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CONTRIBUTORS

Martin S. Banks  School of Optometry, University of California, Berkeley, Berkeley, California (CHAP. 25).
Jean M. Bennett  Research Department, Michelson Laboratory, Naval Air Warfare Center, China Lake, California (CHAP. 5).
Craig F. Bohren  Meteorology Department, Pennsylvania State University, University Park, Pennsylvania (CHAP. 6).
J. E. Bowers  Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, California (CHAP. 17).
David H. Brainard  Department of Psychology, University of California, Santa Barbara, Santa Barbara, California (CHAP. 12).
Stephen A. Burns  The Schepens Eye Research Institute, Boston, Massachusetts (CHAP. 26).
W. N. Charman  Institute of Science and Technology, Department of Ophthalmic Optics, University of Manchester, Manchester, United Kingdom (CHAP. 24).
E. L. Church  Brookhaven National Laboratory, Upton, New York (CHAP. 7).
William Cowan  Department of Computer Science, University of Waterloo, Waterloo, Ontario, Canada (CHAP. 27).
M. George Graford  Hewlett-Packard Company, San Jose, California (CHAP. 12).
Pamela L. Derry  Boeing Defense and Space Group, Aerospace and Electronics Division, Seattle, Washington (CHAP. 13).
Jean-Claude Diels  Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico (CHAP. 14).
J. A. Dobrowolski  Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, Canada (CHAP. 42).
Chris J. Evans  National Institute of Standards and Technology, Gaithersburg, Maryland (CHAP. 41).
Bart Farell  Institute for Sensory Research, Syracuse University, Syracuse, New York (CHAP. 29).
Luis Figueroa  Boeing Defense and Space Group, Aerospace and Electronics Division, Seattle, Washington (CHAP. 13).
Wilson S. Geisler  Department of Psychology, University of Texas, Austin, Texas (CHAP. 25).
Douglas S. Goodman  Polaroid, Cambridge, Massachusetts (CHAP. 1).
Joseph W. Goodman  Department of Electrical Engineering, Stanford University, Stanford, California (CHAP. 30).
John E. Greivenkamp, Jr.  Optical Sciences Center, University of Arizona, Tucson, Arizona (CHAP. 2).
Roland H. Haitz  Hewlett-Packard Company, San Jose, California (CHAP. 12).
Michael E. Harrigan  Eastman Kodak Company, Electronic Imaging Research Laboratory, Rochester, New York (CHAP. 33).
Brian Henderson  Department of Physics and Applied Physics, University of Strathclyde, Glasgow, United Kingdom (CHAP. 8).

Chi-Shain Hong  Boeing Defense and Space Group, Aerospace and Electronics Division, Seattle, Washington (CHAP. 13).


Abhay M. Joshi  Discovery Semiconductors, Inc., Cranbury, New Jersey (CHAP. 16).

Dennis K. Killinger  Department of Physics, University of South Florida, Tampa, Florida (CHAP. 44).

Walter F. Kosonocky  Electrical and Computer Engineering, New Jersey Institute of Technology, University Heights, Newark, New Jersey (CHAP. 23).

Lester J. Kozlowski  Rockwell International Science Center, Thousand Oaks, California (CHAP. 23).

Paul W. Kruse  Consultant, Edina, Minnesota (CHAP. 19).

Anthony LaRocca  ERIM, Ann Arbor, Michigan (CHAP. 10).

Masud Mansuripur  Optical Sciences Center, University of Arizona, Tucson, Arizona (CHAP. 31).

A. S. Marathay  Optical Sciences Center, University of Arizona, Tucson, Arizona (CHAP. 3).

Alan Miller  Department of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, United Kingdom, and Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida, Orlando, Florida (CHAP. 9).

Curtis D. Mobley  Senior Research Engineer, Applied Electromagnetics and Optics Laboratory, SRI International, Menlo Park, California (CHAP. 43).

