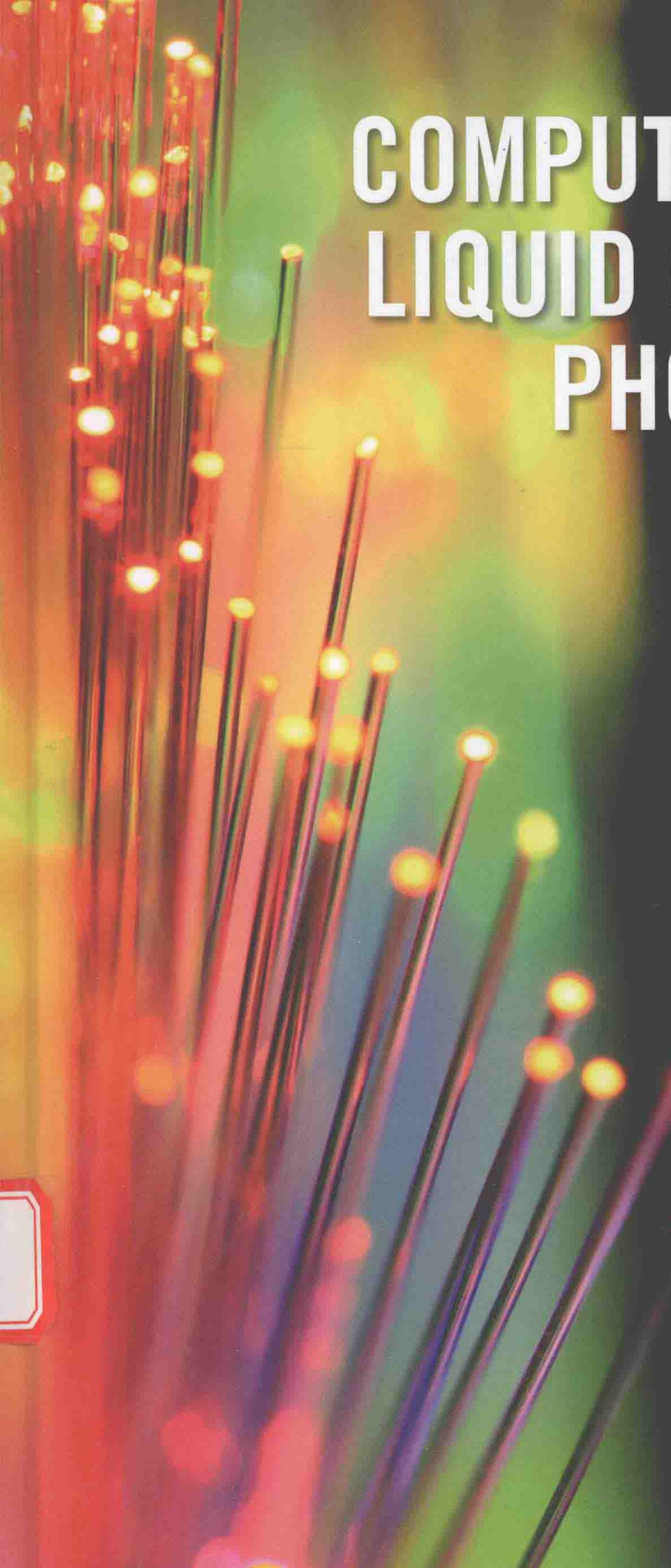
COMPUTATIONAL LIQUID CRYSTAL PHOTONICS

FUNDAMENTALS, MODELLING AND APPLICATIONS



SALAH OBAYYA

MOHAMED FARHAT O. HAMEED

NIHAL F. F. AREED

WILEY

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Salah Obayya
Center for Photonics and Smart Materials
Zewail City of Science and Technology
Giza
Egypt

Mohamed Farhat O. Hameed and Nihal F.F. Areed
Center for Photonics and Smart Materials
Zewail City of Science and Technology
Giza
and
Faculty of Engineering
Mansoura University
Mansoura
Egypt

WILEY

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All Praise is due to Allah, and peace and blessings be upon. Prophet Muhammad and upon his family and his Companions.

The authors would like to dedicate this book to Prof. Ahmed Zewail for his continuous encouragement, support, and the opportunity to contribute to the Egypt National project of renaissance: Zewail City of Science and Technology.

The authors would also like to dedicate the book to their families, whose love, support, patience, and understanding are beyond any scope.

