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光波导模式

——偏振、耦合与对称

Optical Waveguide Modes

Polarization, Coupling and Symmetry

〔美〕Richard J. Black
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内容简介

本书是一本关于波导模式对称性分析的学术专著。在简要介绍传统导波光学内容的基础上，重点以光波导弱导微扰理论和群论作为理论分析手段，对单模和少模光波导，特别是单芯和多芯光纤的波导模式结构和分类进行了系统的介绍，并讨论了模式对称性分析方法对周期结构、非线性波导和光子晶体等复杂波导结构的应用。

本书的理论描述简洁，适合于具有较好的电磁理论基础，并对导波光学理论和群论有一定了解的科研人员阅读参考。

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推荐序

本书是一本利用群论分析光学波导模式结构的专著。全书共7章。第1章回顾了光学波导的一般概念，对群论在光学波导模式结构理论分析中的作用做了简单介绍。在第2章中，介绍了各向异性媒质构成的光学波导的电磁理论，并针对纵向不变的光纤结构，给出了弱导近似下的标量波动方程和全矢量波动方程及其各阶微扰形式。第3章针对各向同性媒质构成的圆对称光纤，利用群论分别分析了由弱导近似下的波动方程、零阶微扰形式的矢量方程和全矢量方程求解出的光纤模式结构。第4章讨论了光学波导结构对称性破缺情况下波导模式的群论分析方法和模式结构特点。第5章讨论了波导中的各种双折射形式及其与波导对称性的关系。第6章介绍了多波导组合结构及其分立的旋转对称分析。第7章是全书的总结，讨论了非线性波导、光子晶体和光子准晶、光子晶体光纤和光纤光栅等复杂波导结构的特点和模式分析结构要点。书的最后给出了书中应用的群论基本概念和结论。

本书的两位作者长期从事光纤光学、导波光学和相关电磁与数学理论的研究，并且有很强的工业界背景，书的内容体现了他们深厚的理论基础和丰富的研究经验。作为一本导波光学专著，本书没有将重点放在电磁波动方程的求解上，而是利用群论作为理论分析工具，系统地阐明了光学波导模式结构与结构对称性间的关系，内容非常新颖，并且有相当的理论深度。本书在写作上特别注意避免复杂的数学推导，力图以图表等直观形式表达理论分析的过程和结论。同时，本书提供了大量参考文献，较全面地覆盖了光学波导群论分析发展过程中的重要原始资料，是读者在该领域继续深造的宝贵参考。

本书有助于电磁理论研究者了解对称分析在光学波导研究中的应用，同时对导波光学和光纤光学研究者了解光学波导模式结构构成的规律有重要的参考价值。

张　巍

2012年6月于清华大学

PREFACE

This book is about the modes of single- and few-mode optical waveguides with an emphasis on single-core and multicore optical fibers and couplers including a large range of geometries and anisotropies, both standard and exotic. It provides both an "atlas" of modal field forms and an understanding of the physical properties resulting from waveguide symmetries. In addition to optical waveguide and fiber-optic designers, researchers, and students, this book may appeal to quantum and solid-state chemists and physicists interested in the application by analogy of techniques they know well in the continually expanding field of photonics.

To aid in rapid understanding, we emphasize a building-block approach with approximate modes and simplified structures forming a basis for more exact analyses and more complex structures. Accordingly we commence with single-core fibers and the symmetry consequences arising from specific forms of the azimuthal and radial dependence of the index profile.

The mathematical tools involve (1) the weak-guidance perturbation formalism facilitating the incorporation of polarization effects following a scalar analysis together with (2) a group theoretic approach for systematic exploitation of symmetry.

Scalar modes provide a basis for vector modes. Field constructions for transverse and hybrid polarized modes in terms of both linearly and circularly polarized modes are given. Degeneracy splittings and vector mode field transformations are considered depending on the relative strengths of the refractive index profile height and deformations from a circular cross section (e.g., elliptical, triangular, square) or birefringence (linear, radial or azimuthal, circular). Both microscopic and macroscopic anisotropies are considered: The polarization effects arising from a single interface may be regarded as a macroscopic manifestation of form birefringence. Single-core results are then used as a building block in the analysis arrays of few-mode lightguides: multicore fibers and multifiber couplers.

The organization of material is as follows:

- Chapter 1 provides an introduction including a motivation for the study of waveguide mode forms.
- Chapter 2 starts from the fundamental Maxwell equations for electrically anisotropic and isotropic media to provide a

comprehensive treatment of the resulting wave equations. For longitudinally invariant optical waveguides, it emphasizes the weak-guidance formalism which in general leads to perturbation expansion in terms of the typically small fractional refractive index difference between the waveguide core and cladding.

