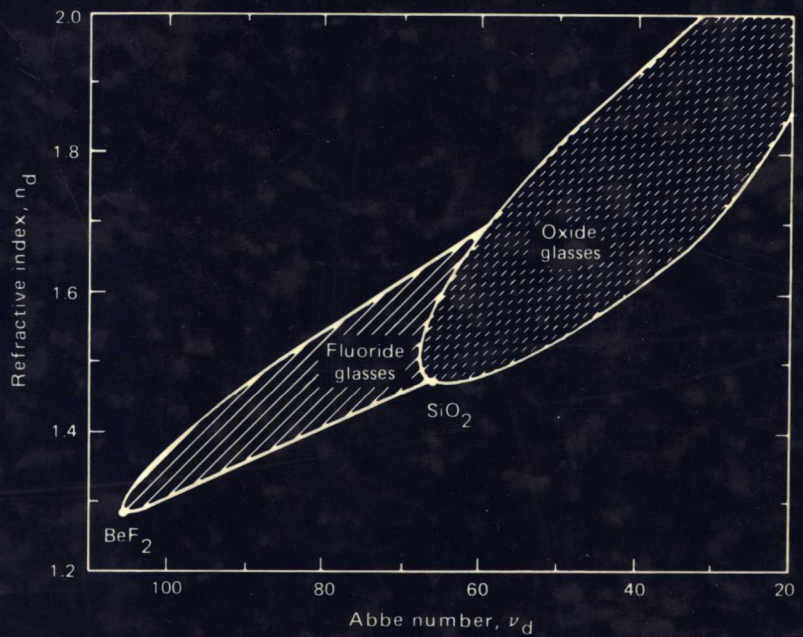
Optical Engineering / Volume 6

OPTICAL MATERIALS

AN INTRODUCTION TO SELECTION AND APPLICATION



SOLOMON MUSIKANT

OPTICAL MATERIALS

AN INTRODUCTION TO SELECTION AND APPLICATION

Solomon Musikant
Paoli, Pennsylvania

MARCEL DEKKER, INC. New York and Basel

Library of Congress Cataloging in Publication Data

Musikant, Solomon.
Optical materials.

(Optical engineering ; 6)
Includes bibliographies and index.
1. Optical materials. I Title. II. Series: Optical engineering (Marcel Dekker, Inc.) ; v. 6.
QC374.M87 1985 621.36 84-28704
ISBN 0-8247-7309-8

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MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York 10016

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

ABOUT THE SERIES

Optical science, engineering, and technology have grown rapidly in the last decade so that today optical engineering has emerged as an important discipline in its own right. This series is devoted to discussing topics in optical engineering at a level that will be useful to those working in the field or attempting to design systems that are based on optical techniques or that have significant optical subsystems. The philosophy is not to provide detailed monographs on narrow subject areas but to deal with the material at a level that makes it immediately useful to the practicing scientist and engineer. These are not research monographs, although we expect that workers in optical research will find them extremely valuable.

Volumes in this series cover those topics that have been a part of the rapid expansion of optical engineering. The developments that have led to this expansion include the laser and its many commercial and industrial applications, the new optical materials, gradient index optics, electro- and acousto-optics, fiber optics and communications, optical computing and pattern recognition, optical data reading, recording and storage, biomedical instrumentation, industrial robotics, integrated optics, infrared and ultraviolet systems, etc. Since the optical industry is currently one of the major growth industries this list will surely become even more extensive.

Brian J. Thompson
University of Rochester
Rochester, New York

PREFACE

The aim of this book is to provide the optics designer or user with information on the broad range of materials used as optical elements in systems and devices. For each class of materials (glasses, crystalline materials, plastics, coatings) fundamental performance requirements, basic characteristics, principles of fabrication, possibilities for new or modified materials, and key characterization data are provided.

This volume will give the reader a broad perspective on the optical materials now available and the possibilities for their future development, as well as provide data useful for preliminary materials selections and optical design. The bulk of the discussion relates to refracting materials, because this is the area of greatest variety and most generalized applicability in the optic arts.

The contents are intended to be useful to a wide range of readers, including

Optical system and device designers and developers
Optics designers and optics engineers
Materials engineers
Physical measurements engineers
Test engineers
Students of optical sciences
Students of materials sciences

It is hoped that these practitioners will find the organization of the information to be a helpful aid in appreciating and therefore properly evaluating the various materials available for specific applications.

