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Photonic Crystal Fibers: Properties and Applications

光子晶体光纤
——特性及应用

（影印版）

〔意〕波利（F. Poli）
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序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会 主任

中国科学院院士，北京大学教授

王恩哥

2010 年 5 月于燕园

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Photonic Crystal Fibers

Properties and Applications

With 129 Figures

Springer

Preface

Photonic crystal fibers, also known as microstructured or holey fibers, have recently generated great interest in the scientific community thanks to the new ways provided to control and guide light, not obtainable with conventional optical fibers. Proposed for the first time in early 90's, photonic crystal fibers have driven an exciting and irrepressible research activity all over the world, starting in the telecommunication field and then touching metrology, spectroscopy, microscopy, astronomy, micromachining, biology and sensing.

A variety of very interesting publications and high level books have been already presented, describing the different kinds of these new fibers, the physics of their behavior, as well as a huge range of design tools. These aspects will not be considered again in this work.

This book, instead, is intended to provide an expert guidance through the properties of photonic crystal fibers, with a specific focus on the telecommunication aspects. Although standard fibers for telecommunication can rely on a well-established technology and standard fiber based devices and systems represent a consolidated reality, hardly replaceable, the authors believe that photonic crystal fibers can revolutionize the field of guided optics and its applications, even if much easier and close opportunities can be foreseen in many other fields. This belief gets firmer when considering signal processing and specific functions rather than the usage of photonic crystal fibers in long distance transmission.

The long expertise of the authors in fiber based device analysis is reflected in a deep analysis aimed to practically understand how the physical and geometrical characteristics of these new fibers can be tailored to achieve the goal of ad hoc performances. The study, mainly performed with the help of the finite element method, a powerful numerical approach the authors are very expert in, has enabled to understand how best to optimize the fiber design, always keeping in mind actual possibilities and limits of photonic crystal fiber fabrication technology.

This book will thus benefit researchers approaching this very dynamic and evolving subject with the interest to explore this field of telecommunication, looking at current as well as emerging applications.

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The authors would like to thank all the people who have actively participated in their research activity regarding photonic crystal fibers in the last years. A special thanks is due to Matteo Foroni for his constant support in the experimental activity and in the theoretical analysis, and for his fundamental help in the book writing; to Lorenzo Rosa for his valuable work on the finite element code improvement and development; to Luca Vincetti for the fruitful and stimulating discussions.

The authors are grateful to Crystal Fiber A/S for providing all the pictures of the photonic crystal fibers inserted in this book.

Contents

Introduction

Until recently, an optical fiber was a solid thread surrounded by another material with a lower refractive index. Today, photonic crystal fibers (PCFs) are established as an alternative fiber technology. PCFs, which have been first demonstrated in 1995, are optical fibers with a periodic arrangement of low-index material in a background with higher refractive index. The background material in PCFs is usually undoped silica and the low-index region is typically provided by air-holes running along their entire length.

Two main categories of PCFs exist: high-index guiding fibers and photonic bandgap ones.

PCFs belonging to the first category are more similar to conventional optical fibers, because light is confined in a solid core by exploiting the modified total internal reflection mechanism. In fact, there is a positive refractive index difference between the core region and the photonic crystal cladding, where the air-hole presence causes a lower average refractive index. The guiding mechanism is defined as “modified” because the cladding refractive index is not a constant value, as in standard optical fibers, but it changes significantly with the wavelength.

This characteristic, as well as the high refractive index contrast between silica and air, provides a range of new interesting features. Moreover, a high design flexibility is one of the distinctive properties of PCFs. In particular, by changing the geometric characteristics of the air-holes in the fiber cross-section, that is, their dimension or position, it is possible to obtain PCFs with diametrically opposite properties. For example, PCFs with a small silica core and large air-holes, that is, with a high air-filling fraction in the transverse section, have better nonlinear properties compared with conventional optical fibers, and so they can be successfully used in many applications, like supercontinuum generation. On the contrary, fibers can be designed with small air-holes and large hole-to-hole distances, in order to obtain a large modal area, useful for high-power delivery. Differently from standard fibers, PCFs with proper geometric characteristics can be endlessly single mode, that is, only the fundamental mode is guided, regardless of the wavelength. In addition, a significant asymmetry can be introduced in a simple way in the PCF core, thus creating fibers with very high level of birefringence. Moreover, the PCF dispersion properties can be tailored with high flexibility, that is, it is possible to move the zero-dispersion wavelength to the visible range, as well as to obtain dispersion curves ultraflattened or with a strong negative slope.

When the PCF core region has a lower refractive index than the surrounding photonic crystal cladding, light is guided by a mechanism different from total internal reflection, that is, by exploiting the presence of the photonic bandgap (PBG). In fact, the air-hole microstructure which constitutes the PCF cladding is a two-dimensional photonic crystal, that is a material with periodic dielectric properties characterized by a photonic bandgap, where light in certain wavelength ranges cannot propagate. The PBG effect can be also found in nature, since it is responsible, for example, of the beautiful and bright colors seen in butterfly wings. PCFs with a low index core are created by introducing a defect in the photonic crystal structure, for example, an extra air-hole or an enlarged one, and light is confined because the PBG makes propagation in the microstructured cladding region impossible. This guiding mechanism cannot be obtained in conventional optical fibers and it opens a whole new set of interesting possibilities.

