Handbook of Optical Sensors

Edited by

José Luís Santos
Faramarz Farahi

CRC Press
Taylor & Francis Group

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CRC Press
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Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20140910

International Standard Book Number-13: 978-1-4398-6685-6 (Hardback)

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http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

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To Our Families

Preface

The progress of science and technology has led to the development of complex structures with increasing sophistication, but still nothing comparable to what we observe in biological systems. Complex biological systems have three key characteristics associated with their operation: (1) Energy flow inside the system and energy exchange with its surrounding environment are coordinated to achieve specific functionalities. (2) Such flow of energy derives from analysis of the system about its internal state, also conditioned by the external environment, and the consequent identification of actions that must be performed to restore the balances necessary for adequate functioning of the system. (3) This analysis is fed by a constant stream of information from the internal state and external surroundings of the system, which increases markedly with the system's complexity.

This last characteristic relies on a sensing mechanism, where sensors are designed for specific quantities according to natural laws that determine the quantitative relationship between different variables. Therefore, distinct phenomena and representation can be related to the measurement of certain quantities such as mechanical, thermodynamic, electrical, magnetic, optical, and other properties, each of which offers specific advantages and unique representation, where the natural choice depends on a number of factors with emphasis on the intended application. Electromagnetic radiation described by its amplitude, frequency (wavelength), polarization, and phase provides a range of options to design sensors for a wide range of parameters with performances that can be adjusted according to the needs. It is not surprising that electromagnetism has long been regarded as an important phenomenon in the field of sensors. Because of the central role of vision as a sensory mechanism of living beings, the optical band of the electromagnetic spectrum is of particular importance. Optical sensors refer to sensing mechanisms that use electromagnetic radiation in the optical band, although recently longer (terahertz) and shorter (x-ray) wavelengths have been used within the context of optical systems. Since one important means of communication of humans with the environment is within the optical band of the electromagnetic spectrum, it seems natural for us to think of optics as a branch of science and technology for sensing. Over time, technological progress has increased our abilities to control the properties of light, and, with that, the construction of better sensor devices and optical instruments, enabling rapid progress in the field of optical sensing.

The importance of optical sensing is now recognized and its potential in future technological advances is immeasurable. But the truth is, if we ignore the sensing systems associated with vision, it was only in the second half of the twentieth century that the designation of the *optical sensor* became common. A survey of the publications of the Optical Society of America (OSA) shows that in 1961 the word *optical sensor* appeared in an OSA journal for the first time. The reason for this relatively late bloom is the level of technological demands it requires, which is not only due to the difficulties associated with sensor fabrication, but also the requirement for advanced optical sources, detectors, modulators, and waveguides that allow light propagation to and from the measurement region. Remarkable achievements in all these areas in recent decades allowed for the rapid progress in the field of optical sensing. In particular, optical fibers that play a dual role as light transporters and communication channels enable the relatively straightforward implementation of the sensors network.

The accelerated growth recently seen in the field of optical sensors is driven by two factors: the demands introduced by the applications and the progress of science and technology in other fields such as materials science, microelectronics, metamaterials, and quantum physics. This interesting dynamic has motivated us to seek help from many experts in this field and coordinate an effort with the objective of providing a comprehensive and integrated view of optical sensors, where each specific area is presented in detail, but within a general context. With this approach, our intention has been to offer a source of information to practitioners and those seeking optical solutions for their specific needs, and a reference for the students and investigators who are the intellectual driving force of this exciting field.

In pursuit of this objective, the book is organized into four sections, with a total of 21 chapters. In the first section, Optical Sensing and Measurement, the basic aspects of optical sensors and the principles of optical metrology are discussed in two chapters and a brief historical review of the subject is presented. The second section, Optical Measurement Principles and Techniques, starts with a chapter focused on the role of optical waveguides in sensing, followed by four chapters that discuss sensor technologies based on intensity modulation, phase modulation (interferometric), fluorescence, and plasmonic waves, followed by three chapters describing wavefront sensing, multiphoton microscopy, and imaging based on optical coherence tomography.

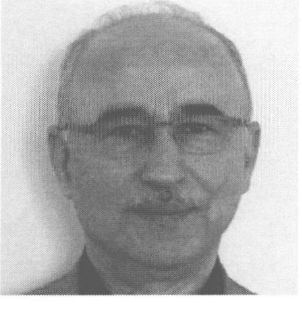
The third section, Fiber-Optic Sensors, explores the specific but increasingly important field of optical fiber sensing, which includes ten chapters starting with a historical overview of this subject, and a chapter specifically on light guiding in standard and microstructured optical fibers. Sensor technologies based on fiber optics benefit from techniques such as the modulation of intensity and phase of light, therefore the next two chapters address sensing supported by these modulation formats. This is followed by chapters on sensor multiplexing and distributed sensing. A chapter is devoted to fiber Bragg grating because of its importance in the field of fiber sensors. The next chapters focus on the application of fiber sensors for the detection of chemicals, with a chapter that can be considered a case study on the impact of the fiber-optic sensing approach through analysis and comparison with electrical- and optical-based strain gages. This part concludes with a discussion of the important issue of standardization in optical sensors.

