Field Guide to

Lens Design

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Field Guide to Lens Design

Optical design has a long and storied history, from the magnifiers of antiquity, to the telescopes of Galileo and Newton at the onset of modern science, to the ubiquity of modern advanced optics. The process for designing lenses is often considered both an art and a science. While advancements in the field over the past two centuries have done much to transform it from the former category to the latter, much of the lens design process remains encapsulated in the experience and knowledge of industry veterans. This *Field Guide* provides a working reference for practicing physicists, engineers, and scientists for deciphering the nuances of basic lens design. Because the optical design process is historically (and quite practically) closely related to ray optics, this book is intended as a companion to the *Field Guide to Geometrical Optics*, in which first-order optics, thin lenses, and basic optical systems are treated in more detail. Note that this compact reference is not a substitute for a comprehensive technical library or the experience gained by sitting down and designing lenses.

This material was developed over the course of several years for undergraduate and graduate lens design classes taught at the University of Rochester. It begins with an outline of the general lens design process before delving into aberrations, basic lens design forms, and optimization. An entire section is devoted to techniques for improving lens performance. Sections on tolerancing, stray light, and optical systems are followed by an appendix covering related topics such as optical materials, nonimaging concepts, designing for sampled imaging, and ray tracing fundamentals, among others.

Thanks to both of our families—Danielle, Alison, Ben, Sarah, Julia, and especially our spouses, Jon and Kelly. The cats will now get fed, and all soccer parents beware!

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Glossary of Symbols and Acronyms

A	Area
AOI	Angle of incidence
AR	Antireflection
BBAR	Broadband antireflection coating
BFL	Back focal length
BFS	Best fit sphere
BRDF	Bidirectional reflectance distribution function
BSDF	Bidirectional scattering distribution function
BTDF	Bidirectional transmittance distribution function
c	Surface curvature
C	Lens conjugate factor
CA	Clear aperture
CCD	Charge-coupled device
CDF	Cumulative distribution function
CGH	Computer-generated hologram
CMOS	Complementary metal-oxide semiconductor
CRA	Chief ray angle
CT	Center thickness
CTE	Coefficient of thermal expansion
CTF	Contrast transfer function
d	Airspace
d	Thickness
DLS	Damped least squares
dn/dT	Thermo-optic coefficient
DOE	Diffractive optical element
EFL	Effective focal length
EPD	Entrance pupil diameter
ESF	Edge-spread function
ETD	Edge thickness difference
f	Focal length
$f/\#$	f-number or relative aperture
FEA	Finite-element analysis

Glossary of Symbols and Acronyms

FFL	Front focal length
FFOV	Full field of view
FFT	Fast Fourier transform
FOV	Field of view
GQ	Gaussian quadrature
GRIN	Gradient index
h, h'	Object/image height
H	Lagrange invariant
H	Normalized field coordinate
HFOV	Half field of view
HO	Higher order
HOE	Holographic optical element
HR	High-reflection
i, i'	Angle of incidence w.r.t. surface normal
i, i_a	Marginal ray angle w.r.t. surface normal
$\bar{i}$, i_b	Chief ray angle w.r.t. surface normal
ID	Inner diameter of a lens barrel or mount
IR	Infrared
L	Radiance
LOS	Line of sight
LR	Limiting resolution
LSF	Line spread function
LWIR	Long-wave infrared
m	Diffraction order
m	Magnification
MP	Magnifying power (magnifier or telescope)
MTF	Modulation transfer function
MWIR	Midwave infrared
n, n'	Index of refraction
$n(z)$, $n(r)$	Gradient index profile function
NA	Numerical aperture
NITD	Narcissus-induced temperature difference
NRT	Nonsequential ray tracing
NUC	Nonuniformity correction

Glossary of Symbols and Acronyms

OAP	Off-axis parabola
OAR	Off-axis rejection
OD	Outer diameter (of a lens)
OPD	Optical path difference
OTF	Optical transfer function
p	Pixel pitch in sampled detector arrays
P	Partial dispersion
PDF	Probability distribution function
PSF	Point spread function
PSNIT	Point-source normalized irradiance transmittance
PST	Point-source transmittance
P–V	Peak to valley
Q	Sampling ratio
r	Radial surface coordinate
R, ROC	Radius of curvature
RI	Relative illumination
RMS	Root mean square
RSS	Root sum square
RT	Reflective triplet
s, s'	Object/image distance
SA	Spherical aberration
SLR	Single-lens reflex
t	Thickness or airspace
T	Temperature
TIR	Total indicator runout
TIR	Total internal reflection
TIS	Total integrated scatter
TMA	Three-mirror anastigmat
TML	Three mirror long
u, u'	Paraxial ray angles w.r.t. optical axis
u, u_a	Marginal ray angle w.r.t. optical axis
$\bar{u}$, u_b	Chief ray angle w.r.t. optical axis
UV	Ultraviolet
V	Abbe number
W	Wave aberration function

Glossary of Symbols and Acronyms

W_{ijk}	Wavefront aberration coefficient
WD	Working distance
y, y_a	Marginal ray height at a surface
$\bar{y}$, y_b	Chief ray height at a surface
z	Optical axis
$z(r)$	Surface sag/profile function
Z_n	Zernike polynomial coefficient
β	Lens shape factor
$\Delta\lambda$	Wavelength range or bandwidth
δz	Defocus
ε	Obscuration ratio
$\varepsilon, \varepsilon_x, \varepsilon_y$	Transverse ray error
θ, θ'	Angle of incidence/refraction
θ	Half field of view
θ	Pupil azimuthal coordinate
κ	Conic constant
λ	Wavelength
λ_0	Center wavelength
ρ, ρ_x, ρ_y	Normalized radial pupil coordinate
Φ	System power
ϕ	Element or surface power
ϕ	Merit or penalty function