CRC Handbook of Laser Science and Technology

Volume IV
Optical Materials
Part 2: Properties

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PREFACE

Laser action has been observed in all forms of matter and spans a spectrum ranging from radiowaves to X-rays. The object of the *CRC HANDBOOK OF LASER SCIENCE AND TECHNOLOGY* is to provide a concise, readily accessible source of critically evaluated data for workers in all areas of laser research and development. The emphasis is on the presentation of tabular and graphical data compiled by recognized authorities. Definitions of properties and references to the original data sources and to supplementary reviews and surveys are also provided, as appropriate. The previous two volumes in this series dealt with laser action in all media and contained extensive tables of laser transitions and references. Volumes III, IV, and V are devoted to the physical and chemical properties of optical materials used in laser systems and applications.

The earlier *CRC Handbook of Lasers with Selected Data on Optical Technology* contained several sections on optical materials. These sections have been updated and expanded and many new sections added to form Volumes III to V. The materials covered are almost exclusively condensed matter. Because many properties are dependent in varying degrees on preparation methods, materials imperfections and measurement techniques, several sections included discussions and descriptions of these specific characteristics and of materials compositions.

Optical materials for laser systems encompass an extremely wide range of special property requirements and operating wavelengths and environments. Of necessity, the topics covered in these volumes are selective. In some sections it was possible to be exhaustive; in others a more general survey is provided because extensive data tabulations already exist elsewhere. The applications of optical materials are continually expanding. Therefore an attempt has been made throughout to include not only currently useful materials but also representative examples of broader classes of materials of possible future interest. One can frequently use observed trends in materials properties with composition to select and tailor new materials having specific operating characteristics.

Data on optical materials can be presented from different points of view — by material, by properties, or by application. For laser materials no single approach seemed fully appropriate, therefore several formats have been utilized. A number of properties may be relevant to a given application. As an example, for transmitting materials one may be interested in optical, thermal, and mechanical properties, thus these properties are grouped together within a single section. However, not all properties are covered within a particular section. Because of their special character, properties such as optical nonlinearities, radiation damage, and fabrication are discussed separately. Characteristics of specific classes of materials such as glasses may also be covered in several sections depending upon its use as a transmitting material, a filter material, an optical waveguide material, or a laser host material. Indices at the end of each volume list individual materials and where data on specific properties are located.

With the advent of lasers, nonlinear optical phenomena have become important and have been the subject of intense study and application. The properties of materials for harmonic generation and two-photon absorption, nonlinear refractive index, and stimulated Raman scattering properties of various opticals materials are included in Volume III. Data on radiation damage of optical crystals and glasses are also surveyed in this volume. Volume IV covers materials for fundamental uses: transmission (laser windows and lenses), filtering, reflection, and polarization. Materials for more specialized uses involving linear electrooptic, magnetooptic, elastooptic, and photorefractive effects and liquid crystals are also covered in this volume. Volume V presents data on properties of materials for optical waveguides, optical storage and recording, phase conjugation, lasers, and quantum counter applications. Other sections cover optical coatings and thin films. The final section describes fabrication techniques and procedures for all types of optical materials.

Laser-induced damage to optical components is an extremely important consideration for many laser applications. Although it was originally planned to include a section on laser damage, this topic will be covered separately elsewhere. In this regard, I welcome comments about the contents and presentation in the present volumes and suggestions for materials and properties to be included in future editions.

A handbook can never be completely current with the journal literature. Because of the very nature of the preparation and publication process, one must accept the fact that a handbook becomes out-of-date at the time of the final type setting. Although all sections for Volumes III to V were solicited concurrently, there were delays in the receipt of some manuscripts. Some sections were updated, but variations in timeliness, as evident from the reference dates, remain.

These volumes are the result of the efforts and talents of many people to whom I am indebted. I thank especially the contributors for the time devoted to preparing these compilations and texts and the Advisory Board and contributors for their numerous helpful comments and suggestions regarding the content and format. The staff of CRC Press, and Senior Editor Marsha Baker in particular, have my thanks and appreciation for the preparation of these volumes. Finally, I am grateful to my wife Pauline for her generous support of this project.

