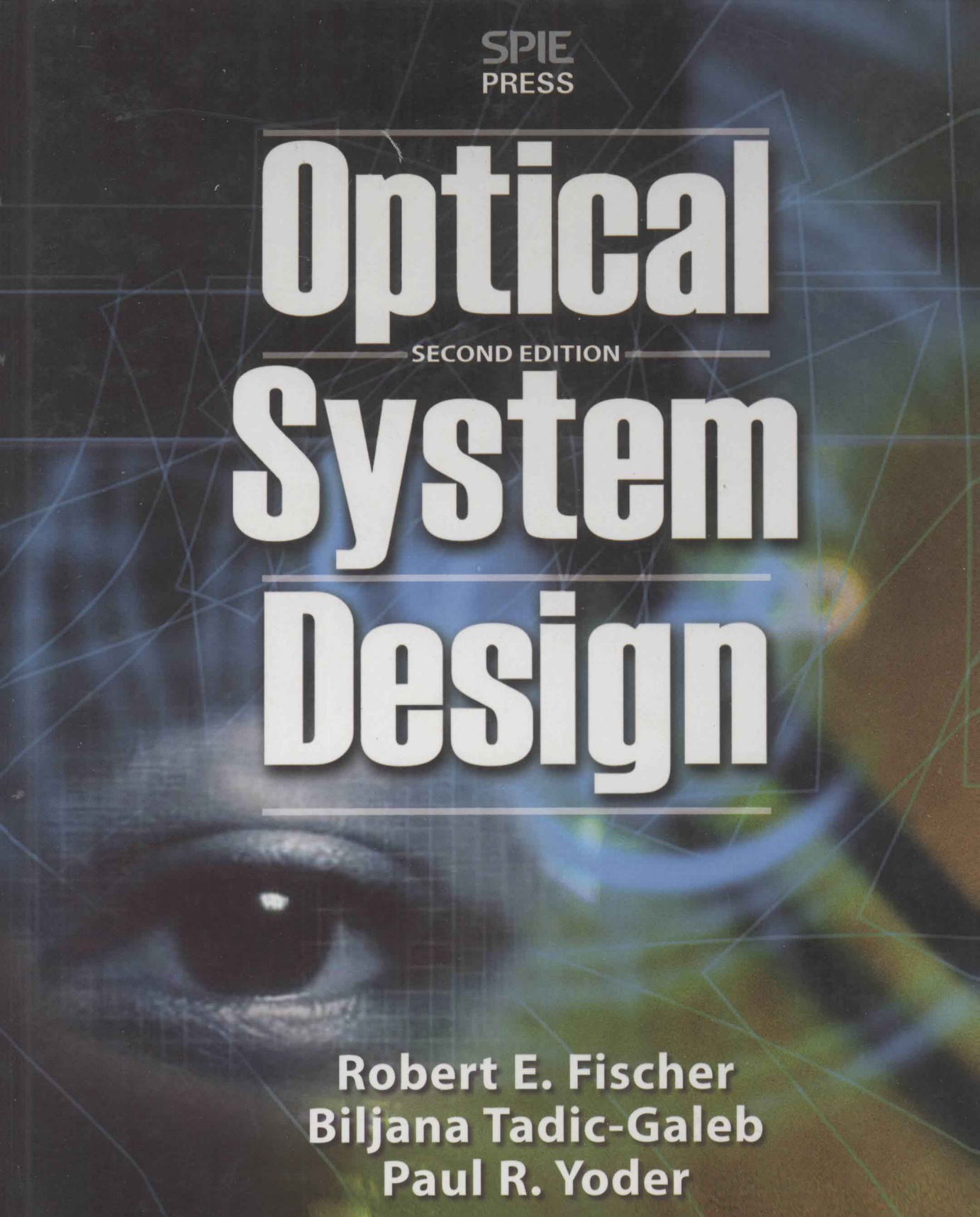
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Robert E. Fischer
Biljana Tadic-Galeb
Paul R. Yoder

