Electro-Optical System Analysis and Design

A Radiometry Perspective

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SPIE

To my fellow traveler in life, Riana;
my two sons, Bernard and Martinus;
my mother, Agnes;
and in the memory of my father, Jan Benardus.

Contents

Nomenclature

α	Absorptance, absorptivity, absorption (fraction)
α	Absorption attenuation coefficient with units $[\mathrm{m}^{-1}]$
α_λ	Spectral absorption with units $[\mathrm{m}^{-1}]$
α_B	Temperature coefficient of resistance with units [K^{-1}]
β	Diode p-n junction nonideal factor (unitless)
β	Optical thickness (unitless)
γ	Attenuation coefficient with units $[\mathrm{m}^{-1}]$
Γ	Γ point: smallest energy difference in bandgap (condition)
$\delta()$	Dirac delta function (unitless)
Δ_ϵ	Spatial texture variation in emissivity (unitless)
Δ_ρ	Spatial texture variation in reflectivity (unitless)
$\Delta\Phi$	Change in optical flux with units [W] or [q/s]
$\Delta\Phi_e$	Change in radiant optical flux with units [W]
$\Delta\Phi_p$	Change in optical photon flux with units [q/s]
Δf	Noise equivalent bandwidth with units [Hz]
Δn_e	Change in number of electrons with units [quanta]
Δn_h	Change in number of holes with units [quanta]
ΔT	Change in temperature with units [K]
ϵ	Emissivity (unitless)
ε	Electric field across a distance with units [V/m]
ϵ_λ	Spectral emissivity (unitless)
η	Detector quantum efficiency (unitless)
η_a,η_b	Image fill efficiency along the a and b directions (unitless)
η_s	Scanning efficiency in an image-forming system (unitless)
θ	Angle with units [rad]
θ	Dimensional symbol for temperature, or thermal (unitless)
λ	Wavelength with units [µm]
λ_c	Cutoff wavelength with units [µm]
μ	Carrier mobility with units [$\mathrm{cm}^2/(\mathrm{s}\cdot\mathrm{V})$]
μ_e	Electron carrier mobility with units [$\mathrm{cm}^2/(\mathrm{s}\cdot\mathrm{V})$]
μ_h	Hole carrier mobility with units [$\mathrm{cm}^2/(\mathrm{s}\cdot\mathrm{V})$]
ν	Frequency with units [Hz] or [s^{-1}]
$\tilde{\nu}$	Wavenumber with units [cm^{-1}]
ρ	Material density with units [$\mathrm{g/m}^3$]

ρ	Reflectance, reflectivity, reflection (fraction)
ρ_λ	Spectral reflection (unitless)
ρ_d	Diffuse reflection (unitless)
ρ_s	Specular reflection (unitless)
σ	Material electrical conductivity with units [$\mho$/m]
σ	Scattering attenuation coefficient with units [m^{-1}]
σ	Surface roughness (root-mean-square) with units [m]
σ_e	Stefan–Boltzmann constant with units [$\mathrm{W/(m^2 \cdot K^4)}$]
σ_q	Stefan–Boltzmann constant with units [$\mathrm{q/(s \cdot m^2 \cdot K^3)}$]
τ	Transmittance, transmissivity, transmission (fraction)
τ_λ	Spectral transmittance (unitless)
τ_θ	Thermal time constant with units [s]
τ_a	Atmospheric transmittance (unitless)
τ_c	Contrast transmittance (unitless)
τ_e	Electron lifetime with units [s]
τ_h	Hole lifetime with units [s]
τ_{RC}	Electronic resistor–capacitor time constant with units [s]
Φ	Optical flux with units [W] or [q/s]
Φ_λ	Optical flux spectral density with units [W/µm]
Φ_e	Radiant optical flux with units [W]
Φ_p	Optical photon flux with units [q/s]
Φ_q	Optical photon flux with units [q/s]
ψ	Solar irradiance geometry factor with units [sr/sr]
ψ	Wave function for a free electron (unitless)
ω	Electrial frequency with units [rad/s]
ω	Geometric solid angle with units [sr]
ω	Pixel field of view solid angle with units [sr]
Ω	Projected solid angle with units [sr]
Ω_r	Field of regard in an image-forming system with units [sr]
A	Area with units [m^2]
A_d	Detector area with units [m^2]
A_s	Source area in units [m^2]
A_v	Voltage gain of an amplifier or filter with units [V/V]
BRDF	Bidirectional reflection distribution function with units [sr^{-1}]
c	Specific heat with units [$\mathrm{J/(g \cdot K)}$]
c	Speed of light in vacuum with units [m/s]
C	Contrast (unitless)
C, C_s	Thermal detector element heat capacity with units [J/K]
C_v	Contrast threshold (unitless)
CODATA	Committee on Data for Science and Technology
D	Diameter of an optical aperture or lens with units [m]
D	Detectivity with units [W^{-1}]

