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Devices, Measurements,
and Properties

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PREFACE

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 If we had, the Handbook would have been many volumes long and would have been too soon outdated.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. Tourtlotte 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

GLOSSARY AND FUNDAMENTAL CONSTANTS

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 α 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 ISO¹ and the International Union of Pure and Applied Physics, IUPAP.²

Prefixes

Similarly, a list of the numerical prefixes¹ 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 constants³ 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, λ , frequency, ν , wave number, σ , ω 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 $\tilde{\nu}$ for wave number, but, because of typography problems and agreement with ISO and IUPAP, we have chosen σ ; it should not be confused with the Stephan Boltzmann constant. For spatial frequencies we have chosen ξ and η , 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 [$\text{Wcm}^{-2}\text{sr}^{-1}$], M for radiant emittance or exitance [Wcm^{-2}], E for irradiance or incidence [Wcm^{-2}], and I for intensity [Wsr^{-2}]. The previous terms, W , H , N and J respectively, are still in many texts, notably Smith and Lloyd⁴ 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 $\text{Wcm}^{-2}\text{sr}^{-1}$, *field intensity* when they are Wcm^{-2} , and *radiometric intensity* when they are Wsr^{-1} .

There are two sets of terms for these radiometric quantities, that 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 *ivity* 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, exitance [*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_λ) 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 $\tilde{n} = n - ik$. 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 $e\!f\!l$ 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 θ and ϕ ; 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 σ_i 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, ρ for volume charge density, σ 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 vs ρ and τ . 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 $\alpha = \epsilon$. The law of conservation of energy for light on a surface is also usually written as $\alpha + \rho + \tau = 1$.

Base SI Quantities

length	m	meter
time	s	second
mass	kg	kilogram
electric current	A	ampere
Temperature	K	kelvin
Amount of substance	mol	mole
Luminous intensity	cd	candela

Derived SI Quantities

energy	J	joule
electric charge	C	coulomb
electric potential	V	volt
electric capacitance	F	farad
electric resistance	Ω	ohm
electric conductance	S	siemens

magnetic flux	Wb	weber
inductance	H	henry
pressure	Pa	pascal
magnetic flux density	T	tesla
frequency	Hz	hertz
power	W	watt
force	N	newton
angle	rad	radian
angle	sr	steradian

Prefixes

Symbol	Name	Common name	Exponent of ten
E	exa		18
p	peta		15
T	tera	trillion	12
G	giga	billion	9
M	mega	million	6
k	kilo	thousand	3
h	hecto	hundred	2
da	deca	ten	1
d	deci	tenth	-1
c	centi	hundredth	-2
m	milli	thousandth	-3
μ	micro	millionth	-6
n	nano	billionth	-9
p	pico	trillionth	-12
f	femto		-15
a	atto		-18

Constants

c	speed of light in vacuo [299792458 ms ⁻¹]
c_1	first radiation constant = $2\pi c^2 h = 3.7417749 \times 10^{-16}$ [Wm ²]
c_2	second radiation constant = $hc/k = 0.01438769$ [mK]
e	elementary charge [$1.60217733 \times 10^{-19}$ C]
g_n	free fall constant [9.80665 ms ⁻²]
h	Planck's constant [$6.6260755 \times 10^{-34}$ Js]
k_B	Boltzmann constant [1.380658×10^{-23} JK ⁻¹]
m_e	mass of the electron [$9.1093897 \times 10^{-31}$ kg]
N_A	Avogadro constant [6.0221367×10^{23} mol ⁻¹]
R_∞	Rydberg constant [10973731.534 m ⁻¹]
ϵ_o	vacuum permittivity [$\mu_o^{-1} c^{-2}$]
σ	Stefan Boltzmann constant [5.67051×10^{-8} Wm ⁻² K ⁻⁴]
μ_o	vacuum permeability [$4\pi \times 10^{-7}$ NA ⁻²]
μ_B	Bohr magneton [$9.2740154 \times 10^{-24}$ JT ⁻¹]