Paul R. Norton  Santa Barbara Research Center, Goleta, California (CHAP. 15).


Robert E. Parks  Optical Sciences Center, University of Arizona, Tucson, Arizona (CHAP. 40).

Denis G. Pelli  Institute for Sensory Research, Syracuse University, Syracuse, New York (CHAP. 29).

Richard L. Rhorer  Group Leader, Fabrication Development, Los Alamos National Laboratory, Los Alamos, New Mexico (CHAP. 41).

M. Roberts  Pilkington Optronics, St. Asaph, Clwyd, Wales, United Kingdom (CHAP. 39).

P. J. Rogers  Pilkington Optronics, St. Asaph, Clwyd, Wales, United Kingdom (CHAP. 39).

Laurence S. Rothman  Air Force Geophysics Directorate/Phillips Laboratory, Optical Environment Division, Hanscom Air Force Base, Massachusetts (CHAP. 44).

Robert R. Shannon  Optical Sciences Center, University of Arizona, Tucson, Arizona (CHAP. 35 and 36).

William T. Silfvast  Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida, Orlando, Florida (CHAP. 11).


P. Z. Takacs  Brookhaven National Laboratory, Upton, New York (CHAP. 7).


Robert H. Webb  The Schepens Eye Research Institute, Boston, Massachusetts (CHAP. 28).

Robert H. Weissman  Hewlett-Packard Company, San Jose, California (CHAP. 12).

Y. G. Wey  Department of Electrical and Computer Engineering, University of California, Santa Barbara, California (CHAP. 17).


William L. Wolfe  Professor, Optical Sciences Center, University of Arizona, Tucson, Arizona (CHAP. 19).

Paul R. Yoder, Jr.  Consultant in Optical Engineering, Norwalk, Connecticut (CHAP. 37).

Xin Miao Zhao  Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico (CHAP. 14).
The *Handbook of Optics*, Second Edition, is designed to serve as a general purpose desktop reference for the field of Optics yet stay within the confines of two books of finite length. Our purpose is to cover as much of optics as possible in a manner enabling the reader to deal with both basic and applied problems. To this end, we present articles about basic concepts, techniques, devices, instruments, measurements, and optical properties. In selecting subjects to include, we also had to select which subjects to leave out. The criteria we applied when excluding a subject were: (1) was it a specific application of optics rather than a core science or technology and (2) was it a subject in which the role of optics was peripheral to the central issue addressed. Thus, such topics as medical optics, laser surgery, and laser materials processing were not included. The resulting *Handbook of Optics*, Second Edition, serves the long-term information needs of those working in optics rather than presenting highly specific papers of current interest.

The authors were asked to prepare archival, tutorial articles which contain not only useful data but also descriptive material and references. Such articles were designed to enable the reader to understand a topic sufficiently well to get started using that knowledge. They also supply guidance as to where to find more in-depth material. Most include cross references to related articles within the Handbook. While applications of optics are mentioned, there is not space in the Handbook to include articles devoted to all of the myriad uses of optics in today’s world. If we had, the Handbook would have been many volumes long and would have been too soon outdated.

The *Handbook of Optics*, Second Edition, contains 83 chapters organized into 17 broad categories or parts. The categorization enables the reader to find articles on a specific subject, say Vision, more easily and to find related articles within the Handbook. Within the categories the articles are grouped to make it simpler to find related material.

Volume I presents tutorial articles in the categories of Geometric Optics, Physical Optics, Quantum Optics, Optical Sources, Optical Detectors, Imaging Detectors, Vision, Optical Information and Image Processing, Optical Design Techniques, Optical Fabrication, Optical Properties of Films and Coatings, and Terrestrial Optics. This material is, for the most part, in a form which could serve to teach the underlying concepts of optics and its implementation. In fact, by careful selection of what to present and how to present it, the contents of Volume I could be used as a text for a comprehensive course in Optics.