Marvin J. Weber
Danville, California
February 1984

THE EDITOR

Marvin J. Weber received his education at the University of California, Berkeley, and was awarded the A.B., M.A., and Ph.D. degrees in physics in 1954, 1956, and 1959. After graduation Dr. Weber joined the Research Division of the Raytheon Company where he was a Principal Scientist. As Manager of Solid State Lasers, his group developed many new rare earth laser materials. While at Raytheon, he also discovered luminescence in bismuth germanate, a scintillator crystal widely used for the detection of high energy particles and radiation.

During 1966-67 Dr. Weber was a Visiting Research Associate in the Department of Physics, Stanford University.

In 1973 Dr. Weber joined the Laser Fusion Program at the Lawrence Livermore National Laboratory. As Head of Basic Materials Research, he had the responsibility for the physics and characterization of optical materials for high-power laser systems. His work on laser glass resulted in an Industrial Research IR-100 Award in 1979 for research and development of fluorophosphate laser glasses. In 1983 Dr. Weber was the recipient of the George W. Morey Award from the Glass Division of the American Ceramics Society for his basic studies of fluorescence and stimulated emission in glasses and for the insight that research has provided into glass structure.

Dr. Weber has published numerous scientific papers and review articles in the areas of lasers, luminescence, optical spectroscopy, and magnetic resonance in solids and has been granted several patents on solid-state laser materials. He is a Fellow of the American Physical Society, a Fellow of the Optical Society of America, and a member of the American Ceramics Society, the Materials Research Society, and the American Association for Crystal Growth.

Among other activities, Dr. Weber has been a consultant for the National Science Foundation's Division of Materials Research, a member of the National Academy of Science - National Research Council Evaluation Panel for the National Bureau of Standard's Inorganic Materials Division, and a participant in various national advisory panels. He is currently an Associate Editor of the *Journal of Luminescence* and a member of the Editorial Advisory Board of the *Journal of Non-Crystalline Solids*.

In 1984 Dr. Weber began a temporary transfer assignment with the Division of Materials Sciences, Office of Basic Energy Sciences, of the U.S. Department of Energy in Washington, D.C., where he has been involved with planning for advanced synchrotron radiation facilities and applications of computers for materials simulations.

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HANDBOOK OF LASER SCIENCE AND TECHNOLOGY

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HANDBOOK OF LASER SCIENCE AND TECHNOLOGY

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SECTION 1. FUNDAMENTAL PROPERTIES

1.1 TRANSMITTING MATERIALS

INTRODUCTION

Transmitting optical materials are those having high transparency in the general spectral range from the infrared to the ultraviolet. The materials and properties covered in this section are those of interest primarily for window and lens materials. These materials are subdivided into optical crystals, glasses, and plastics. Within each section are discussions and tabulations of the following properties: transmission, refractive index and dispersion, thermal properties, mechanical and elastic properties, and chemical durability.

The tabulations are not intended to be exhaustive, but include most materials which have been demonstrated to be useful. In addition, representative examples of other materials that have been investigated and which are indicative of the wider range of property values possible are included. Systematic variations of property values with chemical composition and structure can frequently guide the selection of materials to achieve specific operating characteristics.

1.1.1 OPTICAL CRYSTALS

M. J. Weber

INTRODUCTION

Most optical crystals, by the nature of their application, are transparent. Therefore, in addition to traditional window and lens materials — which constitute the majority of the crystals covered in this section — other crystals used principally for laser hosts, harmonic generation, modulators, and polarizers are also included because many of these materials are well characterized and may have properties appropriate for particular applications. The size and availability of many crystals may, however, limit their practical usefulness.

The names and chemical formulas of crystals covered in this section are given in Table 1.1.1.1. Common acronyms and other designations are added in parentheses following the name. In the tables to follow, these crystals are listed alphabetically by chemical formula.

GENERAL PROPERTIES

The following general properties are compiled in Table 1.1.1.1.

Crystal system — Additional information about space groups and crystal structure is given in Wyckoff.[1]

Band gap — Extensive compilations of data on energy band gaps for simple compound semiconductors and insulators are given in Reference 2. Most band gaps listed in Table 1.1.1.1 are for direct transitions at 300 K. If the band gap was measured at a different temperature, this temperature (K) is given in parentheses. Band gaps involving indirect and excitonic transitions are denoted by I and E, respectively.

