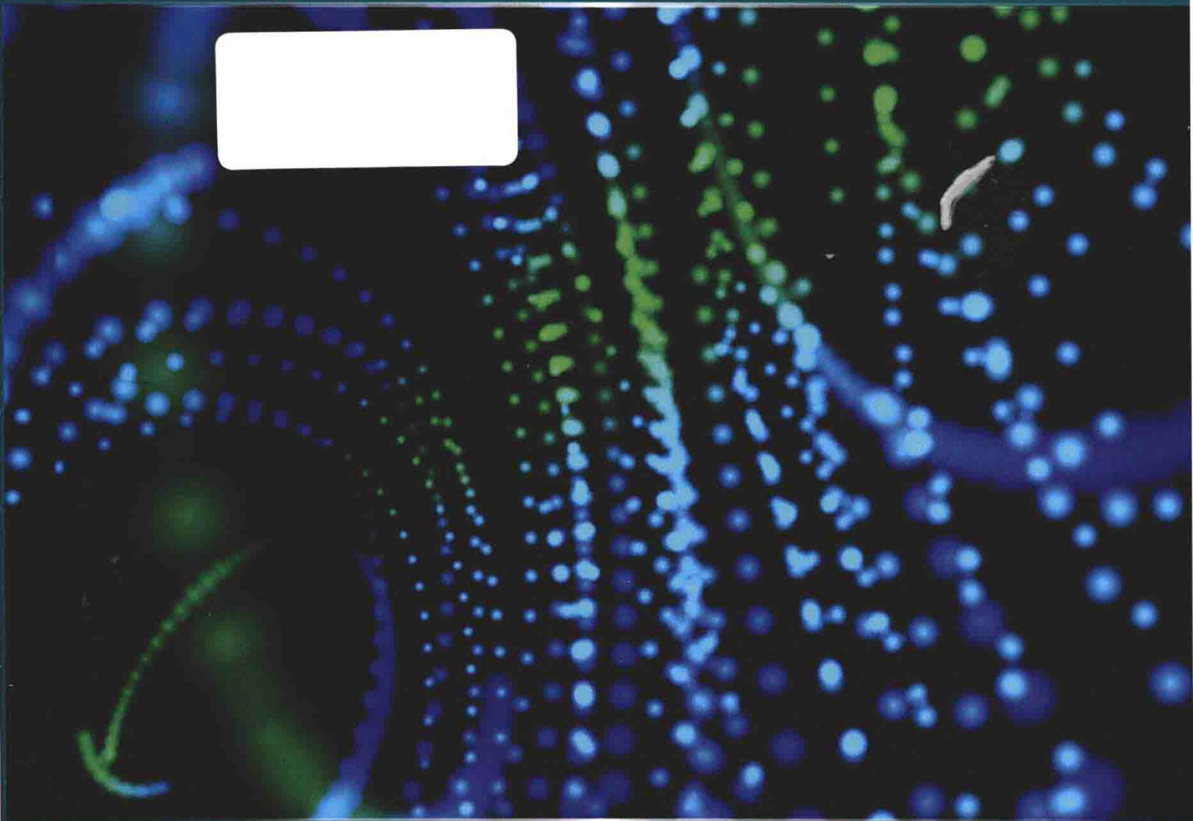
A Wiley-Science Wise Co-Publication



Photonics Volume 2

NANOPHOTONIC STRUCTURES AND MATERIALS

David L. Andrews

SCIENCE WISE PUBLISHING

WILEY

PHOTONICS

Scientific Foundations, Technology and Applications

Nanophotonic Structures and Materials

Volume II

Edited by

DAVID L. ANDREWS
School of Chemical Sciences
University of East Anglia
Norwich, UK

WILEY

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Nanophotonic structures and materials / edited by David L. Andrews.
pages cm. – (Photonics ; volume II)
Includes bibliographical references and index.
ISBN 978-1-118-22551-6 (cloth)
1. Nanophotonics. 2. Nanostructured materials–Optical properties. I. Andrews, David L., 1952-
TA1530.N346 2015
621.36′5–dc23 2014041370

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

PHOTONICS

LIST OF CONTRIBUTORS

Carmen Atienza Departamento de Químíca Orgánica, Facultad de Química, Universidad Complutense, Madrid, Spain

Wim Bogaerts Ghent University, imec, Department of Information Technology, Gent, Belgium

Juan Luis Delgado IMDEA-Nanoscience, Campus de Cantoblanco, Madrid, Spain

Eitan Ehrenfreund Department of Physics and Solid State Institute, Technion-Israel Institute of Technology, Haifa, Israel

Bob C. Fitzmorris Department of Chemistry and Biochemistry, University of California, Santa Cruz, CA, USA