The subjects covered in Volume II are Optical Elements, Optical Instruments, Optical Measurements, Optical and Physical Properties of Materials, and Nonlinear and Photorefractive Optics. As can be seen from these titles, Volume II concerns the specific devices, instruments, and techniques which are needed to employ optics in a wide variety of problems. It also provides data and discussion to assist one in the choice of optical materials.

The *Handbook of Optics*, Second Edition, would not have been possible without the support of the staff of the Optical Society of America and in particular Mr. Alan N. Tourlottle and Ms. Kelly Furr.

For his pivotal roles in the development of the Optical Society of America, in the development of the profession of Optics, and for his encouragement to us in the task of preparing this Handbook, the editors dedicate this edition to Dr. Jarus Quinn.

*Michael Bass, Editor-in-Chief*
*Eric W. Van Stryland, Associate Editor*
*David R. Williams, Associate Editor*
*William L. Wolfe, Associate Editor*
Introduction

This glossary of the terms used in the Handbook represents to a large extent the language of optics. The symbols are representations of numbers, variables, and concepts. Although the basic list was compiled by the author of this section, all the editors have contributed and agreed to this set of symbols and definitions. Every attempt has been made to use the same symbols for the same concepts throughout the entire Handbook, although there are exceptions. Some symbols seem to be used for many concepts. The symbol \( \alpha \) is a prime example, as it is used for absorptivity, absorption coefficient, coefficient of linear thermal expansion, and more. Although we have tried to limit this kind of redundancy, we have also bowed deeply to custom.

Units

The abbreviations for the most common units are given first. They are consistent with most of the established lists of symbols, such as given by the International Standards Organization ISO and the International Union of Pure and Applied Physics, IUPAP.

Prefixes

Similarly, a list of the numerical prefixes that are most frequently used is given, along with both the common names (where they exist) and the multiples of ten that they represent.

Fundamental Constants

The values of the fundamental constants are listed following the sections on SI units.

Symbols

The most commonly used symbols are then given. Most chapters of the Handbook also have a glossary of the terms and symbols specific to them for the convenience of the reader. In the following list, the symbol is given, its meaning is next, and the most customary unit of measure for the quantity is presented in brackets. A bracket with a dash in it indicates that the quantity is unitless. Note that there is a difference between units and dimensions. An angle has units of degrees or radians and a solid angle square degrees or steradians, but both are pure ratios and are dimensionless. The unit symbols as recommended in the SI system are used, but decimal multiples of some of the dimensions are sometimes given. The symbols chosen, with some cited exceptions, are also those of the first two references.
RATIONALE FOR SOME DISPUTED SYMBOLS

The choice of symbols is a personal decision, but commonality improves communication. This section explains why the editors have chosen the preferred symbols for the Handbook. We hope that this will encourage more agreement.

**Fundamental Constants**

It is encouraging that there is almost universal agreement for the symbols for the fundamental constants. We have taken one small exception by adding a subscript $B$ to the $k$ for Boltzmann’s constant.

**Mathematics**

We have chosen $i$ as the imaginary almost arbitrarily. IUPAP lists both $i$ and $j$, while ISO does not report on these.

**Spectral Variables**

These include expressions for the wavelength, $\lambda$, frequency, $\nu$, wave number, $\sigma$, $\omega$ for circular or radian frequency, $k$ for circular or radian wave number and dimensionless frequency $x$. Although some use $f$ for frequency, it can be easily confused with electronic or spatial frequency. Some use $\tilde{v}$ for wave number, but, because of typography problems and agreement with ISO and IUPAP, we have chosen $s$; it should not be confused with the Stefan-Boltzmann constant. For spatial frequencies we have chosen $j$ and $h$, although $f_x$ and $f_y$ are sometimes used. ISO and IUPAP do not report on these.

