

INTEGRATED PHOTONICS: FUNDAMENTALS

Ginés Lifante

Universidad Autónoma de Madrid, Spain



WILEY

INTEGRATED PHOTONICS

INTEGRATED PHOTONICS: FUNDAMENTALS

Ginés Lifante

Universidad Autónoma de Madrid, Spain



WILEY

Copyright © 2003

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk

Visit our Home Page on www.wileyeurope.com or www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 33 Park Road, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Lifante, Ginés.

Integrated photonics : fundamentals / Ginés Lifante.

p. cm.

ISBN 0-470-84868-5

1. Photonics. I. Title.

TA1520 .L54 2002

621.36—dc21

2002191051

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-470-84868-5

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India

Printed and bound in Great Britain by Antony Rowe Limited, Chippenham, Wiltshire

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

To Victoria and Pepe

CONTENTS

Preface	xi
About the Author	xiii
1 Introduction to Integrated Photonics	1
Introduction	1
1.1 Integrated Photonics	1
1.2 Brief History of Integrated Photonics	4
1.3 Characteristics of the Integrated Photonic Components	6
1.4 Integrated Photonics Technology	10
1.5 Basic Integrated Photonic Components	13
1.6 Some Examples of Integrated Photonics Devices	18
1.7 Structure of the Book	21
References	22
Further Reading	23
2 Review of the Electromagnetic Theory of Light	24
Introduction	24
2.1 Electromagnetic Waves	25
2.1.1 Maxwell's equations: wave equation	25
2.1.2 Wave equation in dielectric media	27
2.1.3 Monochromatic waves	29
2.1.4 Monochromatic plane waves in dielectric media	30
2.1.5 Polarisation of electromagnetic waves	32
2.1.6 Light propagation in absorbing media	34
2.2 EM Waves at Planar Dielectric Interfaces	37
2.2.1 Boundary conditions at the interface	37
2.2.2 Reflection and transmission coefficients: reflectance and transmittance	40
2.2.3 Total internal reflection	47
References	50
Further Reading	51

3 Theory of Integrated Optic Waveguides	52
Introduction	52
3.1 Optical Waveguides: Basic Geometries	52
3.2 Types of Modes in Planar Optical Waveguides	58
3.3 Wave Equation in Planar Waveguides	61
3.4 Guided Modes in Step-index Planar Waveguides	66
3.5 Graded-index Planar Waveguides	73
3.5.1 Multi-layer approximation	74
3.5.2 The ray approximation	76
3.5.3 Reconstruction of index profiles: the inverse WKB method	80
3.6 Guided Modes in Channel Waveguides	83
3.6.1 Marcatili's method	85
3.6.2 The effective index method	91
Notes	96
References	96
4 Coupled Mode Theory: Waveguide Gratings	98
Introduction	98
4.1 Modal Coupling	98
4.1.1 Modal orthogonality and normalisation	98
4.1.2 Modal expansion of the electromagnetic field	100
4.1.3 Coupled mode equations: coupling coefficients	102
4.1.4 Coupling mode theory	106
4.1.5 Co-directional coupling	110
4.1.6 Contra-directional coupling	116
4.2 Diffraction Gratings in Waveguides	121
4.2.1 Waveguide diffraction gratings	121
4.2.2 Mathematical description of waveguide gratings	122
4.2.3 Collinear mode coupling induced by gratings	124
4.2.4 Coupling coefficients calculation	127
4.2.5 Coupling coefficients in modulation index gratings	128
4.2.6 Coupling coefficients in relief diffraction gratings	131
References	134
Further Reading	135
5 Light Propagation in Waveguides: The Beam Propagation Method	136
Introduction	136
5.1 Paraxial Propagation: Fresnel Equation	137
5.2 Fast Fourier Transform Method (FFT-BPM)	138
5.2.1 Solution based on discrete fourier transform	139
5.3 Method Based on Finite Differences (FD-BPM)	142
5.4 Boundary Conditions	146
5.4.1 Transparent boundary conditions	148
5.5 Spatial Frequencies Filtering	150
5.6 Modal Description Based on BPM	153
5.6.1 Modal field calculation using BPM	157

