Edited by
Herbert Gross

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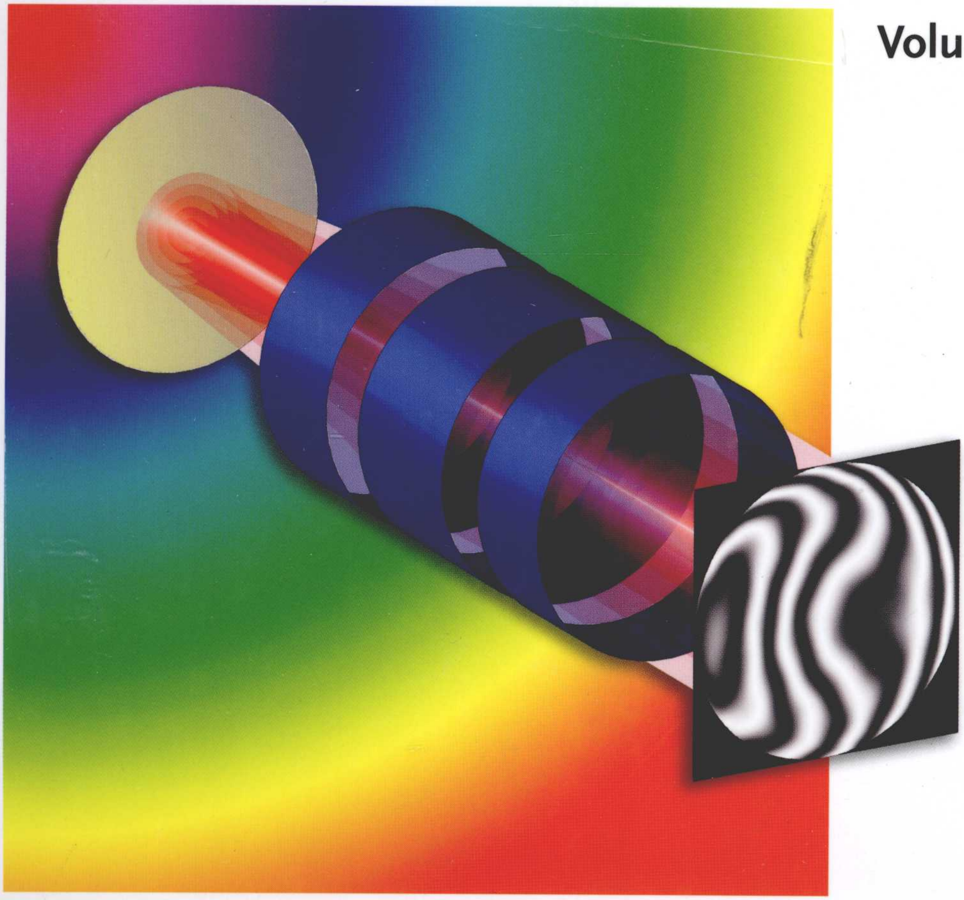
Handbook of Optical Systems

B. Dörband, H. Müller, H. Gross
Metrology of Optical Components and Systems

Volume 5



Handbook of Optical Systems

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Volume 5: Metrology of Optical Components and Systems

Bernd Dörband, Henriette Müller, and Herbert Gross

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Bernd Dörband

Bernd Dörband was born in 1949. He was educated as an optometrist and studied physics at the Technical University in Berlin, Germany. In 1986, he received his Ph.D. from the University of Stuttgart for a thesis on "Analysis of Optical Systems by Means of Optical Metrology and Mathematical Simulation". Since 1986 he has been working with the Carl Zeiss, Oberkochen, Germany, as a specialist for optical metrology. His areas of interest are the design and the development of optical test setups for different kinds of applications with a strong focus on interferometry and surface form measurement techniques. In 1992, he started teaching as a lecturer on optical metrology at the University of Aalen. From 1995 to 2001, Dr. Dörband was head of the metrology department at the Center of Technology of the Carl Zeiss company. In 2001, he accepted a post as a principal scientist in the Lithography Optics Division of Carl Zeiss.

Henriette Müller

Henriette Müller was born in 1952. She studied physics at the University of Jena, Germany, and joined Carl Zeiss, Jena, Germany, in 1976, where she worked in the department of optical metrology. Her main fields of interest were the development of optical test equipment for different applications including infrared sensor systems and microscopic and interferometric devices. From 1994 to 2001, she worked as a scientist and project manager at the Center of Technology of the Carl Zeiss company in Oberkochen, with a focus on interferometry and surface form measurement techniques. In 2001, she started working as a senior scientist in the Lithography Optics Division of Carl Zeiss.