The book is designed mainly for the technical worker who already has become knowledgeable in one or more aspects of optical phenomena, applications, and/or materials science.

The volume, furthermore, is intended to be practical and not mathematically involved.

Solomon Musikant

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ACKNOWLEDGMENTS

I wish to thank my many co-workers and collaborators at the General Electric Company, especially Drs. R. J. Charles, S. Prochazka, G. A. Slack and R. A. Tanzilli, and those at the Society of Photo-Optical Instrumentation Engineers, particularly R. E. Fischer, for the stretching of my knowledge engendered by these associations. In addition, I am grateful to the various university and U.S. government scientific personnel who have supported and encouraged the optical materials research work in which I have been engaged. Although this is indeed a long list, I wish to express special appreciation to Drs. A. L. Bement, H. E. Bennett, A. M. Diness, W. A. Harrison, W. T. Messick, R. Pohanka, E. vanReuth, R. Rice, and W. B. White.

Finally, in this review of acknowledgments, warm thanks go to my wife, Shirley, who encouraged me throughout the preparation of this book.

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1
TRANSMISSION, REFLECTION, AND ABSORPTION OF LIGHT

1.1 ELECTROMAGNETIC SPECTRUM

The true nature of light is probably impossible to know. However, Maxwell's theory (James Clerk Maxwell, 1831–1879) and the quantum theory provide a consistent theoretical explanation of all optical phenomena. Maxwell assumed that light is merely one form of electromagnetic energy that has a wave form and a periodic nature.

These electromagnetic waves travel at a fixed velocity in a given medium and have a range of frequencies, or wavelengths. In a vacuum, electromagnetic waves propagate at a velocity v_0 of 3×10^{10} cm/s. The relationship among wavelength λ, frequency ν, and velocity in the medium, v, is given by

$$\lambda = \frac{v}{\nu}$$

where λ is the wavelength (cm), ν the frequency (Hz), and v the velocity (cm/s).

The units of length commonly used when discussing wave motion in the optical region are

Unit	Symbol	Length
Micrometer	μm	10^{-6} m
Nanometer	nm	10^{-9} m
Angstrom	Å	10^{-10} m

The unit of frequency is the hertz (cycles per second) abbreviated Hz.

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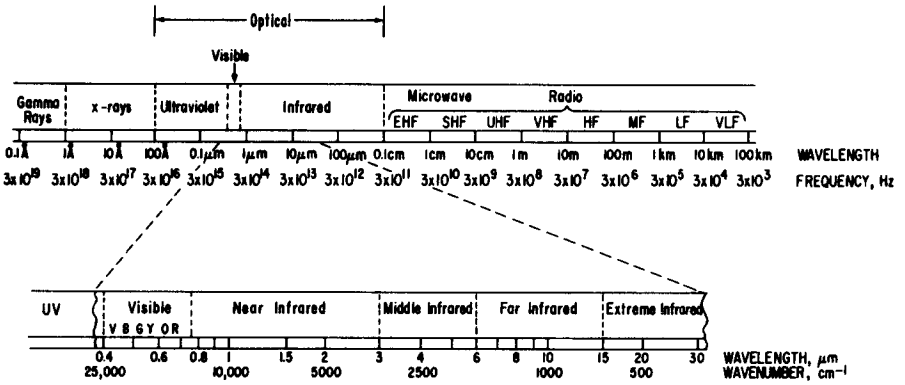

Figure 1.1 Electromagnetic spectrum. (Reprinted with permission of F. Grum and R. J. Becherer, *Optical Radiation Measurements*, Academic Press, New York, 1979, Vol. 1.)

The electromagnetic spectrum is partitioned into various classes of electromagnetic waves, based on ranges of wavelength. Visible electromagnetic waves (light) extend from 400 to 750 nm. Electromagnetic waves with wavelengths down to 10 nm are called ultraviolet light. The lower limit is a matter of definition. The infrared band extends from 750 to 10^6 nm (10^3 μm). The electromagnetic spectrum designations are shown in Fig. 1.1.

We will be directing our discussion to the portion of the spectrum bounded by the ultraviolet (UV) region on the short-wavelength side to the infrared (IR) on the long-wavelength side.