Note	161
References	161
Further Reading	162
Appendix 1 Complex Notation of the Electric and Magnetic Fields	163
Appendix 2 Phase Shifts for TE and TM Incidence	164
Appendix 3 Marcatili's Method for Solving Guided Modes in Rectangular Channel Waveguides	166
Appendix 4 Demonstration of Formula (4.3)	171
Appendix 5 Derivation of Formula (4.4)	172
Appendix 6 Fast Fourier Algorithm	174
Appendix 7 Implementation of the Crank-Nicolson Propagation Scheme	176
Appendix 8 List of Abbreviations	179
Appendix 9 Some Useful Physical Constants	180
Index	181

PREFACE

If the last century was the era of electronics, the twenty-first century is probably the era of photonics. In particular, the miniaturisation of optical components will play an important role in the success of advanced photonic devices, based on optical waveguides. This book presents the basic concepts of waveguides necessary to understand and describe integrated photonic devices, from Maxwell's equations to the modelling of light propagation in arbitrary guiding structures.

The topics, as well as their depth of analysis in the book, have been established, benefiting from the experience of several years teaching this subject at the Universidad Autónoma de Madrid. Since integrated photonic devices have applications in very different areas, such as optical communication, environmental monitoring, biological and chemical sensing, etc., students following this course may have different backgrounds. Therefore, after the introductory chapter devoted to presenting the main characteristics of integrated photonic technology, in Chapter 2 we review the electromagnetic theory of light. In it the basis of electromagnetic waves is described, emphasising the most relevant concepts connected to optical waveguides, such as the phenomenon of total internal reflection.

Subsequent chapters deal with the fundamentals of integrated photonics: the theory of optical waveguides, the coupling mode theory and light propagation in guiding structures. Although the treatment given to the different topics is based upon fundamental principles, numerical examples based on real situations are given throughout, which permit the students to relate theory to practice.

I am indebted to Professor F. Cussó, who encouraged me to write this book. I would like also to thank Professor I. Aguirre and Professor J.A. Gonzalo who carefully read the manuscript, and to Professor F. Jaque, in particular, who helped me with his invaluable suggestions.

I also want to express my very special appreciation to A. Bagney for her kind help in correcting and preparing the book in its final form.

ABOUT THE AUTHOR

Ginés Lifante Pedrola, a native of Jumilla (Spain), is a graduate of the Universidad Autónoma de Madrid. After a master's degree completed with a thesis on "Luminescent Solar Concentrators", he received his PhD under the direction of Professor F. Cussó, with a thesis on the topic of "Materials for Colour Centre Lasers". He has undertaken research study at Strathclyde University, Glasgow, with Professor B. Henderson working on colour centres lasers, at Sussex University, working with Professor P.D. Townsend doing theoretical and experimental research on non-linear waveguides made by ion implantation, and at CNRS-LAAS, Toulouse, working with Dr A. Muñoz-Yagüe on active waveguides grown by MBE using UV transparent materials.

His present research topic is the field of integrated photonic devices based on active and functional materials with applications in optical communication technology and environmental sensing. He is in charge of several projects in this field, is co-author of a hundred papers, and has several patents.

Professor Lifante has a broad teaching experience covering different teaching levels, including optics, optoelectronics and integrated photonics, and has directed several doctoral theses on integrated optics.

When not working, he is the respected coach of the Soccer Physics Team at the UAM.

1

INTRODUCTION TO INTEGRATED PHOTONICS

Introduction

The term “integrated photonics” refers to the fabrication and integration of several photonic components on a common planar substrate. These components include beam splitters, gratings, couplers, polarisers, interferometers, sources and detectors, among others. In turn, these can then be used as building blocks to fabricate more complex planar devices which can perform a wide range of functions with applications in optical communication systems, CATV, instrumentation and sensors. The setting-up of integrated photonic technology can be considered as the confluence of several photonic disciplines (dealing with the control of light by electrons and vice versa) with waveguide technology. In fact, optical waveguides are the key element of integrated photonic devices that perform not only guiding, but also coupling, switching, splitting, multiplexing and demultiplexing of optical signals. In this chapter we will introduce the main characteristics of integrated photonic technology, showing relevant aspects concerning material and fabrication technologies. Also, we will briefly describe some basic components present in integrated photonic devices, emphasising the differences in their design compared to conventional optics. Some examples of integrated photonic devices (passive, functional, active and non-linear) are given at the end of the chapter to show the elegant solution that this technology proposes for the development of advanced optical devices.

