Lenses are used in a great variety of applications, ranging from photography to fiberoptic communications systems. This book is a comprehensive introduction to lens design, covering the fundamental physical principles and key engineering issues. It describes clearly how to carry out the design of a lens, from the initial layout to the final analysis and tolerance evaluation. In illustrating this process, several practical examples of modern computer-aided lens design are worked out in detail from start to finish.

The basic theory and results of geometrical and physical optics are presented early on in the book, along with a discussion of optical materials. Aberrations, and their correction, and image analysis are then covered in great detail. Subsequent chapters deal with design optimization and tolerance analysis. Several design examples are then given, beginning with basic lens design forms, progressing to zoom and aspheric lenses, and to advanced systems, such as gradient index and diffractive optical components.

In covering all aspects of optical design, from the fundamental physical principles through to the use of modern lens design software, this book will be invaluable to students of optical engineering as well as to anyone engaged in optical design at any stage.

THE ART AND SCIENCE OF OPTICAL DESIGN

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To Helen,
the light of my life,
and
the focus of my endeavors.

CONTENTS

PREFACE

The purpose of this book is to provide an introduction to the practice of lens design. As the title suggests, successful design will require the application of individual creativity as well as artful manipulation and thorough comprehension of the numeric tools available in lens design programs. The technology, user connection, and breadth of the commercial lens design programs have reached a very high level. The availability of inexpensive, high-speed personal computers and user-friendly operating systems has brought the computational tools within economic reach of any individual.

This book covers the basics of image formation, system layout, and image evaluation, and contains a number of examples of lens designs. There are several excellent books in existence that are principally a compilation of the results of the design of several types of lenses. In this book, it is my intention to describe the process rather than the results. The explanations of the basics are provided here in a practical manner and in a level of detail sufficient to provide an understanding of the principles. The selected examples of designs include a narrative of the thinking and approach toward the decisions that need to be made by the designer when carrying out the work. The principles are, of course, independent of the software used. Each example shown does provide the opportunity to exploit different avenues of approach to the design.

Several different lens design programs have been used to provide the majority of the illustrations in this book. All of the programs can handle most of the problems posed in this book, but of course in somewhat different ways. The capabilities of the programs do, of course, differ, and some programs will be easier to use for a specific purpose than others. The selection of the programs for a given purpose was almost random, but knowledge of the program properties did play some role. The reader is not to presume that any program is better in certain operations or different from the others except as may specifically be mentioned in the text. In general one or another program is used consistently for a specific design example, although in some cases it is useful to show the same or similar data as it appears from different programs. In order to give credit to the software supplier, the source of the information

used in each figure will be identified with the program. In several cases, to improve clarity within the page space limitations of this book, the graphical output of the program has been rearranged to retain just the significant information.

It is important to note the following. CODE V® is a trademark of Optical Research Associates Inc.; OSLO® is a trademark of Sinclair Optics, Inc.; ZEMAX® is a trademark of Focus Software, Inc.; Excel® is a trademark of Microsoft Inc. The programs used were in versions current in 1995.

There are so many possible optical design problems in existence today that only a few examples can be covered in a single book. The exposition of the principles and approaches discussed here will serve as a basis for a designer exploring other regions of design space. I hope that this book is helpful in conveying the reasons why lens design is done the way it is, and that it provides insight helpful for any designer or design student to understand how to go about the process of lens design.

Tucson, Arizona; January 1996

ACKNOWLEDGMENTS

Any individual depends more on the knowledge and encouragement that he or she gains from those around him or her than often seems the case. I am no exception in this regard. My first introduction to lens design occurred at the Institute of Optics at the University of Rochester in the 1950s. Lens design was just moving from tedious hand calculation toward the broad and interesting field that computers have made possible. I was fortunate to have the opportunity to learn the practical aspects of design from Professor Robert Hopkins, who properly saw the possibilities engendered in the new resources of digital computers. His influence can be seen in many of the ideas and explanations that appear in this book. The basic theory of aberrations was at that time taught by Professor Rudolf Kingslake. The solidity of his organization of the subject served as a basis for understanding much of what goes on inside a lens.

Following education at Rochester, I spent a fascinating decade at Itek Corporation in Lexington, Massachusetts. During that time, the applications of lenses to many topics, including high altitude photographic reconnaissance, began to explode. I am grateful to such people as F. Dow Smith and Richard W. Philbrick for encouraging and permitting me to spend my career in industry in the many interesting projects that provided much practical experience in the design and fabrication of optical systems. During that time I benefited greatly from association with such now well-known colleagues in the business as Edward O'Neill, Berge Tatian, Robert Hilbert, Richard Forkey, Richard Barakat, and many others who provided an opportunity to understand the different aspects of the total system problem.

A special note needs to be made of the contributions of the late H. H. Hopkins, who during this time taught me much about the basic theory of image formation. Conversations with Dave Grey and Warren Smith added much to my understanding of the theoretical and practical basis of lens design.

A move, in 1969, to the then new and growing Optical Sciences Center at the University of Arizona provided a new opportunity. Not only did I have to work on design problems, I had to learn to explain to students how to do

design. This provided many new, and frequently unexpected, challenges. Since beginning at Arizona, more than 300 students have been through the two-course sequence of design offered at the Optical Science Center. I have also been the supervisor to forty-five PhD and MS students. All of these students contributed to my education in the subject as I did to theirs. I have to especially thank my faculty colleagues at the Center for discussions and insight provided over the years. In particular, Aden Meinel, James Wyant, Roland Shack, William Wolfe, George Lawrence, and John Greivenkamp are to be particularly thanked.

Within this book, several different lens design programs are used to describe the process of design. The program suppliers have been extremely generous in permitting me to have access to their product, and have made the programs freely available over the years to the students in the design courses at the Optical Sciences Center. I wish to express extreme gratitude to Robert Hilbert, Tom Harris, Chuck Rimmer, Rick Juergens, and others at Optical Research Associates for access to CODE V. Doug Sinclair at Sinclair Optics has provided access to successive versions of the OSLO series of programs. Ken Moore of Focus Software has made available up-to-date versions of the ZEMAX program. In addition, Michael Kidger provided access to his Sigma program, and Don Dilworth to his SYNOPSYS program. These companies and individuals constitute the state of the art in the optical design software business, and have been instrumental in providing the opportunity for a wide variety of engineers and scientists to participate in the process of lens design. These programs are continuously changing, and the versions next year will undoubtedly be even better than those of today.

Credit for getting me interested in writing a book goes to Beatrice Shube, a good friend for many years. At Cambridge University Press, Simon Capelin and Philip Meyler provided the opportunity to convert thoughts into printed material. The excellent work by Richard Cook and others at Keyword Publishing Services, Ltd is gratefully acknowledged.

Finally, I must express the deepest thanks to my family. Betsy, Barbara, Jennifer, Amy, John, and Rob provided the stimulus to find a productive and profitable career. But beyond that, they made, and still make, life fun. Without the constant encouragement, friendly criticism, and willing partnership of my wife, Helen Lang Shannon, none of this would have been possible.