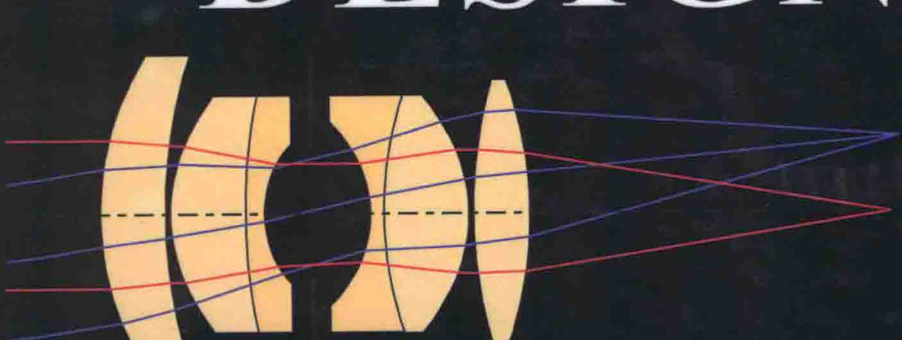
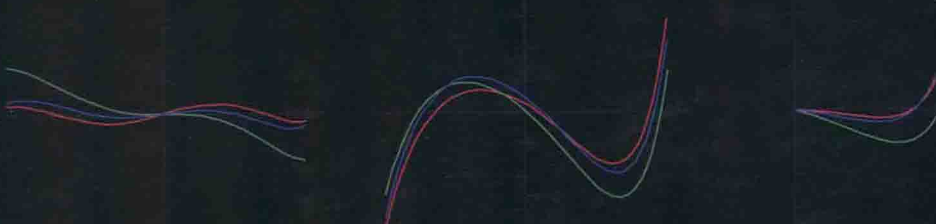
Daniel Malacara-Hernández
Zacarías Malacara-Hernández

THIRD EDITION

Handbook of OPTICAL DESIGN





CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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CRC Press is an imprint of Taylor & Francis Group, an Informa business

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Printed in the United States of America on acid-free paper
Version Date: 20121003

International Standard Book Number: 978-1-4398-6799-0 (Hardback)

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Library of Congress Cataloging-in-Publication Data

Malacara, Daniel, 1937-
Handbook of optical design / Daniel Malacara-Hernández and Zacarias Malacara.
-- 3rd ed.
p. cm. -- (Optical science and engineering)
Includes bibliographical references and index.
ISBN 978-1-4398-6799-0 (hardback)
1. Lenses--Design and construction--Handbooks, manuals, etc. 2. Mirrors--Design and construction--Handbooks, manuals, etc. 3. Optical instruments--Design and construction--Handbooks, manuals, etc. I. Malacara, Zacarias, 1948- II. Title.

QC385.2.D47M35 2013
681'.42--dc23 2012031496

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Preface to the Third Edition

The first two editions of this book had been extensively used by our students in several lens design courses since its first publication. This experience has allowed us to improve the book in every new edition. In this third edition, several important modifications have been made.

To make the figures clearer and attractive, all of them have been redrawn in color. The book has been updated in many aspects to include the results in many important publications in the last few years. New material suggested by our students and several readers has been included. Additional new references have been added to include some of the new most important publications, in order to make the book more complete and up to date.

Additional material has been added. We will mention only a few examples. Buchdahl high-order aberrations are described. The section on the calculation of wavefront aberrations based on optical path has been enlarged and improved. Most of the optical systems mentioned here have been redesigned using the new available glasses. The lists of optical materials in the appendix had been updated. The description of the primary aberrations has been made clearer and more detailed.

We would like to thank our friends and students who used the previous edition of this book. In particular, we would like to thank the great help and support of Dr. Armando Gomez-Vieyra.

Daniel Malacara-Hernández
Zacarías Malacara-Hernández

Preface to the Second Edition

The first edition of this book was used by our students in a lens design course for several years. Taking advantage of this experience, this second edition has been greatly improved in several aspects.

Most of the material in the original second chapter was considered quite important and useful as a reference. However, to make an introductory course on lens design more fluid and simple, most of the material was transferred to the end of the book as an appendix. In several other sections, the book was also restructured with the same objective in mind.

Some of the modifications introduced include the clarification and a more complete explanation of some concepts, as suggested by some readers. Additional material was written, including additional new references to make the book more complete and up to date. We will mention only a few examples. Some gradient index systems are now described in greater detail. The new wavefront representation by means of arrays of Gaussians is included. The Delano diagram section was enlarged. More details on astigmatic surfaces with two different curvatures in orthogonal diameters are given.

