Handbook of Optical Constants of Solids, Volumes I, II, and III

SUBJECT INDEX AND CONTRIBUTOR INDEX

Indexed by

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FOREWORD TO THE SET

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Foreword

IVAN P. KAMINOW

INTRODUCTION

This set of five volumes (three volumes edited by Edward D. Palik, and accompanying index, and a volume by Gorachand Ghosh) is a unique resource for any science and technology library. It provides materials researchers and optical device designers with reference facts in a context not available elsewhere. The singular functionality of the set derives from the unique format for the three core volumes that comprise the *Handbook of Optical Constants of Solids (HOC)*. The *Handbook* satisfies several essential needs: First, it affords the most comprehensive database of the refractive index and extinction (or loss) coefficient of technically important and scientifically interesting materials. This data has been critically selected and evaluated by authorities on each material. Second, the dielectric constant database is supplemented by tutorial chapters covering the basics of dielectric theory and reviews of experimental techniques for each wavelength region and material characteristic. As an additional resource, two of the tutorial chapters summarize the relevant characteristics of each of the materials in the database.

The data in the core volumes have been collected and analyzed over a period of 12 years with the most recent completed in 1997. The volumes systematically define the dielectric properties of 143 of the most engaging materials, including metals, semiconductors, and insulators. Together, the three Palik books contain nearly 3000 pages, with about two-thirds devoted to the dielectric-constant data. The tutorial chapters in the remaining one-third of the pages contain a wealth of information, including some dielectric data. Hence, the separate volume, *Subject Index and Contributor Index,* which is included as part of the set, substantially enhances the utility of the Handbook and in essence, joins all the Palik volumes into one unit. This is of great importance to the users of the set.

A final volume rounds out the set. The *Handbook of Thermo-Optic Coefficients of Optical Materials with Applications* collects refractive-index measurements and their temperature dependence for a large number of crystals and glasses. Mathematical models represent these data, and in turn, are used in the design of nonlinear optical devices.

As I outline in more detail below, the community of materials researchers, spectroscopists, and optical device designers has reason to welcome this five-volume reference tool. The selected materials include all those of technical importance for the design of classical and photonic components. Every technical library will want this unique resource on its shelves.

HANDBOOK OF OPTICAL CONSTANTS OF SOLIDS

The optical constants referred to in the title above are the components of the complex dielectric constant

$$\epsilon = \epsilon_1 + i\epsilon_2 = (n + ik)^2.$$

To be specific, the refractive index *(n)* and the extinction (or loss) coefficient *(k)* are tabulated against wavelength. The defined optical range comprises wavelengths from millimeters (10^{-3}m) to angstroms (10^{-10}m), a potential seven-order span, although few materials have been measured over the full range. The solids include elemental metals and semiconductors, compound semiconductors, oxides and other insulators, even two liquids, mercury and water. For the most part, the solids are single crystals or polycrystalline thin films. Since thin films are sensitive to deposition conditions, the *Handbook* values are best taken only as a guide. Ideally, the films actually employed in an application should be measured directly. Glasses, which can vary widely in composition, are not included. An exception is the technologically important and chemically simple silica (SiO_2) glass.

Since the resonant modes or band structure of the medium define the spectral variation of dielectric constant, the dielectric constant is fundamental to other optical properties as well. In addition, the dielectric behavior is key to any device design. Hence, the constants in this *Handbook* are of interest to both condensed-matter scientists and optical-device designers in academics and industry. The wide spectral range covered by the databases for each material is essential for designing nonlinear optical interactions. Electro-optic modulation, second-harmonic generation, and four-wave mixing comprise as many as four widely-spaced discrete wavelengths.

Edward D. Palik edited the series, *Handbook of Optical Constants of Solids.* He spent most of his career as a materials researcher and spectroscopist at the Naval Research Laboratory in Washington, D.C. Since his retirement in 1988, he has been associated with the Institute for Physical Science and Technology of the University of Maryland at College Park. The format and goals set for *HOC* differ from traditional handbooks that tabulate measurements from the literature in narrow ranges of wavelength. Compilers of such tables tend to take the most recent data as most reliable, with the tacit assumption that the ultimate user will eventually check the original sources for reliability. It certainly is a good idea for the user to confirm the original source, especially if accuracy is essential to his purpose. However, many users are not sufficiently expert in the measurement and materials fields to make a valid judgment, and those who are qualified may not have the time or resources to gather and evaluate data from the widespread literature. The plan of *HOC* is to select experts in the experimental techniques peculiar to each spectral range and class of materials, and have them review those methods. Other experts summarize the relevant theory of dielectrics. Finally, a group of materials experts each survey, or critique, the literature for a particular material, selecting the best data in the widest possible spectral range for the tables.

HOC I

The format of the first volume (832 pages) in the set, *HOC I,* follows this plan with 11 tutorial chapters on basic theory and measurement methods, and 28 critiques covering 37 specific materials. Examples of measurement methods include vacuum ultraviolet reflectivity, ellipsometry, thin-film techniques, and techniques for the millimeter range. The critiques evaluate, combine, and present measurements from diverse sources. They cover 13 metals, including aluminum, platinum, gold, silver, copper, and tungsten; 14 semiconductors, including silicon (both crystalline and amorphous, used in solar cells and imaging tubes), germanium, gallium arsenide and indium phosphide (employed in lasers and photodiodes), and cadmium telluride; and 12 insulators, including diamond, lithium fluoride, lithium niobate (used in electro-optic modulators and harmonic generators), silicon dioxide (both crystalline and glass, used in optical fiber and planar waveguides), silicon nitride, and sodium chloride. The measurements are generally at a nominal "room temperature." The "critiquers" are careful to account for their choices of data and to explain the limitations in precision and accuracy. The tabulated values of n and k may have been measured directly or may have been derived from Kramers–Kronig relations or from Sellmeier models or other representations of the wavelength dispersion in the dielectric material. The measurements are given in both graphical and tabular forms, along with the mathematical representations. Each format has its own uses: The graphs show at a glance where the resonances, or band edges, and loss peaks occur, and where the transmission windows can be found. The tables allow precise numbers to be read off or interpolated. And the mathematical models allow the materials to be represented in computer simulations. The positions and shapes of resonance peaks may also be compared with spectroscopic measurements, such as infrared absorption, and Raman and Brillouin scattering.