**Radiometry**

Radiometric terms are contentious. The most recent set of recommendations by ISO and IUPAP are $L$ for radiance [W cm$^{-2}$ sr$^{-1}$], $M$ for radiant emittance or exitance [W cm$^{-2}$], $E$ for irradiance or incidance [W cm$^{-2}$], and $I$ for intensity [W sr$^{-2}$]. The previous terms, $W$, $H$, $N$, and $J$, respectively, are still in many texts, notably Smith and Lloyd, but we have used the revised set, although there are still shortcomings. We have tried to deal with the vexatious term *intensity* by using *specific intensity* when the units are W cm$^{-2}$ sr$^{-1}$, *field intensity* when they are W cm$^{-2}$, and *radiometric intensity* when they are W sr$^{-1}$.

There are two sets of terms for these radiometric quantities, which arise in part from the terms for different types of reflection, transmission, absorption, and emission. It has been proposed that the *ion* ending indicate a process, that the *ance* ending indicate a value associated with a particular sample, and that the *ity* ending indicate a generic value for a “pure” substance. Then one also has reflectance, transmittance, absorptance, and emittance as well as reflectivity, transmissivity, absorptivity, and emissivity. There are now two different uses of the word emissivity. Thus the words *exitance*, *incidence*, and *sterance* were coined to be used in place of emittance, irradiance, and radiance. It is interesting that ISO uses radiance, exitance, and irradiance whereas IUPAP uses radiance, excitation [sic], and irradiance. We have chosen to use them both, i.e., emittance, irradiance, and radiance will be followed in square brackets by exitance, incidence, and sterance (or vice versa). Individual authors will use the different endings for transmission, reflection, absorption, and emission as they see fit.

We are still troubled by the use of the symbol $E$ for irradiance, as it is so close in meaning to electric field, but we have maintained that accepted use. The spectral concentrations of these quantities, indicated by a wavelength, wave number, or frequency subscript (e.g., $L_\lambda$) represent partial differentiations; a subscript $q$ represents a photon.
quantity; and a subscript $v$ indicates a quantity normalized to the response of the eye. Thereby, $L_v$ is luminance, $E_v$ illuminance, and $M_v$ and $I_v$ luminous emittance and luminous intensity. The symbols we have chosen are consistent with ISO and IUPAP.

The refractive index may be considered a radiometric quantity. It is generally complex and is indicated by $\bar{n} = n - ik$. The real part is the relative refractive index and $k$ is the extinction coefficient. These are consistent with ISO and IUPAP, but they do not address the complex index or extinction coefficient.

**Optical Design**

For the most part ISO and IUPAP do not address the symbols that are important in this area.

There were at least 20 different ways to indicate focal ratio; we have chosen $FN$ as symmetrical with $NA$; we chose $f$ and $efl$ to indicate the effective focal length. Object and image distance, although given many different symbols, were finally called $s_o$ and $s_i$ since $s$ is an almost universal symbol for distance. Field angles are $\theta$ and $\phi$; angles that measure the slope of a ray to the optical axis are $u$; $u$ can also be $\sin u$. Wave aberrations are indicated by $W_{ijk}$, while third order ray aberrations are indicated by $\sigma_r$ and more mnemonic symbols.

**Electromagnetic Fields**

There is no argument about $E$ and $H$ for the electric and magnetic field strengths, $Q$ for quantity of charge, $\rho$ for volume charge density, $\sigma$ for surface charge density, etc. There is no guidance from References 1 and 2 on polarization indication. We chose $\perp$ and $\parallel$ rather than $p$ and $s$, partly because $s$ is sometimes also used to indicate scattered light.

There are several sets of symbols used for reflection, transmission, and (sometimes) absorption, each with good logic. The versions of these quantities dealing with field amplitudes are usually specified with lower case symbols: $r$, $t$, and $a$. The versions dealing with power are alternately given by the uppercase symbols or the corresponding Greek symbols: $R$ and $T$ versus $\rho$ and $\tau$. We have chosen to use the Greek, mainly because these quantities are also closely associated with Kirchhoff’s law that is usually stated symbolically as $\alpha + \rho + \tau = 1$.