Herbert Gross

Herbert Gross was born in 1955. He studied physics at the University of Stuttgart, Germany, and joined the Carl Zeiss company in 1982, where he has since been working in the department of optical design. His special areas of expertise are the development of simulation methods, optical design software and algorithms, the modeling of laser systems and simulation of problems in physical optics, and the tolerance and the measurement of optical systems. From 1995 to 2009, he was head of the Central Optical Design Department at Zeiss. In 1995, he received his Ph.D. from the University of Stuttgart, Germany, on the modeling of laser beam propagation in the partial coherent region. From 2009 until 2012, he worked as a principal scientist in the Department of Optical Design and Simulation. In 2012, he accepted a professorship at the University of Jena, Germany.

Preface

The first two volumes of this handbook series on optical systems covered the basics of technical and physical optics. The third volume deals with aberration theory, performance evaluation and the fundamental layout of systems. Furthermore, the reader was introduced to the techniques used to improve and optimize optical systems and give them the right tolerances for manufacture. In the fourth volume, a summary of the well known optical system types and their classification were reviewed. The goal of this collection is to demonstrate and explain the most important thoughts, principles and properties, which lie behind successful solutions in optical design.

These topics provide the reader with the main framework for understanding the description, design and principles of optical systems.

The important link from the computer results in optical design and simulation to the practical realization is addressed in this fifth volume. If manufacturing aspects are considered, the evaluation of the theoretical predictions needs an accurate characterization and measurement of the individual components and the complete system. It is not the goal of this book series to cover all the manufacturing methods for optical components. But if the performance of a built system does not meet the required quality, it is necessary to analyze the realized data and to find out the reasons for the discrepancy. The possible reasons can be component tolerances or problems in the assembly of the complete system. Therefore this volume is concerned with the testing and metrology of optical components and systems.

Many colleagues and friends have helped to collect, prepare and correct the text and have contributed important material to this volume. We would like to thank them all and apologise if we forget to mention any one of them by name.

Matthias Dreher made substantial corrections and improvements to the chapters on interferometry and component geometry. Hans-Jochen Paul and Volker Weidenhof read the chapter on radiometry carefully and gave important hints for improvement. Frank Höller gave substantial input to the chapter on distance and angle metrology and corrected the related manuscript carefully. Michael Totzeck contributed important suggestions for the chapter on polarimetry. From Frank-Thomas Lentes we received pictures related to striae testing in the chapter on the quality of optical materials. Hannfried Zügge and Günther Seitz carefully corrected the manu-

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script on texture and imperfections of optical surfaces. Maren Büchner corrected the chapter on the quality of coatings and gave important hints related to practical applications.

At this point, we must thank Ulrike Werner from Wiley VCH for her understanding and never ending patience during the work on this volume. Without her experience, interest and competence, it would have been impossible to finish this book. Due to difficult circumstances, the time required to complete this volume was much longer than initially planned. We apologize for this delay. Also we want to acknowledge Linda Bristow for her fast and perfect language improvement, which has impoved the readability and understandability of the text.

Aalen, Essingen,
January, 2012

Bernd Dörband
Henriette Müller
Herbert Gross

Introduction

In the first volume of this book series, the basics of technical optics are presented. This provides the fundamental knowledge of optics and in particular optical physics, which is necessary to understand optical systems and instruments with their various technological aspects. The second volume deals with the physical principles of image formation from a more theoretical point of view. The topics covered in the second volume provides a deaper understanding of the principles of optical imaging. In the third volume, the special algorithms, methods and techniques are explained, which are necessary to design and optimize optical systems. This content helps in the practical work to develop optical systems efficiently with available tools. In the fourth volume, a collection of systems types is presented, which shows how the basics can be applied to concrete applications. This gives the reader an overview and simultaneously shows how broad the area is and that quite different knowhow is necessary to cover the design of optical systems completely.

The next step in a practical development of systems is the manufacturing of a prototype with a proper tolerance budget of acceptable deviations from the nominal data. The measurement of the overall system quality is an important step in order to characterize the system properties with respect to the specification required. If the performance of the system in reality does not match the theoretical predictions, it is necessary to evaluate the geometrical shape, the roughness and the coating of all the components and the complete system and to analyze the impact of these real conditions and data on the system performance. Therefore the various metrology aspects of the system verification are a consequent next step in the treatment of optical systems. Volume 5 with its theme optical systems deals with these subjects.

