Optical Design Fundamentals for Infrared Systems

Second Edition

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Max J. Riedl

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Arthur R. Weeks, Jr., Series Editor
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Introduction to the Series

The Tutorial Texts series was initiated in 1989 as a way to make the material presented in SPIE short courses available to those who couldn't attend and to provide a reference book for those who could. Typically, short course notes are developed with the thought in mind that supporting material will be presented verbally to complement the notes, which are generally written in summary form, highlight key technical topics, and are not intended as stand-alone documents. Additionally, the figures, tables, and other graphically formatted information included with the notes require further explanation given in the instructor's lecture. As stand-alone documents, short course notes do not generally serve the student or reader well.

Many of the Tutorial Texts have thus started as short course notes subsequently expanded into books. The goal of the series is to provide readers with books that cover focused technical interest areas in a tutorial fashion. What separates the books in this series from other technical monographs and textbooks is the way in which the material is presented. Keeping in mind the tutorial nature of the series, many of the topics presented in these texts are followed by detailed examples that further explain the concepts presented. Many pictures and illustrations are included with each text, and where appropriate tabular reference data are also included.

To date, the texts published in this series have encompassed a wide range of topics, from geometrical optics to optical detectors to image processing. Each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the processes and technologies under discussion.

During the past nine years, my predecessor, Donald C. O'Shea, has done an excellent job in building the Tutorial Texts series, which now numbers nearly forty books. It has expanded to include not only texts developed by short course instructors but also those written by other topic experts. It is my goal to maintain the style and quality of books in the series, and to further expand the topic areas to include emerging as well as mature subjects in optics, photonics, and imaging.

Arthur R. Weeks, Jr.
Invivo Research Inc. and University of Central Florida

Once more, to Hermine, Renee, Jim, Bryan, and Stephanie.

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Chapter 5. Special Optical Surfaces and Components

Chapter 6. Design Examples

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Chapter 9. Image Evaluation

PREFACE TO THE SECOND EDITION

The many positive remarks about the first edition and listening to the feedback from the students over the past five years encouraged me to expand upon the original material in this second edition.

To that end, the subject of beam expanders was modified, and achromats have been covered in more detail. In a chapter on Special Optical Surfaces and Components, the ball lens, gradient optics, and three-mirror configurations have been added.

New chapters are Wave Aberrations, Thermal Effects, Design Examples, and Diamond Turning. In Wave Aberrations, besides the concept, comparison of spherical aberration with the Seidel coefficient is discussed. The chapter Thermal Effects deals with methods of designing athermats, lenses that compensate for the undesired results caused by temperature excursions. The chapter Design Example is an application-based summary of the subjects covered in the earlier chapters of the book. Because diamond turning is especially suitable for producing aspheres and diffractive infrared elements, a chapter has been added to describe this manufacturing method.

To follow the style of the first edition, the added material contains practical approaches with approximations and many numerical examples.

I thank Rick Hermann and Sharon Streams of SPIE for their support and editorial assistance. I also thank my friend and colleague Robert E. Fischer for reviewing this second edition. His suggestions have been most valuable.

Max J. Riedl
February 2001

PREFACE TO THE FIRST EDITION

This tutorial is intended to provide a basic approach to the optical design of infrared systems. It is written for systems engineers whose expertise is outside the field of optics. The material presented can be applied directly to the initial optical system layout phase to evaluate trade-offs of various configurations. It will also be very helpful in conveying requirements and expectations to an experienced lens designer.

Over the past decades, much emphasis has been placed on the use of computers in lens design. Powerful programs developed for the lens designer have made it possible to explore new and different approaches for finding better solutions to optical design challenges. Unfortunately, the process of using computers to perform the required calculations is often referred to as *automatic lens design*. But to obtain a sensible optical system, one that is practical to manufacture and meets cost-related and other special demands, the starting configuration must have a chance to meet those demands.

Optimization programs only succeed in finding the best available solution from local conditions. Therefore, it is important to start in the right neighborhood. To identify this neighborhood—a promising starting point—is one of the goals of this tutorial text.

Designing lenses for the infrared region is in some ways easier than working in the visible spectrum, since the wavelengths are longer, the index of refraction of most lens materials is higher, and their relative dispersion is lower. This generally results in smaller primary aberrations. Third-order aberration calculations are often sufficient to predict meaningful performance expectations even if the system is simplified to a set of thin lenses. (lenses with zero thickness). The fact that the diffraction limit is 10 to 20 times larger in the infrared than in the visible region adds to the usefulness of applying third-order aberration theory.

Most of the materials used for infrared lenses and mirrors lend themselves to single-point diamond turning. For that reason, aspheric and diffractive surfaces are routinely employed since they are no more difficult to generate by this method than spherical surfaces and offer to the correction of aberrations. Aspheric and diffractive surfaces are discussed in detail and are also treated in several numerical examples.

Throughout this tutorial text, much emphasis has been placed on the practical aspect of the material presented. This is reflected by the many approximations that yield useful answers—especially welcomed during the proposal stage when time and resources are usually scarce.

This book is organized to follow the flow of radiant energy from the source to the detector. This flow is expressed with a simplified radiometric equation whose components identify the major contributors to overall system performance.

While a great deal of material is covered, details had to be limited. It is hoped that what is presented will be of value not only in the predesign stages of infrared systems, but also as a stimulus to dig deeper into the existing literature of this exciting field.

The material presented is a collection of notes from early in-house engineering seminars that led eventually to a more formally structured presentation as part of the SPIE short-course program. Much of what I am sharing in these pages is based on my long-time professional and personal association with Warren J. Smith, who along with Donald C. O'Shea reviewed the manuscript, and Lowell L. Baskins. My special thanks go to the reviewers for their substantial help; their comments and suggestions greatly improved the quality of the text.

Max J. Riedl
October 1995

HISTORICAL REMARKS

It was 200 years ago that Sir William Herschel, the Royal Astronomer to King George III, made his famous discovery. He wanted to find some protection for his eyes while looking into the sun. In his experiments he noticed an increased response as he scanned the thermometer from the blue end of the spectrum toward the red. This was not new; it had been done before. However, when he moved the thermometer into the dark portion beyond the red, where his eyes could not perceive any light, he noticed that the heat effect increased. That is the region we now call *the infrared region.*

Over the years, the thermometer was replaced by other detectors.[1] In 1829, the first thermopile was introduced by Nobili, which was improved four years later by Melloni. During the 1880s, several more sensitive detectors were developed. Most notable was the Langley bolometer, which was about 30 times more sensitive than Melloni's thermopile. In 1917, Case developed the first photoconductive detector, using thallous sulfide.

An interesting discovery occurred during the 1930s at the Institute of Physics at Berlin, when Kutzscher experimented with lead sulfide crystals he had found in Italy. Accidentally he noticed that these crystals were infrared sensitive.[2] This discovery led eventually to an infrared search and tracking device.

In 1952, the U.S Army built the first scanning thermal imagers, which were called *thermographs.*[3] With the development of cooled short-time-constant indium antimonide (InSb) and mercury doped germanium (Ge:Hg) photodetectors in the late 1950s, the first fast framing sensors appeared, and in 1956 the first long wavelength FLIR was built at the University of Chicago.

Now, the technology has advanced to a point where thermal imagers and other infrared devices have found their place in many applications other than military functions. These applications range from medical, border control, safety and security, telecommunication, forensic investigations, and many more.

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