Optical System Design

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OPTICAL SYSTEM DESIGN

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Robert E. Fischer is the president and founder of OPTICS 1, Incorporated, of Westlake Village, California. He has a BS and MS in Optics from the Institute of Optics at the University of Rochester. He has been involved in optical design and engineering since 1967 when he joined the Itek Corporation. Prior to founding OPTICS 1, he was with Hughes Aircraft. His primary areas of technical interest and expertise include lens design, optical engineering, optical system manufacturing and testing, illumination systems, and related engineering technologies. In addition to chairing many conferences with the SPIE, Fischer has held several positions with the society, including president in 1984, and treasurer from 2001 through 2005. His popular short course "Practical Optical System Design" has been widely attended over the years and forms the basis for this book. Mr. Fischer is a Fellow of SPIE and the Optical Society of America. He was awarded the Albert M. Pezzuto award from SPIE in 1986, and the Gold Medal of SPIE in 2000.

Biljana Tadic-Galeb is a Senior Staff Optical Engineer at Panavision of Woodland Hills, California. She has a BS in Physics from the University of Sarajevo, Yugoslavia, and an MS in Optics from Reading University in England. She also holds an MS in Metrology from the University of Beograd, Yugoslavia. Ms. Tadic-Galeb has 30 years of experience as an Optical Systems Engineer with specialties in the development of complex visible, IR, and UV optical systems, projections systems, laser systems, and hybrid systems with diffractive elements and fibers. She was recognized by the National Academy of Engineering in their featured Women Engineers Program.

Paul R. Yoder. Jr. has, since 1951, designed and managed the development of optical systems and instruments for military, aerospace, and commercial applications at the U.S. Army's Frankford Arsenal and at the Perkin Elmer Corporation, as well as ophthalmic laser systems at Taunton Technologies, Inc. Since 1983, he has also served many clients as an independent consultant in optical engineering and optomechanical design. He has published widely in those fields with 66 technical papers, 2 handbook chapters, and 4 reference books to his credit. Yoder received his BS and MS degrees in physics from Juniata College (1947) and Penn State University (1950). Yoder is a Fellow of the SPIE, a Fellow of the OSA, a member of Sigma Xi and a co-founder of the SPIE's Optomechanical/Instrument Working Group. He has taught numerous short courses on optomechanical design and engineering for industry, government agencies, and SPIE in the USA and Europe as well as graduate-level courses for the University of Connecticut. In recognition of his contributions to optomechanical design and engineering, Yoder received the *Engineering Excellence Award* from the OSA in 1997 and the *George W. Goddard Award* from the SPIE in 1999 as well as the SPIE Director's Awards for outstanding service to the Society in 1996 and 2006.

PREFACE

The design of imaging optical systems is an engineering discipline which has been practiced and written about for many years. In many ways, optical design is both a science and an art, and for this reason it is a technology that can cause problems if it is not done properly. Furthermore, most books on the subject tend to be complex and difficult to follow and to understand. With this book, we hope to bring the understanding of our discipline to everyone.

We are all aware of cameras, binoculars, and other optical systems and instruments. In the past several years, the field of optics and photonics has seen a tremendous surge in both technology and in applications. This is fueled by a closer association with electronics in devices such as digital cameras, enhanced machine vision systems, MEMS and microoptical systems for telecommunications and other related applications, many of which have yet to be invented.

With this surge in the applications of optics, the educational process of training experienced optical designers and engineers becomes extremely important if not critical.

We realize that it is difficult to be an expert in everything. We also realize that in addition to optical design which is the core of the book, important topics including optical manufacturing, polarization, and optical coatings are important subjects that need to be covered in this book, and the first edition included these topics. With this new second edition, other critical technologies including optomechanical design, systems modeling and analysis, and stray light suppression are now included. Further, completely revised chapters on diffractive optics and polarization are also included.

We are honored to have contributed chapters written by experts in their fields: Paul Yoder on optomechanical design, Rick Plympton and Bob Wiederhold on optical manufacturing, Steve McClain and Tom Baur on polarization in optical systems, Ranko Galeb on thin films and optical coatings, Bernard Kress on diffractive optics, and Alastair J. Grant on systems modeling and analysis, as well as stray light suppression.

