Second Edition

Zeev Zalevsky
Ibrahim Abdulhalim

INTEGRATED NANOPHOTONIC DEVICES

Micro & Nano Technologies Series

Integrated Nanophotonic Devices

Second edition

Zeev Zalevsky

and

Ibrahim Abdulhalim

ELSEVIER

Amsterdam • Boston • Heidelberg • London • New York • Oxford
Paris • San Diego • San Francisco • Singapore • Sydney • Tokyo
William Andrew is an imprint of Elsevier

William Andrew

William Andrew is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is availabe from the Library of Congress

ISBN: 978-0-323-22862-6

For information on all William Andrew publications
visit our web site at http://store.elsevier.com/

Printed and bound in the USA

14 15 16 17 18 10 9 8 7 6 5 4 3 2 1

Integrated Nanophotonic Devices

Preface

> "I didn't have time to write you a short letter so I wrote you a long one."
>
> Mark Twain

Nanophotonics is a newly developing and an exciting field, with two main areas of interest: imaging/vision and devices for sensing and information transport. By nanophotonics one usually refers to the science and devices involving structures with submicron dimensions (specifically less than 100 nm) and which are interacting with photons. The disciplines developed in the field of nanophotonics have far-reaching influences in both private and public sectors, with potential applications ranging from faster computing power and "smart" eyeglasses, to national safety, security, and medical applications. The recent advances in the field of nanotechnology allow the realization of photonic principles and devices that previously could only be theoretically investigated. The advances in the computing capabilities allow accurate design of such devices before applying the available fabrication process. The diversity of this field is so large that a multidisciplinary research activity involving scientists from the fields of physics, material science, electro-optical engineering, process engineering, and bio-physics is rapidly emerging.

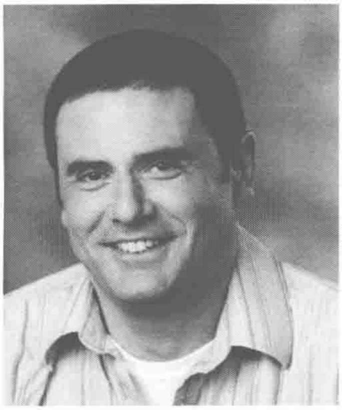
One of the major nanophotonic fields of interest is related to realization of nanointegrated photonic modulation devices and sensors. The attempt to integrate photonic dynamic devices with microelectronic circuits is becoming a major scientific as well as industrial trend due to the fact that, currently, processing is mainly done with microelectronic chips but transmission, especially for long distances, is done over optical links. In addition, photonic processing can resolve several bottlenecks generated in dense microelectronic chips especially when going to high operation frequencies. Such bottlenecks include power dissipation problems, cross-talk problems, etc. This book will present the recent progress in designing, fabricating, and experimenting integrated photonic modulation circuits. Due to the recent leap in the development of nanotechnology fabrication capabilities, the field of integrated nano- and microphotonic devices has significantly changed during the last few years.

This book, which is aimed at the reading audience of graduate students in exact sciences as well as researchers in academy and industry, presents an up-to-date as well as a comprehensive and wide-ranging perspective of existing photonic modulation technologies including several novel approaches that were only recently developed. The book starts by giving a theoretical background of the physical fundamentals that need to be known in order to follow the technical concepts addressed by this emerging field. Those theoretical background chapters can be used as introductory material to undergraduate courses on topics of non-linear optics, wave-guiding light, and semiconductors.

The authors would like to acknowledge the students as well as the research collaborators that were involved in obtaining some of the research results presented in this book. Specifically, special acknowledgment is given to Dr. Arkady Rudnitsky, Dr. Ofer Limon, Dr. Luca Businaro, Dr. Annamaria Gerardino, Dr. Dan Cojoc, Dr. Avraham Chelly, Prof. Joseph Shappir, Mr. Doron Abraham, Prof. Menachem Nathan, Dr. Asaf Shahmoon, Mr. Yoed Abraham, Prof. Reuven Shavit and Mr. Moshik Cohen, Ms. Sophia Buhbut, Prof. Michael Rosenbluh, Prof. Arie Zaban, Dr. Alina Karabchevsky, Miss Olga Krasnykov, Miss Miri Gilbaor, Dr. Atef Shalabney, Mr. Amit Lahav, Mr. Avner Safrani, Mr. Shahar Mor, Mr. Ofir Aharon, and Prof. Mark Auslender.

Last but not least, the authors would like to thank their families for the support given while preparing this manuscript. Specifically, Zeev Zalevsky wishes to thank his wife Anat and his magnificent and passionate kids Oz, Dorit, Gideon, and Nathan. Ibrahim Abdulhalim wishes to thank his wife Fatin and his sons Hisham and Adham for their patience and support.