Preface

The turn toward optical computers and photonic integrated circuits in high-capacity optical networks has attracted the interest of expert researchers. This is because all optical packet switching and routing technologies can provide more efficient power and footprint scaling with increased router capacity. Therefore, it is aimed to integrate more optical processing elements into the same chip and, hence, on-chip processing capability and system intelligence can be increased. The merging of components and functionalities decreases packaging cost and can bring photonic devices one step (or more) closer to deployment in routing systems.

Photonic crystal devices can be used functionally as part of a comprehensive all-photonic crystal-based system where, on the same photonic crystal platform, many functionalities can be realized. Therefore, photonic crystals have recently received much attention due to their unique properties in controlling the propagation of light. Many potential applications of photonic crystals require some capability for tuning through external stimuli. It is anticipated that photonic crystals infiltrated with liquid crystals (LCs) will have high tunability with an external electric field and temperature. For the vast majority of LCs, the application of an electric field results in an orientation of the nematic director either parallel or perpendicular to the field, depending on the sign of the dielectric anisotropy of the nematic medium. The scope of this book is to propose, optimize, and simulate new designs for tunable broadband photonic devices with enhanced high levels of flexible integration and enhanced power processing, using a combination of photonic crystal and nematic LC (NLC) layers. The suggested NLC photonic devices include a coupler, a polarization splitter, a polarization rotator, and a multiplexer–demultiplexer for telecommunication applications. In addition, LC photonic crystal-based encryption and decryption devices will be introduced and LC-based routers and sensors will be presented. In almost all cases, an accurate quantitative theoretical modeling of these devices has to be based on advanced computational techniques that solve the corresponding, numerically very large linear, nonlinear, or coupled partial differential equations. In this regard, the book will also offer an easy-to-understand, and yet comprehensive, state-of-the-art of computational modeling techniques for the analysis of lightwave propagation in a wide range of LC-based modern photonic devices.

There are many excellent books on LCs; however, several of these concentrate on the physics and chemistry of the LCs especially for LC display (LCD) applications. In addition, many books on photonic devices have been published in the recent years. However, it is still difficult to find one book in which highly tunable photonic crystal devices based on LC materials are discussed with a good balance of breadth and depth of coverage. Therefore, the book will represent a unique source for the reader to learn in depth about the modeling techniques and simulation of the processing light through many tunable LC devices.

The primary audience for this book are undergraduate students; the student will be taken from scratch until he can develop the subject himself. The secondary audience are the business and industry experts working in the fields of information and communications technology, security, and sensors because the book intends to open up new possibilities for marketing new commercial products. The audience of this book will also include the researchers at the early and intermediate stages working in the general areas of LC photonics. The book consists of three parts: LC basic principles, numerical modeling techniques, and LC-based applications. The first part includes three chapters where the basic principles of waveguides and modes, photonic crystals, and liquid crystals are given. From Chapters 4 to 6, the numerical techniques operating in the frequency domain are presented. Among them, Chapter 4 presents the governing equations for the full-vectorial finite-difference method (FVFDM) and perfectly matched layer (PML) scheme for the treatment of boundary conditions. The FVFDM is then assessed in Chapter 5 where the modal analysis of LC-based photonic crystal fiber (PCF) is given. The FV beam propagation method (FVBPM) is presented in Chapter 6 to study the propagation along the LC-PCF-based applications. After deriving the governing equations, the FVBPM is numerically assessed through several optical waveguide examples. The conventional finite-difference time domain (FDTD) method in 2D and 3D, as an example of the numerical techniques operating in the time domain is presented in Chapter 7.

The third part consists of six chapters to cover the applications of the LC-based photonic crystal devices. From Chapters 8 to 10, the applications of the LC-PCF for telecommunication devices, such as couplers, polarization rotators, polarization splitters, and multiplexer–demultiplexers, are introduced. In addition, the LC-PCF sensors, such as biomedical and temperature sensors, are explained in Chapter 11. Photonic crystal-based encryption systems for security applications are covered in Chapter 12. Optical computing devices, such as optical routers, optical memory, and reconfigurable logic gates, are introduced in Chapter 13.