Transmission range — Electronic and lattice absorption edges are given in terms of the wavelengths between which the external transmission of a 1-mm thick sample at 300 K is greater than 10% or, alternatively, the absorption coefficient is $\lessapprox 10\ cm^{-1}$. The values are approximate and are only intended as a general guide. As discussed in the next section (Transparency of Window Materials), many factors can affect the apparent absorption edges. These include impurities, imperfections, temperature, crystallographic orientation, compositional variations, and growth techniques. Differences in absorption edges and band gaps cited in the literature arise from these effects and the definitions used. Measurement of the transmission spectrum of the actual material to be used is always recommended.

Spectrum reference — Collections of transmission spectra of crystals are presented in References 7, 10, and 12; included are references to the original data sources. Manufacturer's catalogs also frequently contain spectra (see, e.g., References 3 and 4) and have the advantage that they may be representative of materials actually supplied. The annual *Laser Focus Buyers Guide*[5] usually contains a section devoted to transmission spectra of the more common optical crystals.

Density — Values are given for temperatures of 290 to 300 K and are principally from Reference 6.

Hardness — Hardness of crystals can vary with orientation. Average Knoop hardness numbers at room temperature or ranges of values are given. When known, the indentor load, in grams, is added in parentheses. In some cases only Vicker (V) or Moh hardnesses are reported. If the crystal is known to have a natural cleavage plane, this is denoted by a lower case letter in parentheses; planes are identified by a code given in the table caption. Data are from References 3 and 7 to 12.

Solubility — Solubility is defined as the weight loss in grams per 100 g of materials

Table 1.1.1.1
NAMES AND CHEMICAL FORMULAS OF CRYSTALS INCLUDED IN SECTION 1.1.1

Name	Formula
Aluminum oxide (corundum, Lucalox,[a] alumina)	Al_2O_3
Aluminum phosphate (berlinite)	$AlPO_4$
Aluminum silicate (mullite)	$Al_6Si_2O_{13}$
Ammonium dihydrogen phosphate (ADP)	$NH_4H_2PO_4$
Barium fluoride	BaF_2
Barium fluoride — calcium fluoride (T-12)[a]	BaF_2-CaF_2
Barium titanate	$BaTiO_3$
Beryllium aluminate (chrysoberyl)	$BeAl_2O_4$
Beryllium aluminum silicate (beryl)	$Be_3Al_2Si_6O_{18}$
Beryllium oxide	BeO
Beryllium silicate	Be_2SiO_4
Bismuth germanate (BGO)[b]	$Bi_4Ge_3O_{12}$
Bismuth germanate[b]	$Bi_{12}GeO_{20}$
Boron nitride	BN
Boron phosphide	BP
Cadmium chloride	$CdCl_2$
Cadmium fluoride	CdF_2
Cadmium iodide	CdI_2
Cadmium selenide	CdSe
Cadmium sulfide	CdS
Cadmium tellurite	CdTe
Calcium carbonate (calcite)	$CaCO_3$
Calcium fluoride	CaF_2
Calcium oxide	CaO
Calcium tungstate	$CaWO_4$
Carbon (diamond)	C
Cesium bromide	CsBr
Cesium chloride	CsCl
Cesium fluoride	CsF
Cesium iodide	CsI
Copper bromide (cuprous)	CuBr
Copper chloride (cuprous)	CuCl
Diamond	C
Gadolinium gallium garnet (GGG)	$Gd_3Ca_5O_{12}$
Gallium antimonide	GaSb
Gallium arsenide	GaAs
Gallium oxide	Ga_2O_3
Gallium phosphide	GaP
Germanium	Ge
Germanium oxide	GeO_2
Indium antimonide	InSb
Indium arsenide	InAs
Indium phosphide	InP
Irtran 1[a] (see magnesium fluoride)	
Irtran 2[a] (see zinc sulfide)	
Irtran 3[a] (see calcium fluoride)	
Irtran 4[a] (see zinc selenide)	
Irtran 5[a] (see magnesium oxide)	
Irtran 6[a] (see cadmium telluride)	
KDP (see potassium dihydrogen phosphate)	
KRS-5 (see thallium bromoiodide)	
KRS-6 (see thallium chlorobromide)	
Lanthanum beryllate	$La_2Be_2O_5$
Lanthanum fluoride	LaF_3
Lead chloride	$PbCl_2$

Table 1.1.1.1 (continued)
NAMES AND CHEMICAL FORMULAS OF CRYSTALS INCLUDED IN SECTION 1.1.1