HOC II

The second volume (1120 pages), *HOC II,* continues the original format. The 14 tutorial chapters elucidate "convention confusions" and basics in dielectrics, as well as review the attenuated-total-reflection method, measurements in the ultraviolet and x-ray regions, and calculations of n and k in semiconductors. A tabulation of handy parameters characterizing the materials in *HOC I* and *HOC II* is also included among the tutorials. These parameters comprise crystal structure, symmetry class, irreducible representations for acoustic and optic modes plus their resonance frequencies, plasma frequency for metals, band-gap energy for semiconductors, and dc dielectric constant. The 41 critiques cover 13 metals, including the alkalis, chromium, iron, niobium, tantalum, beryllium, graphite, and mercury; 14 semiconductors, including aluminum gallium arsenide (used in lasers and photodiodes), silicon-germanium alloys, lead tin telluride (used in infrared imaging), selenium, tellurium, and β-silicon carbide; and 19 insulators, including aluminum oxide (a popular coating in optical devices), barium titanate, beryllium oxide (an electrical insulator and good thermal conductor), magnesium fluoride, potassium dihydrogen phosphate plus isomorphs (used as electro-optic switches and harmonic generators in high-power applications), strontium titanate, polyethylene (a common infrared window material and the only polymer in the *Handbook*), and water. The water tabulation takes the prize for widest spectral range, spanning nine orders from 10^{-8}m (100Å) to 10m (30MHz).

HOC III

A new volume (1024 pages), *HOC III,* includes materials missing from the earlier volumes and updates measurements included in those volumes. The tutorial chapters also fill some gaps, including discussions of far-infrared measurements by Fourier transform spectroscopy, photothermal techniques to determine the extinction coefficient, the application of Brillouin scattering to determine optical constants in otherwise difficult circumstances, and theory and measurements of doped n-silicon. A chapter on handy optical parameters for the materials in *HOC I, II,* and *III* supplements the corresponding tabulation in *HOC II.* The 39 critiques cover 19 metals, including titanium, indium, tin, and cesium; 8 rare earths, including erbium; 23 semiconductors (loosely defined), including updates for undoped silicon and silicon-germanium alloys, numerous nitrides, bismuth germanium oxide (a popular nonlinear crystal), chalcopyrites like cadmium germanium arsenide and silver gallium selenide, silver halides (used in photographic film), zinc phosphide, and zinc arsenide; and 17 insulators, including an extensive update of aluminum oxide, barium fluoride, strontium fluoride, calcite (a natural birefringent crystal used for waveplates and polarizers), cesium halides, lead fluoride, lithium tantalate (an efficient electro-optic and acousto-optic crystal), potassium niobate (a nonlinear optics crystal), sulfur, thallium halides, yttrium aluminum garnet (the host for Nd:YAG lasers), and zircon (a gemstone).

HANDBOOK OF THERMO-OPTIC COEFFICIENTS OF OPTICAL MATERIALS WITH APPLICATIONS

The *Handbook of Thermo-Optic Coefficients* by Gorachand Ghosh of the Electrotechnical Laboratory of MITI in Tskuba, Japan is an excellent companion to the *HOC.* The Ghosh tables are a bonus for those in need of additional and/or corroborating (real) refractive index numbers. He has determined Sellmeier coefficients for some 70 technologically interesting crystals, some that are found in *HOC,* and others found in commercial glasses by fitting to published experimental results. He tabulates the results over a wide range of wavelengths, comparing theory and experiment. In addition, he presents tables of the thermo-optic coefficient (dn/dT) for these materials. Finally, he presents mathematical expressions for n as a function of wavelength and temperature. With these representations, he is able to define design criteria for a number of temperature-dependent nonlinear components. They include phase-matched parametric mixing devices, a thermo-optic switch, and an optical-fiber temperature sensor.

CONCLUSION

The three volumes of *HOC* distill measurements of the optical constants of some 143 materials, including 43 elements. By self-selection, most of the materials of industrial or academic importance are included. These materials are employed as gemstones; as classical optics components, such as windows, lenses, waveplates, and polarizers; and in photonic devices such as lasers, modulators, and nonlinear media. If a material has useful or exceptional optical properties, and if it can be produced in a robust and pure form, its optical constants will surely be thoroughly measured. Most of them are scrutinized in *HOC.* Those materials not yet included in *HOC* only await qualified critiquers willing to devote the effort to analyze them for a chapter to be included in a possible *HOC IV.*

For the convenience of libraries and researchers, all three volumes of *HOC* are offered as a set. In addition, two valuable supporting volumes are included in the set: the *Handbook of Optical Constants of Solids, Volume I, II, and III: Subject Index and Contributor Index* and the *Handbook of Thermo-Optic Coefficients of Optical Materials with Applications.* These five books will be an invaluable addition to any researcher's library.

April, 1997 IVAN P. KAMINOW

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