Tutorial Texts Series

- Fundamentals of Polarimetric Remote Sensing, John Schott, Vol. TT81
- Matrix Methods for Optical Layout, Gerhard Kloos, Vol. TT77
- Fundamentals of Infrared Detector Materials, Michael A. Kinch, Vol. TT76
- Bioluminescence for Food and Environmental Microbiological Safety, Lubov Y. Brovko, Vol. TT74
- Introduction to Image Stabilization, Scott W. Teare, Sergio R. Restaino, Vol. TT73
- Introduction to Confocal Fluorescence Microscopy, Michiel Müller, Vol. TT69
- Artificial Neural Networks: An Introduction, Kevin L. Priddy and Paul E. Keller, Vol. TT68
- Basics of Code Division Multiple Access (CDMA), Raghuveer Rao and Sohail Dianat, Vol. TT67
- Optical Imaging in Projection Microlithography, Alfred Kwok-Kit Wong, Vol. TT66
- Metrics for High-Quality Specular Surfaces, Lionel R. Baker, Vol. TT65
- Field Mathematics for Electromagnetics, Photonics, and Materials Science, Bernard Maxum, Vol. TT64
- High-Fidelity Medical Imaging Displays, Aldo Badano, Michael J. Flynn, and Jerzy Kanicki, Vol. TT63
- Diffractive Optics—Design, Fabrication, and Test, Donald C. O’Shea, Thomas J. Suleski, Alan D. Kathman, and Dennis W. Prather, Vol. TT62
- Thin-Film Design: Modulated Thickness and Other Stopband Design Methods, Bruce Perilloux, Vol. TT57
- Optische Grundlagen für Infrarotsysteme, Max J. Riedl, Vol. TT56
- An Engineering Introduction to Biotechnology, J. Patrick Fitch, Vol. TT55
- Image Performance in CRT Displays, Kenneth Compton, Vol. TT54
- Modulation Transfer Function in Optical and Electro-Optical Systems, Glenn D. Boreman, Vol. TT52
- Fundamentals of Antennas, Christos G. Christodoulou and Parveen Wahid, Vol. TT50
- Basics of Spectroscopy, David W. Ball, Vol. TT49
- Resolution Enhancement Techniques in Optical Lithography, Alfred Kwok-Kit Wong, Vol. TT47
- Copper Interconnect Technology, Christoph Steinbrüchel and Barry L. Chin, Vol. TT46
- Fundamentals of Contamination Control, Alan C. Tribble, Vol. TT44
- Evolutionary Computation: Principles and Practice for Signal Processing, David Fogel, Vol. TT43
- Infrared Optics and Zoom Lenses, Allen Mann, Vol. TT42
- Introduction to Adaptive Optics, Robert K. Tyson, Vol. TT41
- Fractal and Wavelet Image Compression Techniques, Stephen Welstead, Vol. TT40
- Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis, Valery Tuchin, Vol. TT38
Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to more than 80 titles covering many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, 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 would 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 science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University
# Contents

Preface................................................................................................................. xi

1. System Considerations................................................................................... 1

   1.1 Radiometry .................................................................................................. 1
     1.1.1 Blackbody radiation .............................................................................. 1
     1.1.2 Planck’s equation ................................................................................. 1
     1.1.3 Stefan-Boltzmann law .......................................................................... 2
     1.1.4 Wien displacement law ........................................................................ 2

   1.2 Atmospheric Transmission .......................................................................... 3
     1.2.1 Scattering ............................................................................................. 3
     1.2.2 Absorption ............................................................................................ 4
     1.2.3 Infrared windows .................................................................................. 4
     1.2.4 Computer calculation ........................................................................... 4

   1.3 Lens Transmission ...................................................................................... 5

   1.4 Coatings ...................................................................................................... 7
     1.4.1 Single-layer coatings ............................................................................ 7
     1.4.2 Multilayer coatings ............................................................................... 8