The interferometric measurement of optical surfaces is one of most important methods used to characterize optical components. The corresponding techniques of measurement are described in this chapter. The basic principles of interferometers are presented, starting with the basic physics of interference. The next section describes the most important types of interferometric setups, their properties, advantages and drawbacks. After a review of important design principles, the detection of the signals and the various algorithms of data evaluation are described. In the remaining section of this chapter, the techniques of calibration are explained

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and a comprehensive description about dynamic ranges, accuracy and errors can be found.

Beneath the interferometric measurement of wavefront quality, there are some further quite different possibilities for testing. The most important measurement approaches of non-interferometric wavefront sensing are described in this second chapter. The use of a Hartmann-Shack wavefront sensor or the classical Hartmann setup are discussed and their properties, accuracies and limitations are explained. Some other possible principles are the phase space analyzer, point filtering techniques of special approaches based on filter and Moiré techniques. A further prominent method is the point spread function phase retrieval, which is represented in more detail. Finally some of the major facts and algorithms to calculate Zernike polynomials out of the measurement rough data are discussed in the last section of this chapter.

In the next chapter, the most important techniques and methods about the measurement of radiometric quantities are presented. After a representation of the various definitions of radiometric quantities, the explanation of the basic principles of energy transport follows. The third section contains a comprehensive representation of the various realization possibilities of monochromators, describing absorption filters, Fabry-Perot systems, interference filters, prism and grating monochromators. The measurement of spectral properties including the description of spectrometers is given in the next sections. Finally the discussion of calibrations techniques, accuracy and sources of errors in corresponding measurements are discussed.

The direct analysis of detected images can be used to determine the quality of optical system, if well known object patterns are used for the image formation. The classical star test is one of the prominent methods of this category, which is used in microscopy for a long time. A special discussion on the measurement of distortion can also be found in the fifth section. Further techniques are deflectometry and the projection of patterns or fringes onto test surfaces. These methods, their accuracy and errors are discussed in this chapter.

In the next chapter, the basics of measuring distances and angles are explained. Methods for long range distances and displacements as low-coherence interferometry, linear encoders or frequency combs are discussed. Triangular principles and confocal sensors for shorter values of spatial dimensions are treated. For the quantitative evaluation of tilt and angle metrology the correspondent techniques like angle encoder, autocollimation setups and heterodyne interferometers are described. A special section was added which discusses the surface profile measurement techniques, which are essential for the metrology of optical systems.

In the next chapter, the measurement of polarization properties are presented in a comprehensive way. First the basic principles of polarimetry are given, starting with the Jones matrix formalism and the Stokes-Mueller approach respectively. The major polarizing components and their model descriptions are then presented in detail. In the fourth section, the measurement techniques are explained for the vectors and matrices of the Jones type as well as for Stokes vectors and Mueller matrices. The setup of polarimeters and ellipsometers are described and finally the calibration, accuracy and error sources of the corresponding methods are discussed.

The next chapter deals with the testing of the quality of the materials in optical systems. Here only optical properties of transparent materials are considered commencing with the basic options of specifications where refractive index is considered the most important quantity. In the third section, the transmittance of materials and its measurement is discussed. Special questions such as the testing of inhomogeneity, striae, birefringence, bubbles and inclusions in optical materials are further topics of this chapter.

The geometry of optical components is one of the most important properties that must be tested in optical production. The basic properties of lenses for example are the radii of curvature, the center thickness and the diameter. More sophisticated types of optical surfaces require a closer look at the shape of the surface, which may be non-spherical and therefore can not be described by one radius only. The relative positioning and in particular the centering errors of optical components must be tested too and the corresponding techniques for measurement are represented in this chapter.

The quality of optical surfaces and the measurement of the corresponding properties are the main topics of the next chapter. First the usual specifications are explained and then the description and the metrology of surface texture and imperfections are the subjects examined.

A special aspect of surface quality is the influence of the coating. After an introduction into the basic principles and specifications of coatings, the understanding of the properties of coatings and their simulation models are presented. Special topics such as graded interfaces, the influence of surface roughness and the role of material parameters and dispersion effects are discussed. Finally, the metrology techniques to characterize and measure the properties of coatings are detailed in this chapter.

If a complete system is to be tested, all the individual components and functions need to work together. The functionality of the whole system then must be checked against the specification. There are basic parameters of the system that must be tested, for example focal length, magnification, aperture size and magnification. In addition, the quality of the system must fulfill the requirements of the application. The system performance can be described in quite different quantities, which must be measured. This can be the wavefront quality the point spread function of the modulation transfer function. The principles of testing some further special properties such as transmission, illumination, glare, M^2 beam quality of polarization aberrations are considered in the last section of this chapter. The test procedures of all these properties are described in this chapter, whereas the basic principles are referred to in the previous parts of this book.

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