Damien Joly IMDEA-Nanoscience, Campus de Cantoblanco, Madrid, Spain

Gediminas Juzeliūnas Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania

Robert H. Lipson Department of Chemistry, University of Victoria, Victoria, BC, Canada

Natalia M. Litchinitser University at Buffalo, The State University of New York, Buffalo, NY, USA

Nazario Martín IMDEA-Nanoscience, Campus de Cantoblanco, Madrid, Spain Departamento de Químíca Orgánica, Facultad de Química, Universidad Complutense, Madrid, Spain

Jesper Mørk DTU Fotonik, Technical University of Denmark, Kongens Lyngby, Denmark

Patrik Öhberg SUPA, Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, UK

Manijeh Razeghi Center for Quantum Devices, Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, IL, USA

Vladimir M. Shalaev Purdue University, West Lafayette, IN, USA

Mark I. Stockman Ludwig Maximilian University, Munich, Germany
Max Plank Institute for Quantum Optics, Garching at Munich, Germany
Georgia State University, Atlanta, GA, USA

Stanley Tsao Center for Quantum Devices, Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, IL, USA

Z. Valy Vardeny Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA

Tetsuzo Yoshimura School of Computer Science, Tokyo University of Technology, Tokyo, Japan

Jin Z. Zhang Department of Chemistry and Biochemistry, University of California, Santa Cruz, CA, USA

PREFACE

Since its inception, the term "photonics" has been applied to increasingly wide realms of application, with connotations that distinguish it from the broader-brush terms "optics" or "the science of light." The briefest glance at the topics covered in these volumes shows that such applications now extend well beyond an obvious usage of the term to signify phenomena or mechanistic descriptions involving photons. Those who first coined the word partly intended it to convey an aspiration that new areas of science and technology, based on microscale optical elements, would one day develop into a comprehensive range of commercial applications as familiar and distinctive as electronics. The fulfilment of that hope is amply showcased in the four present volumes, whose purpose is to capture the range and extent of photonics science and technology.

It is interesting to reflect that in the early 1960s, the very first lasers were usually bench-top devices whose only function was to emit light. In the period of growth that followed, most technical effort was initially devoted to increasing laser stability and output levels, often with scant regard for possibilities that might be presented by truly photon-based processes at lower intensities. The first nonlinear optical processes were observed within a couple of years of the first laser development, while quantum optics at first grew slowly in the background, then began to flourish more spectacularly several years later. A case can be made that the term "photonics" itself first came into real prominence in 1982, when the trade publication that had previously been entitled *Optical Spectra* changed its name to *Photonics Spectra*. At that time the term still had an exotic and somewhat contrived ring to it, but it acquired a new respectability and wider acceptance with the publication of Bahaa Saleh and Malvin Teich's definitive treatise, *Fundamentals of Photonics*, in 1991. With the passage of time, the increasing pace of development has been characterized by the striking progress in miniaturization and integration of optical components, paving the way for fulfilment of the early promise. As the laser industry has evolved, parallel growth in the optical fiber industry has helped spur the continued push toward the long-sought goal of total integration in optical devices.

Throughout the commissioning, compiling, and editing that have led to the publication of these new volumes, it has been my delight and privilege to work with many of the world's top scientists. The quality of the product attests to their commitment and willingness to devote precious time to writing chapters that glow with authoritative expertise. I also owe personal thanks to the ever-professional and dependable staff of Wiley, without whose support this project would never have come to fruition. It seems fitting that the culmination of all this work is a sequence of books published at the very dawning of the UNESCO International Year of Light. Photonics is shaping the world in which we live, more day by day, and is now ready to take its place alongside electronics, reshaping modern society as never before.

David L. Andrews

Norwich, U.K., July 2014

CONTENTS

1

SILICON PHOTONICS

WIM BOGAERTS
Ghent University, imec, Department of Information Technology, Gent, Belgium

1.1 INTRODUCTION

Since the beginning of the century, silicon photonics has grown from a niche research field to a field with strong industrial interest and several near-future applications [1, 2]. This rapid growth can be attributed to several unique characteristics of silicon photonics. First of all, the use of silicon makes it possible to make photonic integrated circuits (PICs) with much smaller building blocks than in other material systems [3]. This enables smaller chips, but also more complex photonic circuits. Also, silicon is the base material for electronic circuits, and huge investments in manufacturing technology can be put to work to make photonic circuits. This offers a route to high volume, low cost photonic circuits that could be applied in many applications in sensing [4, 5] and optical communication [6, 7].

In this chapter, we will discuss current state of the art in silicon photonics. We will look a bit closer in the applications, and from that we derive the functions needed on the chip. Finally, we discuss the technology implementations.