   1.5 Infrared Detectors ....................................................................................... 9
     1.5.1 Basic relations ...................................................................................... 9
     1.5.2 Types ................................................................................................... 9
     1.5.3 Arrays ................................................................................................. 11
     1.5.4 Matching the detector with the optics ................................................ 11

   1.6 References ................................................................................................ 12

2. Optics Fundamentals .................................................................................... 13

   2.1 Lens Equation ........................................................................................... 13
   2.2 Stops and Pupils ....................................................................................... 13
   2.3 Optical Formulas ....................................................................................... 15
   2.4 Optical Performance Criteria ..................................................................... 16
   2.5 Telescopes ................................................................................................ 17
   2.6 Primary Aberrations .................................................................................. 19
     2.6.1 Definition of the Seidel aberrations.................................................... 19
     2.6.2 Variation of primary aberrations with aperture and field height ...... 19
     2.6.3 Stop shift equations ........................................................................... 20
   2.7 Achromatism ............................................................................................. 21
     2.7.1 Primary achromatism ......................................................................... 21
     2.7.2 Secondary spectrum .......................................................................... 22
   2.8 Principal Planes ........................................................................................ 22
2.9 Problems ................................................................................................... 24
2.10 References .............................................................................................. 24

3. Unique Features of the Infrared Region ...................................................... 25

3.1 Optical Materials ....................................................................................... 25
  3.1.1 Materials for the infrared .................................................................... 25
  3.1.2 Calculation of index of refraction ....................................................... 27
3.2 Thermal Compensation ............................................................................. 28
  3.2.1 Focus shift with temperature .............................................................. 28
  3.2.2 Athermalization .................................................................................. 28
  3.2.3 Athermalization methods ................................................................... 29
3.3 Cold Stop and Cold Shield ........................................................................ 30
3.4 Narcissus .................................................................................................. 30
  3.4.1 Types of retroreflections .................................................................... 30
  3.4.2 Reduction techniques ........................................................................ 30
3.5 Glass Substitution ..................................................................................... 31
3.6 References ................................................................................................ 32

4. Optical Design Techniques .......................................................................... 35

4.1 Optical Design Starting Point .................................................................... 35
4.2 Scaling ...................................................................................................... 35
4.3 Optical Materials Selection ....................................................................... 37
4.4 Techniques for Compactness ..................................................................... 37
4.5 Symmetry Principle ................................................................................... 37
4.6 Bending ..................................................................................................... 38
4.7 Aplanatic Condition ................................................................................ 38
4.8 Adding an Element ................................................................................... 39
4.9 Field Lens Utilization ................................................................................. 39
4.10 Conics and Aspheres .............................................................................. 40
4.11 Diffractive Surfaces ................................................................................. 41
4.12 Aperture Stop Location .......................................................................... 41
4.13 Computer Optimization ........................................................................... 41
4.14 Global Search .......................................................................................... 42
4.15 Tolerances .............................................................................................. 44
4.16 References .............................................................................................. 44

5. Zoom Lenses ................................................................................................. 45

5.1 Types of Zoom Lenses .............................................................................. 45
  5.1.1 Optically compensated zoom lens ..................................................... 45
  5.1.2 Mechanically compensated zoom lens ............................................. 48
5.2 Infrared Zoom Lens Specifications ........................................................... 50
  5.2.1 Spectral region ................................................................................... 51
  5.2.2 Optical system performance .............................................................. 51
  5.2.3 Aperture ............................................................................................. 51
  5.2.4 Effective focal length ........................................................................ 51
  5.2.5 Magnification range .......................................................................... 51
  5.2.6 Size constraints ................................................................................ 51
  5.2.7 Operating environment ...................................................................... 51
  5.2.8 Distortion ........................................................................................... 52
5.2.9 Transmission ................................................................. 52
5.2.10 Narcissus ................................................................. 52
5.2.11 Vignetting ................................................................. 52
5.3 Extenders .......................................................................... 52
5.4 References ......................................................................... 53