D	Diffusion constant with units [m^2/s]
D^*	Specific detectivity with units [cm$\cdot\sqrt{\text{Hz}}$/W]
D^*_λ	Spectral specific detectivity with units [cm$\cdot\sqrt{\text{Hz}}$/W]
D^*_{eff}	Wideband specific detectivity with units [cm$\cdot\sqrt{\text{Hz}}$/W]
D_e	Diffusion constant for electrons with units [cm^2/s]
D_h	Diffusion constant for holes with units [cm^2/s]
e	Electron with charge q with units [C]
E	Energy (semiconductor energy level) with units [J] or [eV]
E	Irradiance (Areance) with units [W/m^2]
E_λ	Irradiance (Areance) spectral density with units [W/(m$^2\cdot$µm)]
E_C	Lowest conduction band energy level with units [J] or [eV]
E_F	Fermi level with units [J] or [eV]
E_g	Semiconductor energy bandgap with units [J] or [eV]
E_q	Background photon flux with units [q/(s$\cdot$m^2)]
E_V	Highest valence band energy level with units [J] or [eV]
f	Electrical frequency with units of [Hz]
f	Focal length with units [m]
F	View factor or configuration factor with units [sr/sr]
f_{fill}	Fill factor, fraction of area filled (unitless)
F_F	Frame rate in an image-forming system with units [Hz]
f_r	Bidirectional reflection distribution function with units [sr^{-1}]
F_T	Fourier transform
$f_{-3\text{ dB}}$	-3 dB electronic bandwidth with units [Hz]
$f/\#$	F-number, alternative notation (unitless)
$F_\#$	F-number of a lens, with numerical value # (unitless)
FAR	False alarm rate with units [s^{-1}]
FOM	Figure of merit
FOV	Field of view with units [rad]
FTIR	Fourier transform infrared
G	Detector photon gain with units [electrons/photon]
G	Heat conductance with units [W/K]
G_c	Bias circuit gain (unitless)
G_{ph}	Photoconductive gain with units [electrons/photon]
g_{th}	Rate of thermal carrier generation with units [quanta/s]
h	Planck constant with units [J$\cdot$s]
$\hbar$	$\hbar = h/(2\pi)$ with units [J$\cdot$s], where h is the Planck constant
i	Current with units [A]
i	Noise current density with units [A/$\sqrt{\text{Hz}}$]
I	Intensity (Pointance) with units [W/sr]
$\widehat{I}$	Incident ray unit vector (unitless)
I_0	Reverse-bias-saturation current with units [A]
I_λ	Intensity (Pointance) spectral density with units [W/(sr$\cdot$µm)]