The fourth section, The Dynamic Field of Optical Sensing, is composed of one chapter that intends to provide a broad perspective of the field and to identify possible new trends that could shape the future of this area. It starts by discussing some of the well-established sensing technologies such as wavelength-encoded sensors and distributed sensing, which are expected to experience significant progress in the near future considering the high level of interest and R&D resources they have attracted. Then, the chapter addresses some of the recent developments in optics that could potentially impact the field of optical sensors beyond what can be envisioned today. Metamaterials could certainly provide a new vehicle for the design of novel sensing structures and on the horizon the enticing idea of entangled quantum states of light offers exciting possibilities in optical sensing offers exciting possibilities.

The 28 authors of these chapters are recognized experts in their areas of research and are major contributors to this field. They fully supported us by offering inputs and providing their respective materials in accordance with the main objectives of this project. For having accepted our invitation to participate in this buildup of this book, and also for the understanding they showed in the face of unexpected delays to reach to this point, we express our utmost gratitude. Our objective is to congregate competences of many experts to produce a text in optical sensing that would be useful for students, researchers, and users of these technologies. The output of this endeavor, we think, meets this key objective and, if so, it is very rewarding to us.

Editors

José Luís Santos earned his *licenciatura* in physics from the University of Porto, Portugal, and PhD from the same university, benefiting from a collaboration with the University of Kent at Canterbury, United Kingdom. He is currently a professor of physics at the Physics and Astronomy Department of Faculty of Sciences of the University of Porto, Portugal. He is also researcher of INESC TEC-Centre for Applied Photonics (former INESC Porto—Optoelectronics and Electronic Systems Unit). His main area of research is optical fiber sensing, with a focus on interferometric and wavelength-encoded devices. He is author or coauthor of more than 200 scientific articles and coauthor of 5 patents.



Faramarz Farahi earned his BS in physics from Aryamehr University of Technology (Sharif) in Tehran, his MS in applied mathematics and theoretical physics from Southampton University, and PhD from the University of Kent at Canterbury, United Kingdom. He is currently a professor of physics and optical science at the University of North Carolina at Charlotte, where he is a member of the Center for Optoelectronics and Optical Communications and Center for Precision Metrology. He was chair of the Department of Physics and Optical Science from 2002 to 2010. Dr. Farahi has more than 25 years of experience in the field of optical fiber sensors and devices. His current research interests include integrated optical devices, hybrid integration of micro-optical systems, optical fiber sensors, and optical metrology. He also pursues research on the application of optical imaging and optical sensors in the medical field. He is the author or coauthor of over 200 scientific articles and texts and holds 10 patents.

Contributors

Mehrdad Abolbashari
Department of Physics and Optical Science
University of North Carolina at Charlotte
Charlotte, North Carolina

Francisco Araújo
INESC TEC
FiberSensing
Porto, Portugal

Xiaoyi Bao
Department of Physics
University of Ottawa
Ottawa, Ontario, Canada

José Manuel Baptista
Centre of Exact Sciences and Engineering
University of Madeira
Funchal, Portugal

Liang Chen
Department of Physics
University of Ottawa
Ottawa, Ontario, Canada

Shahab Chitchian
Center for Biomedical Engineering
University of Texas Medical Branch
Galveston, Texas

Geoffrey A. Cranch
Optical Sciences Division
US Naval Research Laboratories
Washington, DC

Angela Davies
Department of Physics and Optical Science
University of North Carolina at Charlotte
Charlotte, North Carolina

Kert Edward
Department of Physics
University of the West Indies at Mona
Mona, Jamaica

Faramarz Farahi
Department of Physics and Optical Science
University of North Carolina at Charlotte
Charlotte, North Carolina

Luís Ferreira
INESC TEC
FiberSensing
Porto, Portugal

Orlando Frazão
Centre of Applied Photonics
INESC TEC
Porto, Portugal

Nathaniel M. Fried
Department of Physics and Optical Science
University of North Carolina at Charlotte
Charlotte, North Carolina

Kenneth T.V. Grattan
School of Engineering and Mathematical Sciences
City University
London, United Kingdom

Banshi D. Gupta
Department of Physics
Indian Institute of Technology Delhi
New Delhi, India

Wolfgang R. Habel
BAM Federal Institute for Materials Research and Testing
Berlin, Germany

Rajan Jha
School of Basic Sciences
Indian Institute of Technology Bhubaneswar
Bhubaneswar, India

Pedro Alberto da Silva Jorge
INESC TEC
Porto, Portugal

Wenhai Li
Department of Physics
University of Ottawa
Ottawa, Ontario, Canada

William N. MacPherson
Institute of Photonics & Quantum Sciences
and
School of Engineering & Physical Sciences
Heriot-Watt University
Edinburgh, United Kingdom

T.H. Nguyen
School of Engineering and Mathematical Sciences
City University
London, United Kingdom

Bishnu P. Pal
Department of Physics
Indian Institute of Technology Delhi
New Delhi, India

Marco N. Petrovich
Optoelectronics Research Centre
University of Southampton
Southampton, United Kingdom

José Luís Santos
Department of Physics and Astromy
University of Porto
Porto, Portugal

Tong Sun
School of Engineering and Mathematical Sciences
City University
London, United Kingdom

Robert K. Tyson
Department of Physics and Optical Science
University of North Carolina at Charlotte
Charlotte, North Carolina

Carmen Vázquez
Electronics Technology Department
School of Engineering
Carlos III University of Madrid
Leganés, Spain

David Webb
Aston Institute of Photonic Technologies
Aston University
Birmingham, United Kingdom

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