**Base SI Quantities**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>m</td>
<td>meter</td>
</tr>
<tr>
<td>time</td>
<td>s</td>
<td>second</td>
</tr>
<tr>
<td>mass</td>
<td>kg</td>
<td>kilogram</td>
</tr>
<tr>
<td>electric current</td>
<td>A</td>
<td>ampere</td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
<td>kelvin</td>
</tr>
<tr>
<td>Amount of substance</td>
<td>mol</td>
<td>mole</td>
</tr>
<tr>
<td>Luminous intensity</td>
<td>cd</td>
<td>candela</td>
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</table>

**Derived SI Quantities**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
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<td>J</td>
<td>joule</td>
</tr>
<tr>
<td>electric charge</td>
<td>C</td>
<td>coulomb</td>
</tr>
<tr>
<td>electric potential</td>
<td>V</td>
<td>volt</td>
</tr>
<tr>
<td>electric capacitance</td>
<td>F</td>
<td>farad</td>
</tr>
<tr>
<td>electric resistance</td>
<td>$\Omega$</td>
<td>ohm</td>
</tr>
<tr>
<td>electric conductance</td>
<td>S</td>
<td>siemens</td>
</tr>
</tbody>
</table>
magnetic flux \( \text{Wb} \) weber
inductance \( \text{H} \) henry
pressure \( \text{Pa} \) pascal
magnetic flux density \( \text{T} \) tesla
frequency \( \text{Hz} \) hertz
power \( \text{W} \) watt
force \( \text{N} \) newton
angle \( \text{rad} \) radian
angle \( \text{sr} \) steradian

**Prefixes**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Common Name of Ten</th>
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<tbody>
<tr>
<td>E</td>
<td>exa</td>
<td>18</td>
</tr>
<tr>
<td>P</td>
<td>peta</td>
<td>15</td>
</tr>
<tr>
<td>T</td>
<td>tera</td>
<td>trillion</td>
</tr>
<tr>
<td>G</td>
<td>giga</td>
<td>billion</td>
</tr>
<tr>
<td>M</td>
<td>mega</td>
<td>million</td>
</tr>
<tr>
<td>k</td>
<td>kilo</td>
<td>thousand</td>
</tr>
<tr>
<td>h</td>
<td>hecto</td>
<td>hundred</td>
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<td>da</td>
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<td>c</td>
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<td>hundredth</td>
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<tr>
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<td>micro</td>
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<td>p</td>
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<td>trillionth</td>
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<tr>
<td>a</td>
<td>atto</td>
<td>trillionth</td>
</tr>
</tbody>
</table>

**Constants**

- \( c \) speed of light in vacuo \([299792458 \text{ m s}^{-1}]\)
- \( c_1 \) first radiation constant \(= 2\pi c^2 h = 3.7417749 \times 10^{-16} \text{ Wm}^2\)
- \( c_2 \) second radiation constant \(= h c / k = 0.01438769 \text{ mK} \)
- \( e \) elementary charge \([1.60217733 \times 10^{-19} \text{ C}]\)
- \( g_0 \) free fall constant \([9.80665 \text{ m s}^{-2}]\)
- \( h \) Planck’s constant \([6.6260755 \times 10^{-34} \text{ Ws}]\)
- \( k_B \) Boltzmann constant \([1.380658 \times 10^{-23} \text{ JK}^{-1}]\)
- \( m_e \) mass of the electron \([9.1093897 \times 10^{-31} \text{ kg}]\)
- \( N_A \) Avogadro constant \([6.0221367 \times 10^{23} \text{ mol}^{-1}]\)
- \( R_A \) Rydberg constant \([10973731.534 \text{ m}^{-1}]\)
- \( \varepsilon_0 \) vacuum permittivity \([\mu_0^{-1} \text{ C}^2 \text{ m}^{-1}]\)
- \( \sigma \) Stefan-Boltzmann constant \([5.67051 \times 10^{-8} \text{ Wm}^{-1} \text{ K}^{-4}]\)
- \( \mu_0 \) vacuum permeability \([4\pi \times 10^{-7} \text{ N A}^{-2}]\)
- \( \mu_B \) Bohr magneton \([9.2740154 \times 10^{-24} \text{ J T}^{-1}]\)