I_b	Bias current with units [A]
i_{gr}	Generation–recombination noise with units [A] or [A/$\sqrt{\text{Hz}}$]
i_n	Noise current with units [A] or [A/$\sqrt{\text{Hz}}$]
I_{ph}	Photocurrent with units [A]
I_{sat}	Reverse-bias-saturation current with units [A]
J	Diffusion current density with units [A/m^2]
J_d	Drift current density with units [A/m^2]
k	Boltzmann constant with units [J/K]
K_λ	Spectral photopic luminous efficacy with units [lm/W]
K'_λ	Spectral scotopic luminous efficacy with units [lm/W]
K_μ	Sky-ground radiance ratio in thermal spectral bands (unitless)
K_v	Sky-ground radiance ratio in the visual spectral band (unitless)
k_f	Time-bandwidth product with units [s·Hz]
k_F	Reciprocal lattice sphere radius with units [m]
k_n	Ratio of noise equivalent bandwidth to -3 dB bandwidth
L	Radiance (Sterance) with units [W/(m^2·sr)]
L_λ	Radiance (Sterance) spectral density with units [W/(m^2·sr·µm)]
L_v	Diffusion length for carriers with units [cm]
L_e	Diffusion length for electrons with units [cm]
L_h	Diffusion length for holes with units [cm]
L_p	Detector packaging inductance with units [H]
LWIR	Long-wave infrared
m	Mass with units [g] or [kg]
M	Exitance (Areance) with units [W/m^2]
M_λ	Exitance (Areance) spectral density with units [W/(m^2·µm)]
M_e	Radiant exitance with units [W/m^2]
m_e	Electron mass with units [g]
m_e^*	Effective electron mass in units of m_e
m_h^*	Effective hole mass in units of m_e
MDT	Minimum detectable temperature with units [K]
MRT	Minimum resolvable temperature with units [K]
MTF	Modulation transfer function
MTV	Magnesium-Teflon®-Viton®
MWIR	Medium-wave infrared
n	Electron concentration with units [cm^{-3}]
n	Index of refraction (unitless)
N	Number of objects, pixels, or detector elements (unitless)
$\widehat{N}$	Surface normal unit vector (unitless)
n_a	Acceptor concentration with units [cm^{-3}]
n_d	Donor concentration with units [cm^{-3}]
n_e	Number of electrons (unitless)
n_h	Number of holes (unitless)

n_i	Intrinsic carrier concentration with units [cm^{-3}]
n_n	Electron concentration in n-type material with units [cm^{-3}]
n_p	Electron concentration in p-type material with units [cm^{-3}]
n_r	Real component of the complex index of refraction (unitless)
NA	Numerical aperture (unitless)
NE$\Delta\rho$	Noise equivalent reflectance (unitless)
NEΔT	Noise equivalent temperature difference with units [K]
NEE	Noise equivalent irradiance with units [W/m^2]
NEL	Noise equivalent radiance with units [$W/(m^2 \cdot sr)$]
NEM	Noise equivalent exitance with units [W/m^2]
NEP	Noise equivalent power with units [W]
NER	Noise equivalent reflectance (unitless)
NETC	Noise equivalent target contrast with units [K]
NETD	Noise equivalent temperature difference with units [K]
NIR	Near infrared
OTF	Optical transfer function
p	Hole concentration with units [cm^{-3}]
$P(\theta)$	Scattering phase function (unitless)
P_d	Probability of detection (unitless)
p_n	Hole concentration in n-type material with units [cm^{-3}]
P_n	Probability of false detection (unitless)
p_p	Hole concentration in p-type material with units [cm^{-3}]
PSD	Power spectral density with units [A^2/Hz] or [V^2/Hz]
PSF	Point spread function (unitless)
q	Absolute humidity with units [g/m^3]
q	Electron charge with units [C]
q	Quanta, as in photon count (unitless)
Q	Energy with units [W·s] or [J]
r	Radius with units [m]
R	Range or distance with units [m]
$\mathcal{R}$	Responsivity with units [A/W] or [V/W]
$\widehat{R}$	Mirror reflection unit vector (unitless)
$\widehat{\mathcal{R}}$	Detector responsivity scaling factor with units [A/W] or [V/W]
$\overline{R}$	Equivalent path length with units [m]
$\widetilde{\mathcal{R}}$	Normalized spectral shape of spectral responsivity (unitless)
$\mathcal{R}_\lambda$	Detector spectral responsivity with units [A/W] or [V/W]
R_0	Dynamic resistance under zero-bias conditions with units [Ω]
R_d	Detector resistance with units [Ω]
$\mathcal{R}_{e\lambda}$	Spectral detector responsivity with units [A/W] or [V/W]
$\mathcal{R}_{q\lambda}$	Spectral detector responsivity with units [C] or [J/A]
R_{eff}	Effective (wideband) responsivity with units [A/W] or [V/W]
R_L	Load resistor or bias resistor with units [Ω]