Contents

Part I
Basic Principles

1

Principles of Waveguides

1.1 Introduction

A waveguide can be defined as a structure that guides waves, such as electromagnetic or sound waves [1]. In this chapter, the basic principles of the optical waveguide will be introduced. Optical waveguides can confine and transmit light over different distances, ranging from tens or hundreds of micrometers in integrated photonics, to hundreds or thousands of kilometers in long-distance fiber-optic transmission. Additionally, optical waveguides can be used as passive and active devices such as waveguide couplers, polarization rotators, optical routers, and modulators. There are different types of optical waveguides such as slab waveguides, channel waveguides, optical fibers, and photonic crystal waveguides. The slab waveguides can confine energy to travel only in one dimension, while the light can be confined in two dimensions using optical fiber or channel waveguides. Therefore, the propagation losses will be small compared to wave propagation in open space. Optical waveguides usually consist of high index dielectric material surrounded by lower index material, hence, the optical waves are guided through the high index material by a total internal reflection mechanism. Additionally, photonic crystal waveguides can guide the light through low index defects by a photonic bandgap guiding technique. Generally, the width of a waveguide should have the same order of magnitude as the wavelength of the guided wave.

In this chapter, the basic optical waveguides are discussed including waveguides operation, Maxwell's equations, the wave equation and its solutions, boundary conditions, phase and group velocity, and the properties of modes.

Computational Liquid Crystal Photonics: Fundamentals, Modelling and Applications, First Edition.
Salah Obayya, Mohamed Farhat O. Hameed and Nihal F.F. Areed.

1.2 Basic Optical Waveguides

Optical waveguides can be classified according to their geometry, mode structure, refractive index distribution, materials, and the number of dimensions in which light is confined [2]. According to their geometry, they can be categorized by three basic structures: planar, rectangular channel, and cylindrical channel as shown in Figure 1.1. Common optical waveguides can also be classified based on mode structure as single mode and multiple modes. Figure 1.1a shows that the planar waveguide consists of a core that must have a refractive index higher than the refractive indices of the upper medium called the cover, and the lower medium called the substrate. The trapping of light within the core is achieved by total internal reflection. Figure 1.1b shows the channel waveguide which represents the best choice for fabricating integrated photonic devices. This waveguide consists of a rectangular channel that is sandwiched between an underlying planar substrate and the upper medium, which is usually air. To trap the light within a rectangular channel, it is necessary for the channel to have a refractive index greater than that of the substrate. Figure 1.1c shows the geometry of the cylindrical channel waveguide which consists of a central region, referred to as the core, and surrounding material called cladding. Of course, to confine the light within the core, the core must have a higher refractive index than that of the cladding.

Figure 1.2 shows the three most common types of channel waveguide structures which are called strip, rip, and buried waveguides. It is evident from the figure that the main difference between the three types is in the shape and the size of the film deposited onto the substrate. In the strip waveguide shown in Figure 1.2a, a high index film is directly deposited on the substrate with finite width. On the other hand, the rip waveguide is formed by depositing a high index film onto the substrate and performing an incomplete etching around a finite width as shown in Figure 1.2b. Alternatively, in the case of the buried waveguide shown in Figure 1.2c,

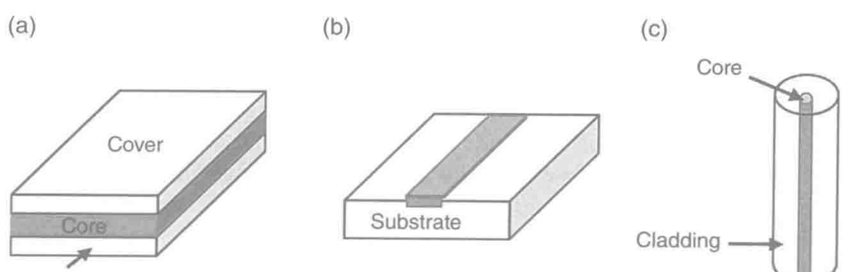

Figure 1.1 Common waveguide geometries: (a) planar, (b) rectangular, and (c) cylindrical

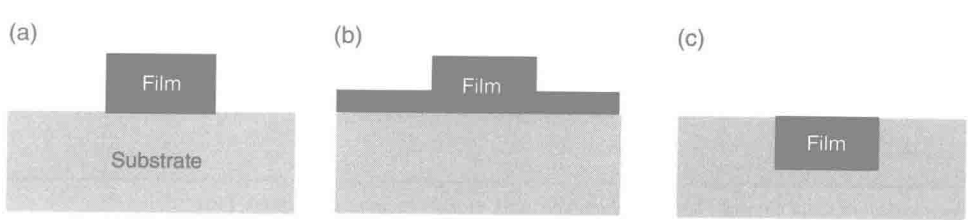

Figure 1.2 Common channel waveguides: (a) strip, (b) rip, and (c) buried