6. Refractive Infrared Zoom Lenses ........................................ 55

6.1 Target Simulators .............................................................. 55
6.1.1 CI Systems ................................................................. 55
6.1.2 Hughes Aircraft Company .............................................. 56
6.1.3 Lockheed Martin .......................................................... 60
6.1.4 Optics 1 ................................................................. 63

6.2 Scanning Systems ............................................................. 65
6.2.1 Barr & Stroud .............................................................. 65
6.2.2 Pilkington P.E. ............................................................. 67
6.2.3 Optics 1 ................................................................. 70
6.2.4 Precision-Optical Engineering ........................................... 71
6.2.5 Zhejiang University, Department of Optical Engineering ........ 73
6.2.6 Electrooptical Industries, Ltd. ........................................... 74

6.2.7 Scotoptix ................................................................. 76
6.2.7.1 Boresighted zoom lens .............................................. 76
6.2.7.2 Athermalized zoom lens ........................................... 76
6.2.7.3 Optically compensated zoom lens .............................. 81
6.2.8 Optimum Optical Systems ............................................. 81
6.2.9 Royal Institute of Technology .......................................... 83
6.2.10 Fuji Photo Optical Company ......................................... 83
6.2.11 Carl Zeiss ............................................................... 84

6.3 Charge-Coupled Device Imaging Systems ......................... 84
6.3.1 Angenieux ................................................................. 84
6.3.2 University of Alabama, Huntsville .................................. 87
6.3.3 National First University of Science and Technology ........ 87
6.3.4 Industrial Technology Research Institute ......................... 88

6.4 Laser Beam Expanders .................................................... 88
6.4.1 Carl Zeiss ............................................................... 88
6.4.2 University of Twente ................................................... 89

6.5 Diffractive Optics ............................................................. 93
6.5.1 Optics 1 ................................................................. 94
6.5.2 Optical E.T.C., Inc. and Teledyne Brown ......................... 95
6.5.3 Wescam ................................................................. 99
6.5.4 Texas Instruments ....................................................... 101
6.5.5 Raytheon .............................................................. 102
6.5.6 Raytheon .............................................................. 104

6.6 Focal Plane Arrays ........................................................ 104
6.6.1 Agency for Defence Development .................................... 104
6.6.2 Royal Institute of Technology ....................................... 106
6.6.3 Royal Institute of Technology ....................................... 106

6.7 References ....................................................................... 108
Preface

This tutorial is an outgrowth of my SPIE short course entitled “Infrared Optics and Zoom Lenses.” The title was selected to reflect the scope of the subject matter, and this has been carried over to the tutorial. The first three chapters present an introduction to the principles of optics and the unique aspects of the infrared region of the wavelength spectrum. This foundation makes it possible for those readers who are not optical engineers to acquire the background information needed for a treatise on infrared zoom lenses.

Chapter 1 presents overall system considerations involved in establishing the requirements for an application that includes an optical system as one of its elements. Chapter 2 sets forth the basic fundamentals of optics involved in the design and analysis of optical systems. Chapter 3 presents the optics features that are unique to the infrared region of the spectrum. Chapter 4 discusses some of the optical design techniques that may be utilized in the optical design of infrared systems. These four chapters could serve as an introduction to any treatise on infrared optical systems. Further discussion of these topics may be found in the tutorial text on this subject by Max J. Riedl.1

Chapters 5 through 8 present the subject matter that is unique to the subject of zoom lenses in the infrared. Chapter 5 sets forth the basic types of zoom lenses and the establishing of specifications to meet the requirements of a particular application. Chapters 6 and 7 present numerous examples of refractive and reflective infrared zoom systems; the optical design techniques from Chapter 4 are employed in designing these representative infrared (IR) zoom lenses to illustrate the utilization of these techniques. Companies identified in Chapters 6 and 7 are the names in existence at the time the reference papers were published; some of them have since merged with other companies and lost their separate identity. Chapter 8 presents a brief discussion of future trends in this subject area. Chapter 9 presents a summary of infrared zoom lens applications.