We would like to thank our friends and students who used the previous edition of this book. They provided us with many suggestions and pointed out a few typographical errors to improve the book.

Daniel Malacara-Hernández
Zacarías Malacara-Hernández

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Preface to the First Edition

This is a book on the general subject of optical design, aimed at students in the field of geometrical optics and engineers involved in optical instrumentation. Of course, this is not the first book in this field. Some classic, well-known books are out of print, however, and lack any modern topics. On the other hand, most modern books are generally very restricted in scope and do not cover important classic or even modern details.

Without pretending to be encyclopedic, this book tries to cover most of the classic aspects of lens design and at the same time describes some of the modern methods, tools, and instruments, such as contemporary astronomical telescopes, Gaussian beams, and computer lens design.

Chapter 1 introduces the reader to the fundamentals of geometrical optics. In Chapter 2, spherical and aspherical optical surfaces and exact skew ray tracing are considered. Chapters 3 and 4 define the basic concepts for the first- and third-order theory of lenses, while the theory of the primary aberrations of centered optical systems is developed in Chapters 5 to 7. The diffraction effects in optical systems and the main wave and ray methods for lens design evaluation are described in Chapters 8, 9, and 10. Chapters 11 to 17 describe some of the main classic optical instruments and their optical design techniques. Finally, Chapter 18 studies the computer methods for optical lens design and evaluation.

In conclusion, not only is the basic theory treated in this book, but many practical details for the design of some optical systems are given. We hope that this book will be useful as a textbook for optics students, as well as a reference book for optical scientists and engineers.

We greatly acknowledge the careful reading of the manuscript and suggestions to improve the book by many friends and colleagues. Among the many friends we would like to mention are Prof. Raúl Casas, Manuel Servín, Ricardo Flores, and several of our students. A generous number of members of the research staff from Optical Research Associates provided wonderful help with many constructive criticisms and suggestions. Their number is large and we do not want to be unfair by just mentioning a few names. We also acknowledge the financial support and enthusiasm of the Centro de Investigaciones en Optica and its general director Arquímedes Morales. Last, but not least, the authors greatly acknowledge the encouragement and understanding of our families. One of the authors (D.M.) especially thanks his sons Juan Manuel and Miguel Angel for their help with many of the drawings and the word processing of some parts.

Daniel Malacara-Hernández
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1 Geometrical Optics Principles

1.1 WAVE NATURE OF LIGHT AND FERMAT'S PRINCIPLE

The nature of light is one of the most difficult concepts in modern physics. Because of its quantum nature, light has to be considered in some experiments as an electromagnetic wave and in others as a particle. However, in ordinary optical instruments, we may just think of light as an electromagnetic wave with an electric field and a magnetic field, mutually perpendicular, and both perpendicular to the path of propagation. If the light beam is plane (linearly) polarized, the electric and the magnetic fields have a constant fixed orientation, changing only in magnitude and sign as the wave propagates. The electric and magnetic fields are in phase with each other, as shown in Figure 1.1. This is the simplest type of wave, but we may find more complicated light beams, where the electric and magnetic fields do not oscillate in a fixed plane. The different manners in which the fields change direction along the light trajectory are called polarization states. It is shown in any physical optics textbook that any polarization state may be considered as a superposition of two mutually perpendicular plane-polarized light beams. The type of polarization depends on the phase difference between the two components and on their relative amplitudes as explained in most physical optics textbooks. The frequency ν and the wavelength λ of this wave are related by the speed of propagation v as follows:

$$\lambda\nu = v \tag{1.1}$$

Light waves with different frequencies have different colors, corresponding to certain wavelengths in the vacuum. In lens design, the frequencies (or corresponding wavelengths in the vacuum) for the solar Fraunhofer lines are used to define the color of the light. These lines are shown in Table 1.1.

Along the path of propagation of a light beam, the magnitude E of the electric field may be written as

$$E = A \exp i(ks - \omega t) = A \exp i(\phi - \omega t) \tag{1.2}$$

where A is the amplitude of the wave, k is the wavenumber, defined by $k = 2\pi/\lambda$, and ω is the angular frequency, defined by $\omega = 2\pi\nu$. The wavelength is represented by λ and the frequency by ν. In this expression, s is the distance traveled along the light path, ϕ is the phase difference between the point being considered and the origin, and $\phi - \omega t$ is the instantaneous phase, assuming that it is zero at the origin for $t = 0$.

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