- Chapter 3 considers the scalar and vector modes of circular optical fibers. It includes a tutorial introduction to the consequences of symmetry, using a group theoretic approach in degeneracy determination and field construction of different modes of circularly symmetric fibers.
- Chapter 4 examines elliptical, triangular, and square deformations of circular waveguide cross sections as illustrations of the modal degeneracy splitting and field transformation resulting when the *azimuthal* circular symmetry is lowered to n-fold rotation-reflection symmetry.
- Chapter 5 considers linearly, radially, and circularly birefringent (gyrotropic) fibers.
- Chapter 6 is devoted to the construction of modes of multicore fibers and multifiber coupler arrays.
- Chapter 7 provides a summary of the results and discusses extensions of the concept of modes for longitudinally invariant structures to modes for structures with longitudinal variations, such as periodic structures and Kerr-type nonlinear waveguides where intensity-dependence induces longitudinal variation in the presence of a propagating wave.
- The appendix provides the essential results of elementary applied group representation theory used for the analysis of many physical and chemical systems involving symmetry. Together with the symmetry tutorial included in Sec. 3.2, this provides an alternative introduction to and/or illustration of concepts which students might apply by analogy in many other fields such as quantum, solid-state, and molecular chemistry and physics.

Richard J. Black
Langis Gagnon

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Following some inspiring discussions and correspondence with Prof. Geoff Stedman in 1986, this book had its origins in two manuscripts [1, 2] prepared by us in the mid to late 1980s while Richard J. Black (RJB) was at the École Polytechnique de Montréal and Langis Gagnon (LG) was at the Université de Montréal. Following the encouragement of Prof. Carlo Someda, the first full version of this book was prepared in 1991–1992, with relevant references up until that time, while RJB was at the École Polytechnique de Montréal. It was later revised for part of a course presented by RJB at the Swiss Federal Institute of Technology [École Polytechnique de Lausanne (EPFL)] in January–February 1995. The present 2010 revised version followed from discussions between RJB and Taisuke Soda of McGraw-Hill, who we thank, together with all the McGraw-Hill and Glyph International team, particularly Shruti Vasishta, for expert preparation of the book. We also thank colleagues at Photon Design, Technix by CBS, IFOS, and CRIM, and many other colleagues, family, and friends too numerous to mention, for their contributions and support.

The present new version includes (a) a simple intuitive introduction to waveguide modes (Sec. 1.5) aimed at those encountering them for the first time, (b) recent developments (Secs. 7.4 through 7.8), and (c) 78 additional references. (With regard to references, the first 138 appeared in the 1992 manuscript, and Refs. 139 and 140 were added for the 1995 manuscript.) While the fundamental theory of optical waveguide modes presented herein remains the same, since 1992 we have witnessed considerable growth in photonics in the commercial sector (particularly rapid in telecom in the late 1990s with steady progress in photonic sensors to the present), with technical and scientific developments in many areas, for example, periodic lightguides [fiber Bragg gratings (FBGs), photonic crystal fibers, and photonic crystals] and waveguide modeling packages. We touch on these areas in added Refs. 141 and above together with new Secs. 7.4 through 7.8.

Richard J. Black
Langis Gagnon
2010

RJB is grateful to Prof. René-Paul Salathé and the Swiss Federal Institute of Technology, Lausanne (EPFL), for providing him with the opportunity to present this material as a course at EPFL, and to those who suggested improvements to the 1992 version, particularly Prof. Carlo Someda.