Appendix A contains three landmark IR zoom lens patents in their entirety as published. This appendix is included not only for the insights contained therein, but also to provide lens prescription data to serve as potential starting points for future design activity. Appendix B presents computer analysis that I have performed on these patents and on one additional patent described in Sec. 7.2.1. A definition of the analysis categories is to be found in Chapter 2. Appendix C gives the answers to self-test problems presented in Sec. 2.9.

The infrared zoom lens literature consists primarily of patents and of papers presented at conferences or published in journals and proceedings. In 1993 SPIE published in its Milestone Series of Selected Reprints a volume on zoom lenses which included a number of infrared papers and patents.2 To my knowledge, this tutorial is the first publication to be devoted exclusively to IR zoom lenses. It
should serve as an introduction to the subject for the uninitiated and as an aid to the engineer who has an infrared zoom lens application to pursue. It is not intended to be a step-by-step instruction manual for this complex optical design activity.

Additions to Infrared Optics and Zoom Lenses are included in the second edition of this tutorial. The additions are based on an expanded short course that I recently presented. There are substantive additions to the topics in the table of contents. They are discussed below. Also, 18 new refractive and reflective systems have been added to the 23 zoom systems in the first edition, bringing the total to 41 optical systems. The 18 new systems were published in the reference literature since publication of the first edition, in the time interval from the year 2000 to 2007. These additional systems are in part the result of adding a new category—focal plane arrays—to the chapter on refractive infrared zoom lenses. In part these additions are a result of including dual field-of-view infrared optical systems in this tutorial. The 18 new zoom systems are intended to bring the technology and the list of refractive and reflective zoom infrared systems up to date. There are 24 additional references.

One of the themes that will be presented is the gradual shift in recent years from the 8- to 12-micrometer (µm) region to the 3- to 5-µm region of the wavelength spectrum. This shift is discussed in Secs. 2.7, 3.1, 3.2, 6.5, and 6.6.

The rationale for the substantive additions is presented below:

2.8 Principal planes: The location of the principal planes is important in order to calculate accurately the separation between lens elements when going from a thin-lens solution to a thick-lens solution. The location also affects the overall length of the zoom system.

2.9 Self-test problems: A problem set is included in order to ensure a clear understanding of optics fundamentals before discussing the infrared spectrum and infrared zoom systems.

3.5 Glass substitution: Glass substitution is a powerful technique for performing computer optimization and athermalization simultaneously by passive substitution of infrared optical materials. I have done this glass substitution successfully, and I present a detailed example with a reference to the paper I wrote on this subject.

4.14 Global search: Global search has been demonstrated in recent years to be a viable computer optimization tool. An example is presented of designing zoom lenses by means of global search without designer intervention. The computer program flowchart of the decision-making process is included in this discussion.

5.3 Extenders: Extenders are a practical means of extending the focal length range of zoom lens systems. It is important to understand the optical limitations of extenders.

6.6 Focal plane arrays: The use of focal plane arrays (FPA) to eliminate scanning is an important development in infrared optical systems. Techniques for
overcoming the limitations of resolution of FPAs at higher spatial frequencies are discussed in this section.

7.3 Special reflective systems: Due to the increase in the number of reflective infrared zoom systems, it is important to understand techniques for dual-channel detector arrays and for designing compact reflective systems through the use of folding mirrors and the Mangin mirror.

Chapter 9 Summary of applications: It is useful to summarize the scope and variety of infrared zoom lens applications. The discussion includes a reference to each of the zoom systems presented in this tutorial. This overview makes this chapter a fitting conclusion.

I would like to thank the reviewers for their helpful comments and suggestions. Acknowledgment is also due to Gwen Weerts of SPIE for her editorial assistance in the publication of this second edition of Infrared Optics and Zoom Lenses.

Allen Mann
January 2009