1.1 Integrated Photonics

Optics can be defined as the branch of physical science which deals with the generation and propagation of light and its interaction with matter. Light, the main subject of optics, is electromagnetic (EM) radiation in the wavelength range extending from the vacuum ultraviolet (UV) at about 50 nanometers to the far infrared (IR) at 1 mm. In spite of being a very ancient science, already studied by the founder of the School of Alexandria, Euclid, in his *Optics* (280 BC), during the last quarter of the past century, the science of optics has suffered a spectacular renaissance, due to various key developments. The first revolutionary event in modern optics was, no doubt, the invention of the laser by T.H. Maiman in 1960 at Hughes Research Laboratories in Malibu [1], which allowed the availability of coherent light sources with exceptional properties,

such as high spatial and temporal coherence and very high brightness. A second major step forward came with the development of semiconductor optical devices for the generation and detection of light, which permitted very efficient and compact opto-electronic devices. The last push was given by the introduction of new fabrication techniques for obtaining very cheap optical fibres, with very low propagation losses, close to the theoretical limits (Figure 1.1).

As a result of these new developments and associated with other technologies, such as electronics, new disciplines have appeared connected with optics: electro-optics, opto-electronics, quantum electronics, waveguide technology, etc. Thus, classical optics, initially dealing with lenses, mirrors, filters, etc., has been forced to describe a new family of much more complex devices such as lasers, semiconductor detectors, light modulators, etc. The operation of these devices must be described in terms of optics as well as of electronics, giving birth to a mixed discipline called *photonics*. This new discipline emphasises the increasing role that electronics play in optical devices, and also the necessity of treating light in terms of photons rather than waves, in particular in terms of matter–light interactions (optical amplifiers, lasers, semiconductor devices, etc.). If electronics can be considered as the discipline that describes the flow of electrons, the term “photonics” deals with the control of photons. Nevertheless, these two disciplines clearly overlap in many cases, because photons can control the flux of electrons, in the case of detectors, for example, and electrons themselves can determine the properties of light propagation, as in the case of semiconductor lasers or electro-optic modulators.

The emergence of novel photonic devices, as well as resulting in the important connection between optics and electronics, has given rise to other sub-disciplines within photonics. These new areas include electro-optics, opto-electronics, quantum optics, quantum electronics and non-linear optics, among others. *Electro-optics* deals with the study of optical devices in which the electrical interaction plays a relevant role in controlling the flow of light, such as electro-optic modulators, or certain types of lasers. *Acousto-optics* is the science and technology concerned with optical devices controlled by acoustic waves, driven by piezo-electric transducers. Systems which involve light

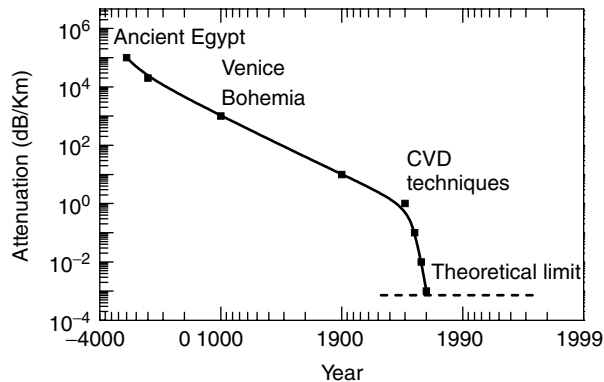


Figure 1.1 Evolution of the attenuation in silica glasses. In the 1980s the dramatic drop in the attenuation coincides with the boom of the optical fibre systems, thanks to the implementation of new fabrication techniques

but are mainly electronic fall under *opto-electronics*; these systems are in most cases semiconductor devices, such as light-emitting diodes (LEDs), semiconductor lasers and semiconductor-based detectors (photodiodes). The term *quantum electronics* is used in connection with devices and systems that are based on the interaction of light and matter, such as optical amplifiers and wave-mixing. The quantum nature of light and its coherence properties are studied in *quantum optics*, and the processes that involve non-linear responses of the optical media are covered by the discipline called *non-linear optics*. Finally, some applied disciplines emerging from these areas include *optical communications*, *image and display systems*, *optical computing*, *optical sensing*, etc. In particular, the term *waveguide technology* is used to describe devices and systems widely used in optical communications as well as in optical computing, optical processing and optical sensors.

