section introduces concepts for characterizing optical components/systems and analysis approaches. Lastly, the measurement tools commonly used in solar engineering and research are described in Section 6.

The fundamentals of each topic are covered. Providing methods or approaches to designs was not the goal of this field guide. However, the fundamental understanding that can be gained from the book can be extended and used for design of components and systems.

Julius Yellowhair
June 2020

Glossary of Symbols and Notation

a	aperture diameter
A	area
AOD	aerosol optical depth
A_{p}	projected area
AU	astronomical unit
B	back focal distance
BCS	beam characterization system
c	speed of light
c_1	first radiation constant in Planck's function
c_2	second radiation constant in Planck's function
C	center of curvature
C	concentration
CCD	charge-coupled device
C_{max}	maximum concentration ratio
CPC	compound parabolic concentrator
CR_{g}	geometrical concentration ratio
CR_{o}	optical concentration ratio
CSP	concentrating solar power
CSR	circumsolar ratio
d	earth-to-sun distance
D	distance or diameter
DNI	direct normal irradiance
E	radiation (light) energy
E_{DNI}	solar direct normal irradiance
E_{sun}	solar irradiance
$E_{\lambda,\mathrm{sun}}$	solar spectral irradiance
f	focal length
F	focal point
$F(x, y)$	irradiance profile using Hermite polynomials
$F_{1\rightarrow 2}$	view factor
G2	Star class second brightest
GHI	global horizontal irradiance
GTI	global tilted irradiance
h	hour
h	Planck's constant
H	heliostat tracking error operator
$H_n(x)$	Hermite polynomials
HPE	Hermite polynomial expansion

Glossary of Symbols and Notation

HTF	heat transfer fluid
$\hat{\imath}$	incident ray
I	radiant intensity
I_θ	Lambertian surface intensity
k	Boltzmann's constant
L, l	length
L	radiance
LCOE	levelized cost of energy/electricity
M	radiant exitance
M_λ	spectral radiant exitance
n	day of the year (1 to 365)
n_i	index of refraction of optical material
$\hat{n}$	surface normal vector
N	north direction
p	probability density function
P	power
PV	photovoltaic
Q_e	radiant energy
r, R	radius of curvature
r_sun	sun mean radius
$\hat{r}$	reflected ray
R	slant range
R	earth-to-sun distance
RMS	root mean square
S	optical ray path
$\hat{\mathrm{S}}$	sun direction unit vector
SCA	solar collector assembly
SCM	solar collector module
SM	solar multiple
ster	steradian
$\hat{t}$	transmitted ray
t_s	solar time
T	temperature
TES	thermal energy storage
TMY	typical meteorological year
u_λ	spectral energy density
V	dwarf star designation
α	absorptance
α	sun altitude angle

Glossary of Symbols and Notation

β	reflected beam angle spread
γ	sun azimuth angle
γ	intercept factor
δ	declination angle
ε	bolt thread count
$\vec{\varepsilon}$	heliostat tracking errors
ε_d	directional emittance
ε_H	hemispherical emittance
η	efficiency
η_E	insolation weighted efficiency
η_{atm}	atmospheric attenuation efficiency
η_{block}	heliostat blocking efficiency
η_{cosine}	cosine efficiency
η_{field}	collector field efficiency
$\eta_{optical}$	optical efficiency
$\eta_{reflect}$	reflectance (soiling) efficiency
η_{shade}	heliostat shading efficiency
θ	projection angle
θ_B	Brewster's angle
θ_c	critical angle
θ_i	angle of incidence
θ_r	angle of reflection
θ_s	sun half angle
θ_t	angle of transmission
λ	radiation (light) wavelength
λ_{peak}	peak wavelength (Wien's displacement law)
ν	radiation (light) frequency
π	pi
$\rho_{s,p}$	reflectivity in *s* and *p* light polarizations
ρ, ρ_t	total reflectance
ρ_d	directional reflectance
σ	mirror slope error, specularity
σ	optical error
σ	Stefan–Boltzmann constant
$\tau_{s,p}$	transmissivity in *s* and *p* light polarizations
τ, τ_t	total transmittance
ϕ	camera pixel phase angle
ϕ	sun latitude angle
ϕ_r	concentrator rim angle

Glossary of Symbols and Notation

ϕ_s	sun subtended angle
$\phi(\theta)$	sunshape
$\varphi(r)$	local material phase
Φ	radiant power or flux
χ	circumsolar ratio
ψ	ground cover ratio
ω	sun hour angle
ω_s	solid angle