R_V	Meteorological range (visibility) with units [km]
RH	Relative humidity, unitless expressed as %
rms	Root-mean-square (unitless)
S, S_1, S_2	Seebeck coefficients for thermoelectricity with units [V/K]
$\mathcal{S}$	Sensor response
$\widehat{S}$	Reflected ray unit vector (unitless)
$\mathcal{S}_\lambda$	Sensor spectral response (unitless)
$S(\omega)$, $S(f)$	Power spectral density with units [A^2/Hz] or [V^2/Hz]
SCR	Signal-to-clutter ratio (unitless)
SNR	Signal-to-noise ratio (unitless)
SWIR	Short-wave infrared
t	Time with units [s]
T	Temperature with units [K]
T	Throughput or étendue with units [sr·m^2]
T_b	Background temperature [K]
T_{filter}	Temperature of an optical filter with units [K]
t_p	Signal pulse width with units [s]
T_s	Source temperature with units [K]
TPM	Technical performance measure
v	Voltage (signal or noise) with units [V]
V	Volume with units [m^3]
V_λ	Spectral photopic luminous efficiency (unitless)
V'_λ	Spectral scotopic luminous efficiency (unitless)
V_{bias}	Bias voltage across a device with units [V]
V_d	Internal potential in a p-n diode with units [V]
v_n	Noise expressed as voltage with units [V] or [V/$\sqrt{\text{Hz}}$]
w	Energy density with units [J/m^3]

Preface

If you have an apple and I have an apple
and we exchange apples,
then you and I will still each have one apple.
But if you have an idea and I have an idea
and we exchange these ideas,
then each of us will have two ideas.
George Bernard Shaw

On Sharing

Teachers cross our paths in life. Some teachers have names, others leave their marks anonymously. Among my teachers at the Optical Sciences Center at the University of Arizona were James Palmer, Eustace Dereniak, and Jack Gaskill. They freely shared their knowledge with their students. Some teachers teach through the pages of their books, and here I have to thank Bill Wolfe, George Zissis, and many more. Many years ago, R. Barry Johnson presented a short course which influenced my career most decisively.

The intent with this book is to now share some of my experience, accumulated through years of practical radiometry: design, measurements, modeling, and simulation of electro-optical systems. The material presented here builds upon the foundation laid at the Optical Sciences Center. I had the opportunity to share this material in an academic environment at graduate level in an engineering school, thereby clarifying key concepts. Beyond the mathematics and dry theory lies a rich world full of subtle insights, which I try to elucidate. May this book help you, the reader, grow in insight and share with others.

Reductionism, Synthesis, and Design

The reductionist approach holds the view that an arbitrarily complex system can be understood by reducing the system to many, smaller systems that can be understood. This view is based on the premise that the complex system is considered to be the sum of its parts, and that by understanding the parts, the sum can be understood. While the reductionist approach certainly has weaknesses, this approach works well for the class of problems considered in this book. The methodology followed here is to develop the theory concisely for simple cases, developing a toolset and a clear understanding of the fundamentals.

The real world does not comprise loose parts and simple systems. Once the preliminaries are out the way, we proceed to consider more complex concepts such as sensors, signatures, and simple systems comprising sources, a medium, and a receiver. Using these concepts and the tools developed in this book, the reader should be able to design a system of any complexity. Two concurrent themes appear throughout the book: fragmenting a complex problem into simple building blocks, and synthesizing (designing) complex systems from smaller elements. In any design process, these two actions take place interactively, mutually supporting each other. In this whirlpool of analysis and synthesis, uncontrolled external factors (e.g., the atmosphere, noise) influence the final outcome. This is where the academic theory finds engineering application in the real world. This book aims to demonstrate how to proceed along this road.

Toward the end of the book, the focus shifts from a component-level view to an integrated-system view, where the 'system' comprises a (simple or composite) source, an intervening medium, and a sensor. Many real-world electro-optical applications require analysis and design at this integrated-system level. Analysis and design, as a creative synthesis of something new, cannot be easily taught other than by example. For this purpose several case studies are presented. The case studies are brief and only focus on single aspects of the various designs. Any real design process would require a much more detailed process, beyond the scope of this book.