General

B	magnetic induction [Wbm ⁻² , kgs ⁻¹ C ⁻¹]
C	capacitance [f, C ² s ² m ⁻² kg ⁻¹]
C	curvature [m ⁻¹]

c	speed of light in vacuo [ms^{-1}]
c_1	first radiation constant [Wm^2]
c_2	second radiation constant [mK]
D	electric displacement [Cm^{-2}]
E	incidence [irradiance] [Wm^{-2}]
e	electronic charge [coulomb]
E_v	illuminance [lux , lmm^{-2}]
E	electrical field strength [Vm^{-1}]
E	transition energy [J]
E_g	band-gap energy [eV]
f	focal length [m]
f_c	Fermi occupation function, conduction band
f_v	Fermi occupation function, valence band
FN	focal ratio (f/number) [—]
g	gain per unit length [m^{-1}]
g_{th}	gain threshold per unit length [m^{-1}]
H	magnetic field strength [Am^{-1} , $\text{Cs}^{-1} \text{m}^{-1}$]
h	height [m]
I	irradiance (see also E) [Wm^{-2}]
I	radiant intensity [Wsr^{-1}]
I	nuclear spin quantum number [—]
I	current [A]
i	$\sqrt{-1}$
$\text{Im}()$	Imaginary part of
J	current density [Am^{-2}]
j	total angular momentum [$\text{kg m}^2 \text{sec}^{-1}$]
$J_1()$	Bessel function of the first kind [—]
k	radian wave number = $2\pi/\lambda$ [rad cm^{-1}]
k	wave vector [rad cm^{-1}]
k	extinction coefficient [—]
L	sterance [radiance] [$\text{Wm}^{-2} \text{sr}^{-1}$]
L_v	luminance [cdm^{-2}]
L	inductance [h , $\text{m}^2 \text{kgC}^{-2}$]
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 [—]
\tilde{n}	complex index of refraction [—]
NA	numerical aperture [—]
OPD	optical path difference [m]
P	macroscopic polarization [C m^{-2}]
$\text{Re}()$	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]

s_o	object distance [m]
s_i	image distance [m]
T	temperature [K, C]
t	time [s]
t	thickness [m]
u	slope of ray with the optical axis [rad]
V	Abbé reciprocal dispersion [—]
V	voltage [V, m ² kgs ⁻² C ⁻¹]
x, y, z	rectangular coordinates [m]
Z	atomic number [—]

Greek Symbols

α	absorption coefficient [cm ⁻¹]
α	(power) absorptance (absorptivity)
ϵ	dielectric coefficient (constant) [—]
ϵ	emittance (emissivity) [—]
ϵ	eccentricity [—]
ϵ_1	Re (ϵ)
ϵ_2	Im (ϵ)
τ	(power) transmittance (transmissivity) [—]
ν	radiation frequency [Hz]
ω	circular frequency = $2\pi\nu$ [rads ⁻¹]
ω_p	plasma frequency [H ₂]
λ	wavelength [μ m, nm]
σ	wave number = $1/\lambda$ [cm ⁻¹]
σ	Stefan Boltzmann constant [Wm ⁻² K ⁻¹]
ρ	reflectance (reflectivity) [—]
θ, ϕ	angular coordinates [rad, °]
ξ, η	rectangular spatial frequencies [m ⁻¹ , r ⁻¹]
ϕ	phase [rad, °]
ϕ	lens power [m ⁻¹]
Φ	flux [W]
χ	electric susceptibility tensor [—]
Ω	solid angle [sr]

Other

\Re	responsivity
$\exp(x)$	e^x
$\log_a(x)$	log to the base a of x
$\ln(x)$	natural log of x
$\log(x)$	standard log of x : $\log_{10}(x)$
Σ	summation
Π	product
Δ	finite difference
δx	variation in x
dx	total differential
∂x	partial derivative of x
$\delta(x)$	Dirac delta function of x
δ_{ij}	Kronecker delta

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CHAPTER 35

PROPERTIES OF METALS

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35.1 GLOSSARY

a	absorptance, absorptivity
a	plate radius (m)
B	support condition
C_{ij}	elastic stiffness constants (N/m ²)
C_p	specific heat (J/kg K)
CTE	coefficient of thermal expansion (K ⁻¹)
D	flexural rigidity (N m ²)
D	thermal diffusivity (m ² /s)
E	elastic modulus (Young's) (N/m ²)
\mathbf{E}	electromagnetic wave vector (J)
e	electron charge (C)
E_o	amplitude of electromagnetic wave at $x = 0$ (J)
G	load factor (N/kg)
G	shear modulus, modulus of rigidity (N/m ²)
g	acceleration due to gravity (m/s ²)
I	light intensity in medium (W/m ²)
i	$(-1)^{1/2}$
I_o	light intensity at interface (W/m ²)
I_o	section moment of inertia (m ⁴ /m)
K	bulk modulus (N/m ²)
k	extinction coefficient
k	thermal conductivity (W/m K)