1.2 BAND STRUCTURE OF METALS, DIELECTRICS, AND SEMICONDUCTORS

Quantum theory was developed during the early part of this century by Planck, Einstein, Bohr, de Broglie, Schrödinger, and Heisenberg. This theory accurately predicts the behavior of a wide range of solid state phenomena. An excellent introductory treatment of this subject was given by Bohm (1951).

The quantum theory employs Newton's idea that light is composed of small discrete bodies, now called photons. Modern theory accepts the dual nature of light, i.e., that light exhibits both the wave character of Maxwell's formulations and the particle character envisaged by Newton. Maxwell's theory treats the propagation of light, while the quantum theory deals with the interaction of light with matter.

Photon energy can be described in terms of wavelength λ, wave number N, joules (J), electron volts (eV), or frequency. These are related through the following equations:

$$v = \lambda\nu \text{ cm/s}$$
$$E = h\nu \text{ J} \quad \text{or} \quad E = 0.6242 \times 10^{19}\, h\nu \text{ eV}$$
$$N = 1/\lambda \text{ cm}^{-1}$$

where v is the velocity in the medium (cm/s), n the frequency (Hz), E the energy of photon (J or eV), $h = 6.62517 \times 10^{-34}$ J/s (Planck's constant), N is the wave number (cm^{-1}) or number of waves in 1 cm of path, and 1 eV = 1.602×10^{-19} J. Frequency, wavelength, and quantum energy in various regions of the electromagnetic spectrum are shown in Table 1.1.

Consider a crystal to be made up of a collection of atoms in a regular array, known as a lattice. Each atom has one or more electrons in its outer electron shell. In an isolated atom, the electrons surrounding the nucleus are restricted to a set of discrete energy levels as required by the quantum theory.

Table 1.1 Frequency, Wavelength, and Quantum Energy for Various Bands in the Electromagnetic Spectrum[a]

Type of radiation				
Wave region	radio waves	10^9 Hz and less	300 mm and longer	0.000004 eV and less
	microwaves	10^9 to 10^{12} Hz	300 to 0.3 mm	0.000004 to 0.004 eV
Optical region	infrared	10^{12} to 4.3×10^{14} Hz	300 to 0.7 μm	0.004 to 1.7 eV
	visible	4.3×10^{14} to 5.7×10^{14} Hz	0.7 to 0.4 μm	1.7 to 2.3 eV
	ultraviolet	5.7×10^{14} to 10^{16} Hz	0.4 to 0.03 μm	2.3 to 40 eV
Ray region	x rays	10^{16} to 10^{19} Hz	300 to 0.3 Å	40 to 40,000 eV
	gamma rays	10^{19} Hz and above	0.3 Å and shorter	40,000 eV and above

[a]From G. R. Fowles, *Introduction to Modern Optics*, Holt, Rinehart and Winston, Inc., New York, 1968. (Reprinted by permission of Holt, Rinehart and Winston, CBS College Publishing.)

Each level can hold up to two electrons. The lower levels are occupied and the higher ones become occupied as the lower energy electrons become excited. In a crystal, the single discrete levels of the individual atoms broaden into a band of closely spaced discrete energy levels.

Figure 1.2 shows a number of band configurations. The ordinate represents energy level. The abscissa can be thought of as the distance from the surface of the crystal. The dark regions represent bands that are filled with electrons. The lighter regions represent unoccupied allowable (quantum) levels. The white regions represent forbidden energy values. That is, in accordance with the quantum theory, no electrons may occupy any energy level in the forbidden bands.

Electrical conduction can take place if the electrons can be excited into an unfilled quantum level. Thus in Fig. 1.2a, a very small increment of energy or excitation will promote the lower (valence) electrons into the empty (conduction) band. Thus Fig. 1.2a represents the band configuration for a metallic conductor.

Figure 1.2b represents the band configuration for an insulator or dielectric material. A tremendous amount of energy must be imparted to the electrons in the valence band to promote them to the conduction band. The difference in energy E_g between the top of the valence band and the bottom of the conduction band is designated as the band gap. E_g values of various materials are shown in Table 1.2.