General Comments

The purpose with this book is to enable the reader to find solutions to real-world problems. The focus is on the application of radiometry in various analysis and design scenarios. It is essential, however, to build on the foundation of solid theoretical understanding, and gain insight beyond graphs, tables and equations. Therefore, this book does not attempt to provide an extensive set of ready-to-use equations and data, but rather strives to provide insight into hidden subtleties in the field. The atmosphere provides opportunity for a particularly rich set of intriguing observations.

The strict dictionary definition of 'radiometry' is the measurement of optical flux. In this book, the term 'radiometry' is used in its wider context to specifically cover the calculation of flux as well. This wider definition is commonly used by practitioners in the field to cover all forms of manipulation, including creation, measurement, calculation, modeling, and simulation of optical flux. The focus of this book is not on radiometric measurement but on the analysis and modeling of measured data, and the design of electro-optical systems.

Antoine de Saint-Exupèry once wrote, "You know you've achieved perfection in design, not when you have nothing more to add, but when you have nothing more to take away." The painful aspect of writing a book is to decide what *not* to include. This book could contain more content on radiometric measurement, emissivity measurement, properties of different types of infrared detectors, or reference information on optical material properties; however, these topics are already well covered by other excellent books, much better than can be achieved in the limited scope of this book.

The book provides a number of problems, some with worked solutions. The scope of problems in the early chapters tend to be smaller, whereas the problems in later chapters tend to be wider in scope. The more-advanced problems require numerical solutions. Although it is certainly possible to read the book without doing the advanced problems, the reader is urged to spend time mastering the skills to do these calculations. This investment will pay off handsomely in the future. Some of the problems require data not readily found in book format. The data packages are identified (e.g., DP01) and are obtainable from the pyradi website (see Section D.3.4).

To the uninitiated, the broader field of radiometry is dangerous territory, with high potential for errors and not-so-obvious pitfalls. Our work in the design labs, on field measurement trials, and in the academic environment led to the development of a set of best practices, called the 'Golden Rules,' which strives to minimize the risk error. Some of these principles come from James Palmer's class, while most were stripes hard earned in battle. The readers are urged to study, use, and expand these best practices in their daily work. Any feedback, on the golden rules or any other aspect of the book, would be appreciated.

A book is seldom the work of one mind only; it is the result of a road traveled with companions. Along this road are many contributors, both direct and inadvertent. My sincere thanks to all who made their precious time and resources available in this endeavor. My sincere thanks goes to

Riana Willers for patience and support, as co-worker on our many projects — her light footprints fall densely on *every single page* in this book: advising, scrutinizing every detail, debating symbols and sentences, editing text and graphics, compiling the nomenclature and index, and finally, acting as chapter contributor. Riana is indeed the ghost writer of this book! Fiona Ewan Rowett for permission to use her exquisite *"Karoo Summer"* on the front cover. The painting beautifully expresses not only the hot, semi-arid Karoo plateau in South Africa, but also expresses radiated light and vibrant thermal energy, the subject of this book. My teachers at the Optical Sciences Center who laid the early foundation for this work. Ricardo Santos and Fábio Alves for contributing to the chapter on infrared detector theory and modeling. The pyradi team for contributing their time toward building a toolkit of immense value to readers of this book. Derek Griffith for the visual and near-infrared reflectance measurements. Hannes Calitz for the spectral measurements, and Azwitamisi Mudau for the imaging infrared measurements. Dr Munir Eldesouki from KACST for permission to use the Bunsen flame measured data in the book. The many colleagues, co-workers, and students at Kentron (now Denel Dynamics), the CSIR, KACST, and the University of Pretoria for influencing some aspect of the book. Scott McNeill and Tim Lamkins for patience and guiding me through the publication process. Scott's untiring patience in detailed correction deserves special mention. Eustace Dereniak for encouraging me to submit the book for publication. Barbara Grant, Eustace Dereniak and an anonymous reviewer for greatly influencing the book in its final form. Finally, Dirk Bezuidenhout, and the CSIR for supporting the project so generously in the final crucial months before publication.

Mark Twain wrote that he did not allow his schooling to get in the way of his education. It is my wish that you, my esteemed reader, will delve beyond these written words into the deeper insights. Someone else said that the art of teaching is the art of assisting in discovery. May you discover many rich insights through these pages.

Nelis Willers
Hartenbos
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