35.2 OPTICAL AND PHYSICAL PROPERTIES OF MATERIALS

L	length (m)
M	materials parameter (kg/N m)
m	electron mass (kg)
\mathbf{N}	complex index of refraction
N	number of dipoles per unit volume (m^{-3})
n	index of refraction
P	plate size (m^4)
q	load (N/m^2)
r	reflectance, reflectivity
R_I	intensity reflection coefficient
S	structural efficiency (m^{-2})
T	temperature (K)
t	time (s)
t	transmittance, transmissivity
V_0	volume per unit area of surface (m)
x	distance (m)
α	coefficient of thermal expansion (K^{-1})
α	absorption coefficient (m^{-1})
β	deflection coefficient
β	dynamic deflection coefficient
Γ	damping constant
δ	skin depth (nm)
δ	deflection (m)
δ_{DYN}	dynamic deflection (m)
ϵ	emittance, emissivity (W/m^2)
ϵ	complex dielectric constant
ϵ_0	permittivity of free space (F/m)
ϵ_1	real part of dielectric constant
ϵ_2	imaginary part of dielectric constant
$\ddot{\theta}$	angular acceleration (s^2)
λ	wavelength (m)
λ_0	wavelength in vacuum (m)
μ	magnetic susceptibility (H/m)
ν	frequency (s^{-1})
ν	Poisson's ratio

ρ	mass density (kg/m ³)
σ	conductivity (S/m)
ω	radian frequency (s ⁻¹)

35.2 INTRODUCTION

Metals are commonly used in optical systems in three forms: (1) structures, (2) mirrors, and (3) optical thin films. In this article, properties are given for metal mirror substrate and structural materials used in modern optical systems. Many other materials have not been included due to their limited applicability. Metal film properties are discussed in the context of thick films (claddings) rather than optical thin films that are covered in Chap. 42, Optical and Physical Properties of Films and Coatings, in Vol. I. Since mirrors are structural elements, the structural properties are equally important as the optical properties to the designer of an optical system. Therefore, the properties addressed here include physical, mechanical, and thermal properties in addition to optical properties. Mechanical and thermal properties of silicon (Si) and silicon carbide (SiC) are included, but not their optical properties since they are given in the article entitled “Optical Properties of Semiconductors,” Vol II, Chap. 36.

After brief discussions of optical properties, mirror design, and dimensional stability, curves and tables of properties are presented, as a function of temperature and wavelength, where available. For more complete discussions or listings, the reader should consult the references and/or one of the available databases.¹⁻³ A concise theoretical overview of the physical properties of materials is given by Lines.⁴

Nomenclature

The symbols and units used in this subsection are consistent with usage in other sections of this Handbook although there are some unavoidable duplications in the usage of symbols between categories of optical, physical, thermal, and mechanical properties. Definitions of symbols with the appropriate units are contained in the table at the beginning of this article.

Optical Properties

The definitions for optical properties given in this section are primarily in the geometric optics realm and do not go into the depth considered in many texts dealing with optical properties of solids.⁵⁻⁸

There is obviously a thickness continuum between thin films and bulk, but for this presentation, bulk is considered to be any thickness of material that has bulk properties. Typically, thin films have lower density, thermal conductivity, and refractive index than bulk; however, current deposition techniques are narrowing the differences. Optical properties of thin films are presented only when bulk properties have not been found in the literature.

The interaction between light and metals takes place between the optical electric field and the conduction band electrons of the metal.⁹ Some of the light energy can be

transferred to the lattice by collisions in the form of heat. The optical properties of metals are normally characterized by the two optical constants: index of refraction n and extinction coefficient k that make up the complex refractive index \mathbf{N} where:

$$\mathbf{N} = n + ik \quad (1)$$

The refractive index is defined as the ratio of phase velocity of light in vacuum to the phase velocity of light in the medium. The extinction coefficient is related to the exponential decay of the wave as it passes through the medium. Note, however, that these “constants” vary with wavelength and temperature. The expression for an electromagnetic wave in an absorbing medium contains both of these parameters:

$$\mathbf{E} = E_o e^{-2\pi kx/\lambda_0} e^{-i(2\pi mx/\lambda_0 - \omega t)} \quad (2)$$

where E_o is the amplitude of the wave measured at the point $x = 0$ in the medium, E is the instantaneous value of the electric vector measured at a distance x from the first point and at some time t , ω is the angular frequency of the source, and λ_0 is the wavelength in vacuum.

The absorption coefficient α is related to the extinction coefficient by:

$$\alpha = 4k/\lambda_0 \quad (3)$$

and for the general case, the absorption coefficient also appears in the absorption equation:

$$I = I_0 e^{-\alpha x} \quad (4)$$

However, this equation implies that the intensities I and I_0 are measured within the absorbing medium. The complex dielectric constant ϵ for such a material is:

$$\epsilon = \epsilon_1 + i\epsilon_2 \quad (5)$$

where the dielectric constants are related to the optical constants by:

$$\epsilon_1 = n^2 - k^2 \quad (6)$$

$$\epsilon_2 = 2nk \quad (7)$$

Two additional materials properties that influence the light-material interaction are magnetic susceptibility μ and conductivity σ that are further discussed later.