A clear example of an emergent branch of optics that combines some of the above disciplines is the field of *integrated optics*, or more precisely, *integrated photonics*. We consider integrated photonics to be constituted by the combining of waveguide technology (guided optics) with other disciplines, such as electro-optics, acousto-optics, non-linear optics and opto-electronics (Figure 1.2). The basic idea behind integrated photonics is the use of photons instead of electrons, creating integrated optical circuits similar to those in conventional electronics. The term “integrated optics”, first proposed in 1960 by S.E. Miller [2], was introduced to emphasise the similarity between planar optical circuits technology and the well-established integrated micro-electronic circuits. The solution proposed by Miller was to fabricate integrated optical circuits through a process in which various elements, passive as well as active, were integrated in a single substrate, combining and interconnecting them via small optical transmission lines called waveguides. Clearly, integrating multiple optical functions in a single photonic device is a key step towards lowering the costs of advanced optical systems, including optical communication networks.

The optical elements present in integrated photonic devices should include basic components for the generation, focusing, splitting, junction, coupling, isolation, polarisation control, switching, modulation, filtering and light detection, ideally all of them

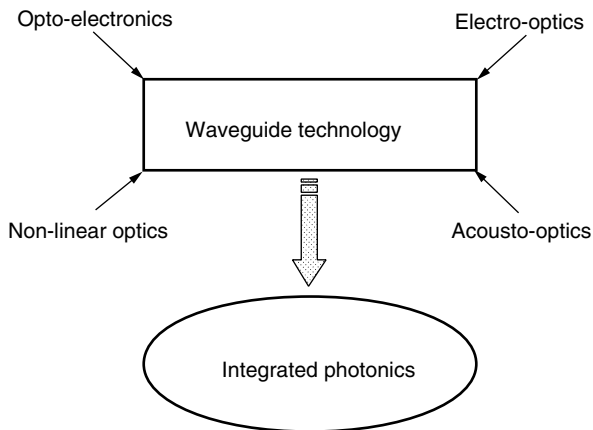


Figure 1.2 Confluence of various disciplines into integrated photonics

being integrated in a single *optical chip*. Channel waveguides are used for the interconnection of the various optical elements. The main goal pursued by integrated photonics is therefore the miniaturisation of optical systems, similar to the way in which integrated electronic circuits have miniaturised electronic devices, and this is possible thanks to the small wavelength of the light, which permits the fabrication of circuits and compact photonic devices with sizes of the order of microns. The integration of multiple functions within a planar optical structure can be achieved by means of planar lithographic production [3]. Although lithographic fabrication of photonic devices requires materials different from those used in microelectronics, the processes are basically the same, and the techniques well established from 40 years of semiconductor production are fully applicable. Indeed, a lithographic system for fabricating photonic components uses virtually the same set of tools as in electronics: exposure tools, masks, photoresists, and all the pattern transfer process from mask to resist and then to device.

1.2 Brief History of Integrated Photonics

For 30 years after the invention of the transistor, the processing and transmission of information were based on electronics that used semiconductor devices for controlling the electron flux. But at the beginning of the 1980s, electronics was slowly supplemented by and even replaced by optics, and photons substituted for electrons as information carriers. Nowadays, photonic and opto-electronic devices based on integrated photonic circuits have grown in such a way that they not only clearly dominate long-distance communications through optical fibres, but have also opened up new fields of application, such as sensor devices, and are also beginning to penetrate in the own field of the information processing technology. In fact, the actual opto-electronic devices may be merely a transition to a future of all-optical computation and communication systems.

The history of integrated photonics is analogous to that of other related technologies: discovery, fast evolution of the devices, and a long waiting time for applications [4]. The first optical waveguides, fabricated at the end of the 1960s, were bidimensional devices on planar substrates. In the mid-1970s the successful operation of tridimensional waveguides was demonstrated in a wide variety of materials, from glasses to crystals and semiconductors. For the fabrication of functional devices in waveguide geometries, lithium niobate (LiNbO_3) was rapidly recognised as one of the most promising alternatives. The waveguide fabrication in LiNbO_3 via titanium in-diffusion was demonstrated at the AT&T Bell Laboratory, and gave rise to the development of channel waveguides with very low losses in a material that possesses valuable electro-optic and acousto-optic effects. In the mid-1980s the viability of waveguide devices based on LiNbO_3 , such as integrated intensity modulators of up to 40 GHz, and with integration levels of up to 50 switches in a single photonic chip had already been demonstrated in laboratory experiments. A few years later, the standard packaging required in telecommunication systems was obtained, and so the devices were ready to enter the market. The rapid boom of monomode optical fibre systems which started in the 1980s was the perfect niche market for these advanced integrated photonic devices that were waiting in the research laboratories. Indeed, the demand for increased transmission capacity (bandwidth) calls urgently for new integrated photonic chips that permit the control and processing of such huge data transfer, in particular