The ultimate goal of this book is to teach optical design and engineering in a fully unintimidating way using clear and easy to understand graphics and explanations. Many authors feel an obligation to

include complex mathematical derivations. We have taken a very different approach. We will make this book clear and easy to understand with the goal that you will learn the subject matter with a combination of complete graphics, easy to follow explanations, and just enough math to be useful, but not too much math to make the book hard to follow or difficult to understand.

This book *Optical System Design* is largely based on the firm foundation of the short course by the same title taught by Bob Fischer to over thousands of students over the past 20 years. The course has been honed, polished, and expanded over the years. It is available on CD ROM and videotape, and finally, via this book. Typical comments have been:

"This course was just what I had hoped it would be. It condensed the vast optical world into the key elements necessary for a broad understanding of the subject and an excellent foundation for future study. Good job!"

"Excellent presentation! This is an invaluable course for those who are engaged in optical systems efforts and have a minimum training in optics."

"A fast paced, well-prepared study, presented by a hands-on instructor."
"I learned what I came to learn, thanks."

"Excellent! Wonderful presentation and technique. Material was well covered."
"Excellent in explaining and answering questions. Very useful rules of thumb, great presentation. Thanks!"

"Very professional and excellent presentation."

This book is for everyone from program managers to seasoned optical designers and engineers, mechanical engineers, electrical engineers, and others. You will find that it is like reading *Gulliver's Travels*. We all read *Gulliver's Travels* in elementary school, some of us again in high school, and some scholars wrote their Ph.D theses on the book. *Gulliver's Travels* can be read at multiple levels, just like this book.

ROBERT E. FISCHER

ACKNOWLEDGMENTS

Welcome to the second edition of *Optical System Design.* When first published in the year 2000 the goal was to create a book in the field of optical system design and engineering that was clear and easy to understand, and at the same time highly useful to the reader. Far too many books are filled with complex mathematics and other "mumbo jumbo" that often makes it difficult to find what you are really looking for. The overriding goal was thus to create a book that was both extremely useful as well as readable, and all indications are that this goal was met.

I recall talking to a professor at a leading university in optics just after the first edition was published who not only liked the book, but he told me that he was reading the book *backwards,* that is to say from the last chapter forward. "Why" I asked with a puzzled look? Because he really liked the "Bloopers and Blunders in Optics" chapter and that was the last chapter in the book!

I am pleased to welcome four new contributing authors for the second edition. Bernard Kress has a new and fully revised chapter on "Diffractive Optics," and Steve McClain along with Tom Baur have a new and fully revised chapter on "Polarization in Optical Systems." In addition to the above, I am honored to welcome to the book a new chapter "Optomechanical Design" by Paul Yoder. Optics and mechanics are both critical technologies that truly go hand-in-hand to make for a complete system. We must never underestimate the importance of mechanics to an optical system. Paul Yoder is one of those true icons in the field! Thanks Paul!

Also welcome to Alastair Grant who has contributed chapters on "Optical sensor systems Modeling and Analysis" and also "Stray Light and Optical scattering."

Finally, a deep and sincere thanks is due to my wife Emilia who so graciously supports my many extracurricular activities in optics. Also thanks to Antonia Petruse Surd, my administrative assistant, who played a major role in coordinating the many inputs from authors.

ROBERT E. FISCHER

CONTENTS

CHAPTER 1

Basic Optics and Optical System Specifications

This chapter will discuss what a lens or mirror system does and how we specify an optical system. You will find that properly and completely specifying a lens system early in the design cycle is an imperative ingredient required to design a good system.

The Purpose of an Imaging Optical System

The purpose of virtually all image-forming optical systems is to resolve a specified minimum-sized object over a desired field of view. The *field of view* is expressed as the spatial or angular extent in object space, and the minimum-sized object is the smallest *resolution element* which is required to identify or otherwise understand the image. The word "spatial" as used here simply refers to the linear extent of the field of view in the plane of the object. The field of view can be expressed as an angle or alternatively as a lateral size at a specified distance. For example, the field of view might be expressed as $10° \times 10°$, or alternatively as 350×350 m at a distance of 2 km, both of which mean the same thing.