Name	Formula
Lead fluoride	PbF_2
Lead molybdate	$PbMoO_4$
Lead oxide	PbO
Lead tungstate	$PbWO_4$
Lead selenide	PbSe
Lead sulfide	PbS
Lead telluride	PbTe
Lithium bromide	LiBr
Lithium chloride	LiCl
Lithium fluoride	LiF
Lithium iodide	LiI
Lithium iodate	$LiIO_3$
Lithium niobate	$LiNbO_3$
Lithium yttrium fluoride (YLF)	$LiYF_4$
Magnesium aluminate (spinel)	$MgAl_2O_4$
Magnesium fluoride	MgF_2
Magnesium oxide	MgO
Manganese fluoride	MnF_2
Manganese oxide	MnO
Mercury selenide	HgSe
Mercury sulfide	HgS
Mercury tellurite	HgTe
Mica (see potassium aluminosilicate)	
Potassium aluminosilicate (mica)	$KAl_3Si_3O_{10} \cdot (OH)_2$
Potassium bromide	KBr
Potassium chloride	KCl
Potassium dihydrogen phosphate (KDP)	KH_2PO_4
Potassium fluoride	KF
Potassium iodide	KI
Quartz (see silicon dioxide)	
Rubidium bromide	RbBr
Rubidium chloride	RbCl
Rubidium iodide	RbI
Ruby (see aluminum oxide)	
Sapphire (see aluminum oxide)	
Selenium	Se
Silicon	Si
Silicon carbide	SiC
Silicon dioxide (quartz)	SiO_2
Silicon nitride	Si_3N_4
Silver arsenic sulfide (proustite)	Ag_3AsS_3
Silver bromide	AgBr
Silver chloride	AgCl
Sodium bromide	NaBr
Sodium chloride	NaCl
Sodium fluoroaluminate (cryolite)	Na_3AlF_6
Sodium fluoride	NaF
Sodium iodide	NaI
Sodium nitrate	$NaNO_3$
Strontium fluoride	SrF_2
Strontium titanate	$SrTiO_3$
T-12[a] (see barium fluoride-calcium fluoride)	
Tantalum oxide	Ta_2O_5
Tellurium	Te
Tellurium oxide	TeO_2

Table 1.1.1.1 (continued)
NAMES AND CHEMICAL FORMULAS OF CRYSTALS INCLUDED IN SECTION 1.1.1

Name	Formula
Thallium bromide	TlBr
Thallium bromoiodide (KRS-5)	Tl(Br,I)
Thallium chloride	TlCl
Thallium chlorobromide (KRS-6)	Tl(Cl,Br)
Thorium oxide	ThO_2
Titanium dioxide (rutile)	TiO_2
Yttrium aluminum garnet (YAG)	$Y_2Al_5O_{12}$
Yttrium aluminum perovskite (YAP, YALO)	$YAlO_3$
Yttrium oxide (Yttralox)[a]	Y_2O_3
Yttrium vanadate	YVO_4
Zinc fluoride	ZnF_2
Zinc oxide	ZnO
Zinc selenide	ZnSe
Zinc sulfide	ZnS
Zinc telluride	ZnTe
Zirconium oxide (cubic zirconia, CZ)	ZrO_2
Zirconium silicate (zircon)	$ZrSiO_4$

[a] Polycrystalline.
[b] Both the 2:3 compound $Bi_4Ge_3O_{12}$ and the 6:1 compound $Bi_{12}GeO_{20}$ of the Bi_2O_3:GeO_2 system have sometimes been called bismuth germanate, bismuth germanium oxide, and BGO.

in H_2O, where the temperature in °C is given in parentheses. If the solubility is less than 10^{-3} g/100 g, the material is generally considered to be insoluble. Solubility data are from References 3, 6, 8, and 9.

Other references — Additional properties of many of the crystals in this section can be obtained from various volumes in the *Landolt-Börstein, New Series* (Springer, Berlin) and from the following sections of the *Handbook of Laser Science and Technology*:

- Volume I, Section 2.1.1 — Paramagnetic Ion Lasers
- Volume III, Section 1.1 — Nonlinear and Harmonic Generation Materials
- Volume IV, Section 1.4 — Polarizer Materials
- Volume IV, Section 2.1 — Linear Electrooptic Materials
- Volume IV, Section 2.4 — Photorefractive Materials
- Volume V, Section 1.5 — Laser Crystals