1.2 APPLICATIONS

1.2.1 Interconnects

Integrated photonics has been mainly used for applications in optical communication, especially in telecom backbone and metro networks. The advent of silicon photonics

Photonics: Scientific Foundations, Technology and Applications, Volume II, First Edition.
Edited by David L. Andrews.

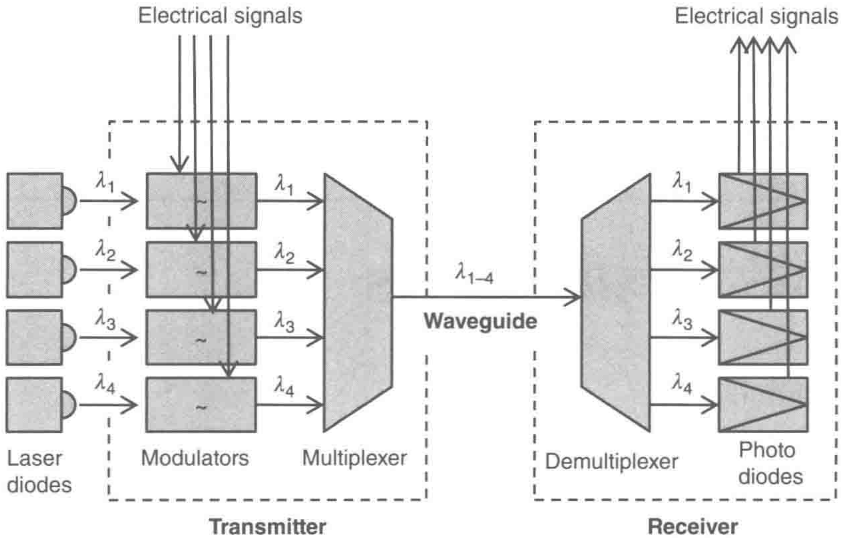


FIGURE 1.1 A WDM optical interconnection.

and its potential for low cost and low power transceiver chips has opened up new, shorter-range interconnect applications in high-performance computing and datacenters [8,9]. Silicon photonic chips might turn out to be a game-changer in interconnects on an even smaller scale: it is the first technology that can offer an attractive solution to solve the off-chip bandwidth bottleneck [10].

Typical optical links involve light sources, signal modulators, a waveguide medium, and a photodetector. These individual functions are described in Section 1.3. In the case of wavelength-division multiplexing (WDM), signals are encoded onto different carrier wavelengths, which are multiplexed into the same waveguide. This technique, illustrated in Figure 1.1, is widely used to increase the bandwidth of optical links. As we will see in Section 1.3.2, silicon photonics can implement WDM filters with a very small footprint.

1.2.2 Sensors and Spectroscopy

Another application field where silicon photonics can enable unique capabilities is that of sensing. As we will see later in this chapter, silicon waveguides can be extremely sensitive to different effects, such as temperature, cladding index [11], strain [12] and deposition of layers [13]. Especially the latter is important, as proper surface chemistry enables selective response to specific effects or molecules, enabling biosensors [5] or specific gas sensors [14]. In addition to high sensitivity, the technology offers integration of many sensor functions on a single chip, potentially with the inclusion of the read-out circuitry. Some examples of photonic sensors that could be integrated on a silicon chip are shown in Figure 1.2: A ring resonator could be

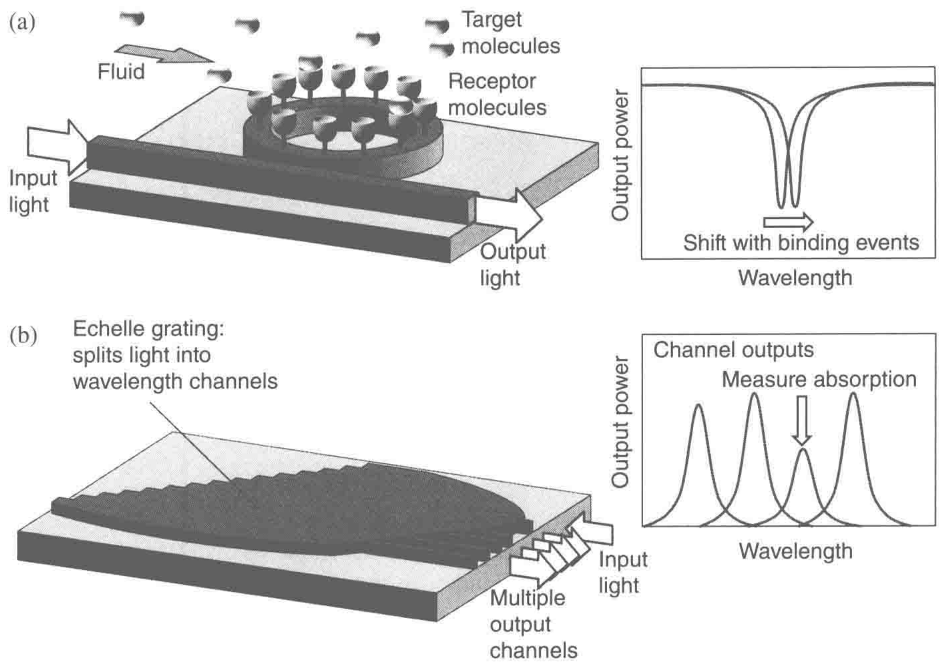


FIGURE 1.2 Two examples of silicon-photonics-based sensor systems. (a) A ring-resonator-based biosensor [4] and (b) an on-chip spectrometer [15].