The equations describing the reflection phenomena, including polarization effects for metals, will not be presented here but are explained in detail elsewhere.^{5-8,10-11} After a brief description of Lorentz and Drude theories and their implications for metals, and particularly for absorption, the relationship among reflection, transmission, and absorption is discussed.⁹

The classical theory of absorption in dielectrics is due to H. A. Lorentz¹² and in metals to P. K. L. Drude.¹³ Both models treat the optically active electrons in a material as classical oscillators. In the Lorentz model, the electron is considered to be bound to the nucleus by a harmonic restoring force. In this manner, Lorentz’s picture is that of the

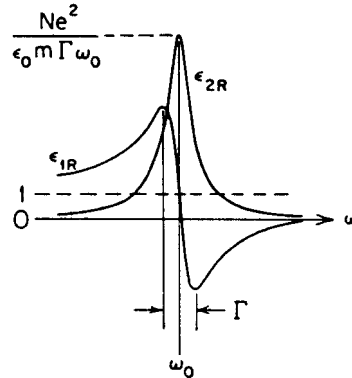


FIGURE 1 Frequency dependences of ϵ_{1R} and ϵ_{2R} .

nonconductive dielectric. Drude considered the electrons to be free, and set the restoring force in the Lorentz model equal to zero. Both models include a damping term in the electron's equation of motion that in more modern terms is recognized as a result of electron-phonon collisions.

These models solve for the electron's motion in the presence of the electromagnetic field as a driving force. From this, it is possible to write an expression for the polarization induced in the medium and from that to derive the dielectric constant. The Lorentz model for dielectrics gives the relative real and imaginary parts of the dielectric constant ϵ_{1R} and ϵ_{2R} in terms of N , the number of dipoles per unit volume; e and m , the electron charge and mass; Γ , the damping constant; ω and ω_0 , the radian frequencies of the field and the harmonically bound electron; and ϵ_0 , the permittivity of free space. These functions are shown in Fig. 1. The range of frequencies where ϵ_1 increases with frequency is referred to as the *range of normal dispersion*, and the region near $\omega = \omega_0$ where it decreases with frequency is called the *range of anomalous dispersion*.

Since the ionic polarizability is much smaller than the electronic polarizability at optical frequencies, only the electronic terms are considered when evaluating optical absorption using the Lorentz model for dielectrics. The Drude model for metals assumes that the electrons are free to move. This means that it is identical to the Lorentz model except that ω_0 is set equal to zero. The real and imaginary parts of the dielectric constant are then given by

$$\epsilon_{1R} = 1 - (Ne^2 \epsilon_0 m) \frac{1}{\omega^2 + \Gamma^2} \quad (8)$$

$$\epsilon_{2R} = (Ne^2 \epsilon_0 m) \frac{\Gamma}{\omega(\omega^2 + \Gamma^2)} \quad (9)$$

The quantity Γ is related to the mean time between electron collisions with lattice vibrations, and by considering electronic motion in an electric field \mathbf{E} having radian frequency ω , an expression for the average velocity can be obtained. An expression for the conductivity σ is then obtained and the parts of the dielectric constant can be restated. At electromagnetic field frequencies that are low, it can be shown that $\epsilon_2 \gg \epsilon_1$ and therefore it follows that:

$$\alpha = (\omega \mu \sigma / 2)^{1/2} \quad (10)$$

In other words, the optical properties and the conductivity of a perfect metal are related

through the fact that each is determined by the motion of free electrons. At high frequencies, transitions involving bound or valence band electrons are possible and there will be a noticeable deviation from this simple result of the Drude model. However, the experimental data reported for most metals are in good agreement with the Drude prediction at wavelengths as short as 1 μm .

From Eq. (10) it is clear that a field propagating in a metal will be attenuated by a factor of $1/e$ when it has traveled a distance:

$$\delta = (2/\omega\mu\sigma)^{1/2} \quad (11)$$

This quantity is called the *skin depth*, and at optical frequencies for most metals it is ~ 50 nm. After a light beam has propagated one skin depth into a metal, its intensity is reduced to 0.135 of its value at the surface.