In particular, light can be guided in air in PCFs with a hollow core, thus providing numerous promising applications, such as low-loss guidance and high-power delivery, without the risk of fiber damage. Moreover, air-guiding PCFs are almost insensitive to bending, even for small bending diameter values, and they present extreme dispersion properties, highly dominated by the waveguide component. Finally, when filled with proper gases or liquids, hollow-core PCFs can be successfully employed in sensor applications or for nonlinear optics.

Since their first demonstration, PCFs have been the object of an intense research activity by the most important groups all around the world. In fact, it is particularly intriguing to study the new light-guiding mechanisms offered by PCFs and the innovative properties related to the presence of the PBG. Moreover, the possibility of modifying the air-hole geometry in the fiber cross-section is limited only by the technological feasibility of the designed PCFs. It is also very interesting to investigate how the PCF properties can be influenced by the changes of the geometric characteristics and "how far" it is possible to go from the well-known and established properties of standard optical fibers.

The research activity described in this book is set in this context, which is in continuous evolution and characterized by a great scientific excitement. The aim of the research carried out and here reported has been to accurately study, and thus to deeply understand, the light-guiding mechanisms exploited in this new kind of optical fibers. PCFs with unusual guiding, dispersion, and amplification properties have been designed by exploring different air-hole arrangements in the fiber cross-section. This has been done with a constant attention to the possible applications of the proposed PCFs, in the field of the optical communications. Moreover, the performances of the traditional optical fibers have been always considered as a useful comparison parameter, in order to evaluate the effective advantages offered by these new fibers. Finally, the results of these studies have been presented in a critical way, that is, by underlining the possible drawbacks, which are usually related to the PCF attenuation, which is still higher than that of the conventional optical fibers.

The book is organized in six chapters. Chapter 1 is a general presentation of the PCF innovative characteristics. Starting from the description of the properties of photonic crystals, materials with a refractive index periodic distribution, the passage from conventional optical fibers to photonic crystal ones is explained. After describing the two light-guiding mechanisms exploited in PCFs, the advantages offered by this new fiber type with respect to the conventional ones are discussed. Then, some meaningful examples of PCFs with unusual guiding, dispersion, and nonlinear properties, proposed in the literature and successfully used in many applications, are reported. Moreover, the different loss mechanisms are presented for both solid- and hollow-core PCFs, since attenuation is still the main drawback which affects this new kind of optical fibers. Once a significant loss reduction is obtained, which can be reached by improving the fabrication process described in the final part of Chapter 1, these new fibers will enter in the market in a significant way.

In Chapters 2–6 the main results of the research activity carried out by the authors in the past years are presented. In each chapter, results concerning the same topic, that is, guiding, dispersion, or amplification properties, are collected. It is important to underline that all the analyses reported in this book have been developed by mainly using the finite element method (FEM), in particular, a full-vector modal solver, as described in Appendix A. This numerical method is particularly suitable to study PCFs, since fibers with any refractive index profile, as well as any air-hole arrangement in the transverse section, including the nonperiodic ones, can be analyzed.

Chapter 2 summarizes the results concerning the PCF guiding properties, which directly come from the complex propagation constant of the guided modes. First of all, the study of the influence of the geometric parameters on the fundamental guided-mode characteristics in a new kind of PCF, with a square lattice of air-holes, is reported. Moreover, the modal cutoff analysis of these PCFs is presented. The same method has been successfully applied to study the single-mode regime of a new kind of triangular PCFs, which have a wide silica core and a large modal area. In fact, it is important to investigate the trade-off between the effective area and the cutoff of the fundamental guided mode, in order to successfully exploit these large-mode area fibers in practical applications. In the final part of the chapter the study of the guiding, leakage, and birefringence properties of hollow-core PCFs with a modified honeycomb lattice, which guide light by exploiting the PBG effect, is reported. Air-guiding has been demonstrated in fibers with a larger bandgap with respect to that obtained with triangular lattices.

The design of PCFs with innovative dispersion properties is described in Chapter 3. In fact, it is possible to significantly change the waveguide contribution to the dispersion parameter by properly changing the geometric characteristics of the air-holes in the cross-section. Triangular PCFs characterized by a high air-filling fraction, that is, with large air-holes and small hole-to-hole spacing, have been designed to compensate the anomalous dispersion and the dispersion slope of single-mode fibers around 1550 nm, as it is reported at the beginning of the chapter. Then, the dispersion properties of fibers with a square lattice of air-holes, obtained with different values of the geometric parameters, are discussed and compared with those of triangular PCFs. In the second part of the chapter the design of triangular PCFs with completely different dispersion characteristics, that is with flattened dispersion curve and zero-dispersion wavelength around 1550 nm, which can be exploited for nonlinear applications, is described. The cross-section geometry around the core of the triangular PCFs has been modified in two different ways, in order to obtain the desired dispersion properties and a small effective area, that is a high nonlinear coefficient.

Chapter 4 deals with the PCF nonlinear properties. Firstly, supercontinuum generation is described, since it is one of the most interesting applications