used to capture selective molecular binding events and thus measure concentrations of specific (bio)molecules in a medium. Or, wavelength filters of multiplexers could be used to make a spectrometer that could be used for a variety of spectroscopic measurement systems [15].

1.3 OPTICAL FUNCTIONS

A PIC can accommodate many different optical functions. The most common functions have to do with transport of light, wavelength filtering and coupling to off-chip elements and fibers. These are called passive functions, as light is typically not altered in the process. Active functions involve electro-optic elements such as light sources, signal modulators, and photodetectors. We will discuss these functions and the state of the art in terms of performance that has been demonstrated in silicon photonics. The actual technology is discussed in Section 1.4

1.3.1 Waveguides and Routing

The key optical function on a PIC is guiding light between parts on a chip. An optical waveguide consists of a high-index core surrounded by a lower-index cladding. The

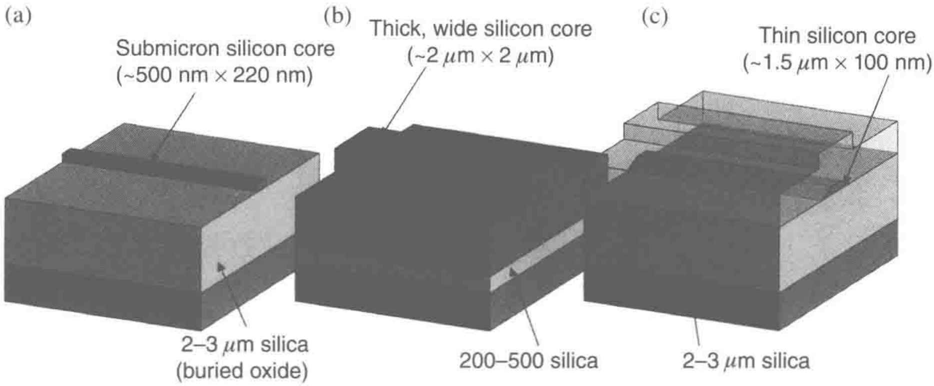


FIGURE 1.3 Silicon waveguides: (a) small-core photonic wires [17], (b) large-core rib waveguides [20], and (c) oxidized waveguide [23].

higher the index contrast, the more compact you can make the waveguide core. As it is, silicon has a very high refractive index in the regime where it is transparent (wavelength > 1.2 μm). This way, it is possible to make high contrast waveguides with core dimensions down to 200–500 nm, using a cladding oxide ($n = 1.45$) or air ($n = 1.0$) [3, 16]. Such waveguides, often called photonic wires, can have bend radii of only a few micrometers with low loss [17].

Apart from photonic wires, it is also possible to use silicon for large-core waveguides. Such waveguides are defined in silicon of several micrometers thick [18–20], and to obtain single-mode condition, they are only partially etched. Such waveguide is shown, together with a photonic wire waveguide, in Figure 1.3. Because the index contrast between the unetched core and the etched cladding is relatively low, such waveguides still require a large bend radius.

The key performance metic for optical waveguides is the propagation loss. Typical photonic wires have a loss of 1–2 dB/cm [16, 17, 21]. Large-core waveguides have a lower loss, on the order of 0.1 dB/cm [20]. To obtain lower loss in the small-code waveguide system, one can also use a shallow-etched rib waveguide geometry, which can reduce the losses with a factor of 3–4, but again with a penalty of larger bend radius [22].

Because waveguide losses are largely caused by scattering at etched sidewalls, alternative definition techniques can reduce the losses. For instance, waveguides can be defined by oxidation, which provides a smooth sidewall surface [23].

The high contrast and submicron dimensions of silicon photonic wire waveguides give them a rather strong dispersion. While the effective index of a 450 nm × 220 nm wire is around 2.4 (at 1550 nm wavelength), its group index is around 4.3. The tight confinement also makes these waveguides very susceptible to small variations, both in geometry and material parameters. A very small deviation of the width or height will have a significant effect on the effective index, to the extent that for some functions, nanometer-scale precision is required. Large-core waveguides, on the other hand, are much less sensitive to geometrical variations.