Another aspect of the absorption of light energy by metals that should be noted is the fact that it increases with temperature. This is important because during laser irradiation the temperature of a metal will increase and so will the absorption. The coupling of energy into the metal is therefore dependent on the temperature dependence of the absorption. For most metals, all the light that gets into the metal is absorbed. If the Fresnel expression for the electric field reflectance is applied to the real and imaginary parts of the complex index for a metal-air interface, the field reflectivity can be obtained. When multiplied by its complex conjugate, the expression for the intensity reflection coefficient is obtained:

$$R_I = 1 - 2\mu\epsilon_0\omega/\sigma \quad (12)$$

Since the conductivity σ decreases with increasing temperature, R_I decreases with increasing temperature, and at higher temperatures more of the incident energy is absorbed.

Since reflection methods are used in determining the optical constants, they are strongly dependent on the characteristics of the metallic surface. These characteristics vary considerably with chemical and mechanical treatment, and these treatments have not always been accurately defined. Not all measurements have been made on freshly polished surfaces but in many cases on freshly deposited thin films. The best available data are presented in the tables and figures, and the reader is advised to consult the appropriate references for specifics.

In this article, an ending of *-ance* denotes a property of a specific sample (i.e., including effects of surface finish), while the ending *-ivity* refers to an intrinsic material property. For most of the discussion, the endings are interchangeable.

Reflectance r is the ratio of radiant flux reflected from a surface to the total incident radiant flux. Since r is a function of the optical constants, it varies with wavelength and temperature. The relationship between reflectance and optical constants is:⁵

$$r = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \quad (13)$$

The reflectance of a good, freshly deposited mirror coating is almost always higher than that of a polished or electroplated surface of the same material. The reflectance is normally less than unity—some transmission and absorption, no matter how small, are always present. The relationship between these three properties is:

$$r + t + a = 1 \quad (14)$$

Transmittance t is the ratio of radiant flux transmitted through a surface to the total incident radiant flux and absorptance a is the ratio of the radiant flux lost by absorption to the total incident radiant flux. Since t and a are functions of the optical constants, they

vary with wavelength and temperature. Transmittance is normally very small for metals except in special cases (e.g., beryllium at x-ray wavelengths). Absorptance is affected by surface condition as well as the intrinsic contribution of the material.

The thermal radiative properties are descriptive of a radiant energy-matter interaction that can be described by other properties such as the optical constants and/or complex dielectric constant, each of which is especially convenient for studying various aspects of the interaction. However, the thermal radiative properties are particularly useful since metallic materials are strongly influenced by surface effects, particularly oxide films, and therefore in many cases they are not readily calculated by simple means from the other properties.

For opaque materials, the transmission is near zero, so Eq. (14) becomes:

$$r + a = 1 \quad (15)$$

but since Kirchoff's law states that absorptance equals emittance, ϵ , this becomes:

$$r + \epsilon = 1 \quad (16)$$

and the thermal radiative properties of an opaque body are fully described by either the reflectance or the emittance. Emittance is the ratio of radiated emitted power (in W/m^2) of a surface to the emissive power of a blackbody at the same temperature. Emittance can therefore be expressed as either *spectral* (emittance as a function of wavelength at constant temperature) or *total* (the integrated emittance over all wavelengths as a function of temperature).

Physical Properties

The physical properties of interest for metals in optical applications include density, electrical conductivity, and electrical resistivity (the reciprocal of conductivity), as well as crystal structure. Chemical composition of alloys is also included with physical properties.

For density, mass density is reported with units of kg/m^3 . Electrical conductivity is related to electrical resistivity, but for some materials, one or the other is normally reported. Both properties vary with temperature.

Crystal structure is extremely important for stability since anisotropy of the elastic, electric, and magnetic properties and thermal expansion depend on the type of structure.¹⁴ Single crystals of cubic metals have completely isotropic coefficient of thermal expansion (CTE), but are anisotropic in elastic properties—modulus and Poisson's ratio. Materials with hexagonal structures have anisotropic expansion and elastic properties. While polycrystalline metals with randomly oriented small grains do not exhibit these anisotropies they can easily have local areas that are inhomogeneous or can have overall oriented crystal structure induced by fabrication methods.

The combined influence of physical, thermal, and mechanical properties on optical system performance is described under "Properties Important in Mirror Design," later in this article.

Thermal Properties

Thermal properties of metals that are important in optical systems design include: coefficient of thermal expansion α , referred to in this section as CTE; thermal conductivity k ; and specific heat C_p . All of these properties vary with temperature; usually they tend to decrease with decreasing temperature. Although not strictly a thermal property, the maximum usable temperature is also included as a guide for the optical designer.

Thermal expansion is a generic term for change in length for a specific temperature