Semiconductors are characterized by a small band gap as indicated in Fig. 1.2c. In this case, E_g is low and small excitations promote the electrons into the conduction band, leaving unfilled positions in the valence band which then becomes conductive by movement of the "holes" left behind. In an intrinsic semiconductor, such as germanium, the number of conducting electrons equals the

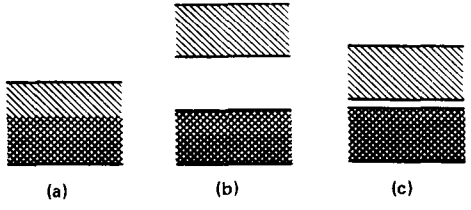

Figure 1.2 Electron occupation in various band configurations: (a) conductor, (b) insulator (dielectric), and (c) semiconductor (from Hutchinson and Baird, 1963).

Table 1.2 Values of the Energy Gap Between the Valence and Conduction Bands at Room Temperature[a]

Crystal	E_g (eV)	Crystal	E_g (eV)
Diamond	5.33	ZnS	3.6
Si	1.14	ZnSe	2.60
GaAs	1.4	AsCl	3.2
SiC	3	AsI	2.8
Al_2O_3	8+	TiO_2	3
Ge	0.75		

[a]Source: Kittel (1966).

number of holes. However, by a process known as "doping," an extrinsic semiconductor can be fabricated to contain a preponderance of electron type conductors upon excitation or a preponderance of hole type conductors upon excitation. The former is called an n-type semiconductor and the latter, p-type.

A fuller treatment of this area can be found in many textbooks on solid state theory such as Kittel (1966), Smith (1961), and Hutchinson and Baird (1963). An excellent text on materials science has been written by van Vlack (1964).

For metals, the band gap is low so that photons of either energy, UV to IR, will excite the metal electronic structure and thus induce reemission of energy.

In the visible, this reemitted energy is observed by the eye as metallic lustre. Semiconductors have an intermediate level of E_g and thus will tend to be excited by photons of an intermediate energy content and be transparent for lower energy photons, i.e., exhibit lustre in the visible and be transparent in the IR, where no interaction of the photon and the electronic structure takes place.

If there is no interaction between the photons of a particular energy level and the electronic structure of the material, then the material is transparent to the photon. Dielectrics have a high E_g and only high-energy photons in the UV can excite the electronic structure. Therefore, dielectrics tend to be transparent in the visible and IR regimes.

In addition to the electronic excitation, photons also excite the ionic lattice. This excitation reveals itself as lattice absorption of photons of relatively low energy in the IR and short millimeter radio frequency bands.

1.3 OPTICAL PROPERTIES OF MATERIALS

The intensity I of an electromagnetic wave is the amount of energy per unit time transmitting through a unit area which is transverse to the propagation direction.

A collection of atoms (a material) interacts with incoming photons (a light beam). The atoms and associated electronic structure which are excited by the photons reemit photons. The propagation pattern which results is observed in terms of surface reflection and transmission characteristics of the optical material.

The optical properties of the material are functions of the wavelength of the incoming light, temperature of and applied pressure on the material, as well as the environment (including electromagnetic fields) acting on the material.

The index of refraction n of a material which transmits light is given by

$$n = \frac{v_0}{v}$$

where v_0 is the velocity of light in a vacuum and v the velocity of light in the medium.

The complex refractive index n* includes the parameter κ, which is related to the energy absorbed by the medium from the light beam as it propagates through the medium. The complex refractive index is given by (Jenkins and White, 1957)

$$n^* = n(1 - i\kappa) \quad \text{and} \quad \kappa = \frac{\alpha\lambda}{4\pi n}$$

where κ is the absorption index and α is the absorption coefficient.

Figure 1.3 characterizes metals, semiconductors, and dielectrics in terms of the index of absorption as a function of wavelength. The specific shape and location of absorption peaks varies with the nature of the specific material involved.

Consider Fig. 1.4, which represents a light beam propagating through a solid. The intensity I_0 of the beam just after entering the medium is attenuated as it passes through the solid medium. That attenuation is given by Bouguer's law (Pierre Bouguer, 1698–1758), which states

$$I = I_0 e^{-\alpha x}$$

where I is the intensity at position x, x the distance along the path, α the absorption coefficient, and e the base of natural logarithms.

The optical region of Fig. 1.3 is shown in an expanded plot for a typical dielectric in Fig. 1.5. In this case, the data are plotted

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