Richard J. Black
1995

We are especially indebted to Prof. Geoffrey E. Stedman, University of Canterbury, New Zealand, for many very perceptive, enlightening discussions and correspondence that provided much of the initial insight and inspiration. We thank Dion Astwood for undertaking a useful student project [94] to clarify points regarding modal transformation properties and splittings. Many others kindly provided ideas, discussions, and support. We are particularly grateful to Prof. Carlo Someda for making this book possible with his very generous contribution of kind and patient correspondence and many ideas that helped to improve the original manuscript as well as the much appreciated hospitality to RJB at the Università di Padova; Prof. George Stegeman for hospitality to RJB at the Optical Sciences Center, University of Arizona, during the initial stages; and Prof. John Shaw of Stanford for extensive hospitality and many discussions regarding few-mode fiber devices. We thank Dr. Ken Hill, Communications Research Center (CRC), Canada, and Dr. Richard Lowe and Costas Saravanos of Northern Telecom for support and discussions regarding modes in couplers, tapered fibers, and modal interferometry; and Dr. Iain M. Skinner, University of New South Wales (formerly of CRC), for comments and enlightening discussions regarding mode transitions [20]. RJB thanks his colleagues at the École Polytechnique de Montréal, Profs. Jacques Bures and Suzanne Lacroix, and Dr. François Gonthier for their support and ideas regarding multifiber couplers and modal interferometry, and Profs. John Harnad and Pavel Winternitz for hospitality at the Centre de Recherches Mathématiques (CRM), Université de Montréal, and discussions regarding nonlinear fibers and group theory, as well as the Australian waveguide theorists Profs. Colin Pask, Allan Snyder, and John Love during RJB's formation of ideas on waveguide modes. LG thanks Prof. Pavel Winternitz, Université de Montréal, and Prof. Pierre-André Bélanger, Centre d'Optique Photonique et Laser, Université Laval, for helpful discussions and support.

Richard J. Black
Langis Gagnon
1992

CONTENTS

Chapter 1

Introduction 1

Chapter 2

Electromagnetic Theory for Anisotropic Media and Weak Guidance for Longitudinally Invariant Fibers 19

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Multicore Fibers and Multifiber Couplers 97

Chapter 7

Appendix

CHAPTER 1

Introduction

In this chapter, Secs. 1.1 through 1.4 introduce the major themes of the book. Section 1.5 provides an intuitive introduction to optical waveguide modes and Sec. 1.6 provides a chapter-by-chapter outline of the remainder of the book highlighting major results.

1.1 MODES

This is a book about *lightguide mode forms*. In particular,

1. We emphasize the basic structure of **modal field patterns** *in optical fiber cross sections* **transverse** to the direction of propagation.
2. We consider the relative **longitudinal** dependencies of modal fields in terms of their *propagation constant degeneracies or splittings*. Our major objective is to provide an understanding of **how transverse optical waveguide geometry influences modal polarization properties** with refractive index variations ranging from macroscopic "global anisotropies" down to scales much smaller than a wavelength where the local refractive indices of the constituent waveguide media can be treated as anisotropic. As in Refs. 1 and 2, we undertake the analysis using extensions of the weak-guidance perturbation formalism [3] together with elementary group representation theory [4–6]; see also Refs. 7 through 10.

As well as providing the basic general electromagnetic formalism and structural description appropriate for analysis of the lowest-order or fundamental modes (i.e., the two polarization states of the modes referred to as HE_{11} and LP_{01} or CP_{01}), we go beyond that mainstay of present-day long-distance telecommunications and include a detailed introduction and classification of diverse forms of higher-order modes and various polarization manifestations thereof, e.g., modes of polarization that are transverse electric (TE), transverse magnetic (TM), hybrid (HE or EH), linear (LP), circular (CP), and "triangular" (TP). We give particular attention to the *second-order modes;* e.g., for circular fibers, these are the TE_{01}, TM_{01}, and HE_{21} modes, each of which may be constructed in terms of two linearly polarized (LP_{11}) "pseudo-modes" or alternatively in terms of circularly polarized (CP_{11}) modes.

Apart from the applications, since the original circular fiber modal classification scheme due to Snitzer [11], few-mode lightguide problems have attained a particular physical interest in their own right, e.g., Ref. 12. Indeed, our major aim is simply **to provide an understanding of the fundamental physics of mode structure**. It is our belief that a valuable basis for future novel waveguide designs and exploitations will be provided by a thorough knowledge of how waveguide structure—ranging from standard to exotic—can be used to create and manipulate modes with the desired properties.

While *we mostly restrict ourselves to the concept of monochromatic independently propagating modes of idealized lightguides with longitudinally invariant linear refractive indices*, **these ideal "linear" modes** may form the **basis** for **adaptations to perturbed and other less idealized situations** including **longitudinal variations** and **"nonlinear" effects** using coupled-mode, local-mode, coupled-local-mode, and other approaches [e.g., 3, 13]. In the context of few-mode fibers, we mention but some of the adaptations of topical interest for which a full understanding of ideal linear guide modes as a fundamental building block can provide useful added insight:

1. Nonlinear (Kerr-type) intensity-dependent modal interferometry [14–17]
2. Nonlinear (second harmonic) frequency conversion via phase matchings of different-order modes [18]
3. (Permanent-) Grating induced frequency conversion and filtering [19, 20]

In general, few-mode lightguides have received attention ranging from visual photoreceptor studies [21] to a particular recent interest in **modal interferometry** [22, 23] and applications thereof, such as