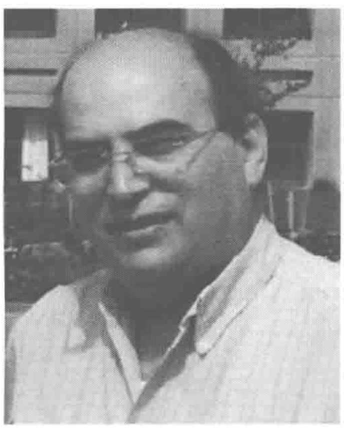
About the Authors



Zeev Zalevsky received his B.Sc. and direct Ph.D. degrees in electrical engineering from Tel-Aviv University in 1993 and 1996, respectively. Zeev is currently a full Professor in the Faculty of Engineering in Bar-Ilan University, Israel, where he is also a Director of the Nano Photonic Center.

In 2007, Zeev received the Krill prize given by the Wolf foundation (Wolf prize for young scientists) and in 2008 the International Commission of Optics (ICO) prize and Abbe medal for his contribution to the field of optical super resolution. In 2009, he won the Juludan prize for advancing technology in medicine and in 2010, he was selected to be a fellow of the SPIE for his significant scientific and technical contributions in the multidisciplinary fields of optics, photonics, and imaging. In 2011, Zeev received the international SAOT (School for Advanced Optical Technologies) Young Researcher Prize for his pioneering contributions in the development of optical techniques for enhanced imaging resolution and its use for biomedical applications. In 2011, he also received the Lean and Maria Taubenblatt Prize for Excellence in Medical Research for the development of a "Multi-functional bio-medical micro probe." In 2012, Zeev was selected to be a fellow of OSA for his significant scientific contribution to the field optical super resolution and extended depth of focus imaging. He was also selected to be an IEEE senior member for his significant contribution in electro-optics. In 2012, Zeev also received the young investigator award in nanoscience and nanotechnology given by the Israel National Nanotechnology Initiative (INNI) together with the Ministry of Industry, Commerce and Labor and was the winner of the international Wearable Technologies (WT) Innovation World Cup 2012 Prize. In 2013, Zeev received the Tesla Award for Outstanding Technical Communication in Electro-Optics.

Zeev has published more than 340 refereed papers, six books, 27 book chapters, and 32 issued patents.



Ibrahim Abdulhalim is currently a professor in the Department of Electro-Optic Engineering at Ben Gurion University, Israel. His current research activities involve nanophotonic structures for biosensing, improved optical imaging techniques such as spectropolarimetric imaging, and full field optical coherence tomography using liquid crystal devices.

Ibrahim has published over 180 articles and several chapters, coauthored one book and co-edited one book.

Contents

CHAPTER

Physical Background

1

CHAPTER OUTLINE

Z. Zalevsky & I. Abdulhalim: Integrated Nanophotonic Devices, Second edition. DOI: http://dx.doi.org/10.1016/B978-0-323-22862-6.00001-3

This chapter aims to provide the basic physical background on the topics that later on will be used in order to understand the operation principle of the various types of nano- and microphotonic devices. The chapter provides the theory behind the basics of non-linear optics, and an introduction to semiconductors and optical waveguides.

1.1 INTRODUCTION TO NON-LINEAR OPTICS

These sub-sections give the basics of non-linear optics [1,2]. The theory presented here will help the readers to understand the non-linear effects that are later used to realize the photonic devices' modulation techniques.

1.1.1 Propagation of Radiation in Anisotropic Medium

Anisotropic crystal is a non-symmetric crystal in which propagation observed in different directions produces different properties. In general the polarization density vector is related to the external electrical field as follows:

$$\bar{P} = \varepsilon_0 \chi \bar{E} \tag{1.1}$$

where χ is the susceptibility tensor, ε_0 is the permittivity constant of free space and E is the electric field (in units of Volt per meter or equivalently Newton per Coulomb). The dependence of χ on E is the basis to non-linearity.

The electrical displacement vector D (in units of Coulomb per square meter) is given by:

$$\bar{D} = \bar{E} + \frac{1}{4\pi}\bar{P} \tag{1.2}$$

which can be written in the following form as one of Maxwell's equations:

$$\bar{D} = \varepsilon \bar{E} \tag{1.3}$$

where ε is the dielectric tensor if the medium is dielectrically anisotropic. This tensor must be symmetric if the medium is non-chiral, non-magneto-optic and lossless:

$$\varepsilon_{ij} = \varepsilon_{ji} \tag{1.4}$$

which means that the tensor matrix is diagonalizable. Therefore the principal axes of the crystal are defined as the axes in which this tensor is diagonal. If one chooses the *xyz* axes to coincide with the principal axis then the equation may be rewritten as:

$$\begin{aligned} D_x &= \varepsilon_{xx} E_x \\ D_y &= \varepsilon_{yy} E_y \\ D_z &= \varepsilon_{zz} E_z \end{aligned} \tag{1.5}$$