**General**

- \( \mathbf{B} \) magnetic induction \([\text{Wb m}^{-2}, \text{kg}^{-1} \text{ C}^{-1}]\)
- \( C \) capacitance \([\text{f, C}^{2} \text{ s}^{-1} \text{ m}^{-1}]\)
- \( C \) curvature \([\text{m}^{-1}]\)
GLOSSARY AND FUNDAMENTAL CONSTANTS  xxv

c speed of light in vacuo [ms⁻¹]
c₁ first radiation constant [Wm²]
c₂ second radiation constant [mK]
D electric displacement [Cm⁻²]
E incandescence [irradiance] [Wm⁻²]
e electronic charge [coulomb]
E₀ illuminance [lux, lmm⁻²]
E electrical field strength [Vm⁻¹]
E transition energy [J]
E₀ band-gap energy [eV]
f₁ Fermi occupation function, conduction band
f₂ Fermi occupation function, valence band
FN focal ratio (f/number) [—]
g gain per unit length [m⁻¹]
g₂ gain threshold per unit length [m⁻¹]
H magnetic field strength [Am⁻¹, Cs⁻¹m⁻¹]
h height [m]
I irradiance (see also E) [Wm⁻²]
I radiant intensity [Wsr⁻¹]
l nuclear spin quantum number [—]
i current [A]
Im() Imaginary part of
J current density [Am⁻²]
j total angular momentum [kg m² sec⁻¹]
J₁() Bessel function of the first kind [—]
k radian wave number = 2π/λ [rad cm⁻¹]
k wave vector [rad cm⁻¹]
k extinction coefficient [—]
L sterance [radiance] [Wm⁻²sr⁻¹]
L₀ luminance [cd m⁻²]
L inductance [h, m² kg C⁻²]
L laser cavity length
L, M, N direction cosines [—]
M angular magnification [—]
M radiant exitance [radiant emittance] [Wm⁻²]
m linear magnification [—]
m effective mass [kg]
MTF modulation transfer function [—]
N photon flux [s⁻¹]
N carrier (number) density [m⁻³]
n real part of the relative refractive index [—]
ᵦ complex index of refraction [—]
NA numerical aperture [—]
OPD optical path difference [m]
P macroscopic polarization [Cm⁻²]
Re() real part of [—]
R resistance [Ω]
r position vector [m]
r (amplitude) reflectivity
S Seebeck coefficient [VK⁻¹]
s spin quantum number [—]
s path length [m]
## Glossary and Fundamental Constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_o$</td>
<td>object distance [m]</td>
</tr>
<tr>
<td>$s_i$</td>
<td>image distance [m]</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature [K, C]</td>
</tr>
<tr>
<td>$t$</td>
<td>time [s]</td>
</tr>
<tr>
<td>$t$</td>
<td>thickness [m]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>slope of ray with the optical axis [rad]</td>
</tr>
<tr>
<td>$V$</td>
<td>Abbé reciprocal dispersion [—]</td>
</tr>
<tr>
<td>$V$</td>
<td>voltage [V, m$^2$ kgs$^{-2}$ C$^{-1}$]</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>rectangular coordinates [m]</td>
</tr>
<tr>
<td>$Z$</td>
<td>atomic number [—]</td>
</tr>
</tbody>
</table>

### Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>absorption coefficient [cm$^{-1}$]</td>
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<tr>
<td>$\alpha$</td>
<td>(power) absorptance (absorptivity)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>dielectric coefficient (constant) [—]</td>
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<tr>
<td>$\varepsilon$</td>
<td>emittance (emissivity) [—]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>eccentricity [—]</td>
</tr>
<tr>
<td>$\varepsilon_i$</td>
<td>Re ($\varepsilon$)</td>
</tr>
<tr>
<td>$\varepsilon_2$</td>
<td>Im ($\varepsilon$)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>(power) transmittance (transmissivity) [—]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>radiation frequency [Hz]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>circular frequency $= 2\pi\nu$ [rads$^{-1}$]</td>
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<tr>
<td>$\omega_p$</td>
<td>plasma frequency [H$_2$]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength [$\mu$m, nm]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>wave number $= 1/\lambda$ [cm$^{-1}$]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan Boltzmann constant [Wm$^{-2}$K$^{-1}$]</td>
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<tr>
<td>$\rho$</td>
<td>reflectance (reflectivity) [—]</td>
</tr>
<tr>
<td>$\theta, \phi$</td>
<td>angular coordinates [rad,$^\circ$]</td>
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<tr>
<td>$\xi, \eta$</td>
<td>rectangular spatial frequencies [m$^{-1}$, r$^{-1}$]</td>
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<tr>
<td>$\phi$</td>
<td>phase [rad,$^\circ$]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>lens power [m$^{-1}$]</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>flux [W]</td>
</tr>
<tr>
<td>$\chi$</td>
<td>electric susceptibility tensor [—]</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>solid angle [sr]</td>
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### Other

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<thead>
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<th>Definition</th>
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<tr>
<td>$\Re$</td>
<td>responsivity</td>
</tr>
<tr>
<td>$\exp(x)$</td>
<td>$e^x$</td>
</tr>
<tr>
<td>$\log_a(x)$</td>
<td>log to the base $a$ of $x$</td>
</tr>
<tr>
<td>$\ln(x)$</td>
<td>natural log of $x$</td>
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<tr>
<td>$\log(x)$</td>
<td>standard log of $x$: $\log_{10}(x)$</td>
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<tr>
<td>$\Sigma$</td>
<td>summation</td>
</tr>
<tr>
<td>$\Pi$</td>
<td>product</td>
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<tr>
<td>$\Delta$</td>
<td>finite difference</td>
</tr>
<tr>
<td>$\delta x$</td>
<td>variation in $x$</td>
</tr>
<tr>
<td>$dX$</td>
<td>total differential</td>
</tr>
<tr>
<td>$\delta x$</td>
<td>partial derivative of $x$</td>
</tr>
<tr>
<td>$\delta(x)$</td>
<td>Dirac delta function of $x$</td>
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<tr>
<td>$\delta_{ij}$</td>
<td>Kronecker delta</td>
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William L. Wolfe
Optical Sciences Center
University of Arizona
Tucson, Arizona
ABOUT THE EDITORS

**Micheal Bass** is Professor of Physics and Electrical and Computer Engineering at the University of Central Florida and is on the faculty of the Center for Research and Education in Optics and Lasers (CREOL). He received his B.S. in Physics from Carnegie-Mellon and his M.S. and Ph.D. in Physics from the University of Michigan.

**Eric Van Stryland** is a professor of Physics and Electrical Engineering at the University of Central Florida for Research and Education in Optics and Lasers. He received his Ph.D. from the University of Arizona.

**David R. Williams** is a Professor of Psychology and Visual Science and the Director of the Center of Visual Science at the University of Rochester. He received his B.S. in Psychology from Denison University, and his M.A. and Ph.D. in Psychology from the University of California, San Diego.

**William L. Wolfe** is a Professor at the Optical Sciences Center at the University of Arizona. He received his B.S. in Physics from Bucknell University, and his M.S. in Physics and M.S.E. in Electrical Engineering from the University of Michigan.
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