

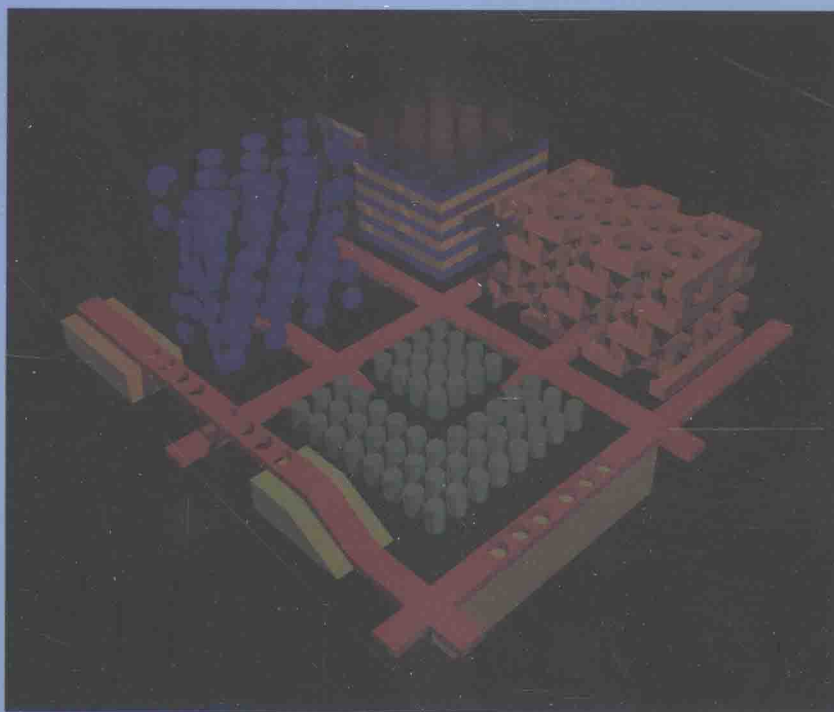
John D. Joannopoulos, Steven G. Johnson,
Joshua N. Winn, Robert D. Meade

Photonic Crystals

Molding the Flow of Light

SECOND EDITION

光子晶体 第2版



PRINCETON UNIVERSITY PRESS

世界图书出版公司
www.wpcbj.com.cn

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图书在版编目 (CIP) 数据

光子晶体: 第2版 = Photonic Crystals: Molding the Flow of Light 2nd ed. : 英文/
(英) 乔安普勒斯 (Joannopoulos, J. D.) 著. —影印本. —北京: 世界图书出版公司北京公司, 2013. 5

ISBN 978-7-5100-6140-0

I. ①光… II. ①乔… III. ①光学晶体—英文 IV. ①O7

中国版本图书馆 CIP 数据核字 (2013) 第 088323 号

书 名: Photonic Crystals: Molding the Flow of Light 2nd ed.
作 者: John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn, Robert D. Meade
中 译 名: 光子晶体 第2版
责任编辑: 高蓉 刘慧

出 版 者: 世界图书出版公司北京公司
印 刷 者: 三河市国英印务有限公司
发 行: 世界图书出版公司北京公司 (北京朝内大街 137 号 100010)
联系电话: 010-64021602, 010-64015659
电子信箱: kjb@wpcbj.com.cn

开 本: 16 开
印 张: 19
版 次: 2013 年 10 月
版权登记: 图字: 01-2013-1436

书 号: 978-7-5100-6140-0 定 价: 149.00 元

Copyright © 2008 by Princeton University Press

Published by Princeton University Press, 41 William Street, Princeton,
New Jersey 08540

In the United Kingdom: Princeton University Press, 3 Market Place,
Woodstock, Oxfordshire OX20 1SY

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Library of Congress Cataloging-in-Publication Data

Joannopoulos, J. D. (John D.), 1947-

Photonic crystals: molding the flow of light / John D. Joannopoulos . . . [et al].
p. cm.

Includes bibliographical references and index.

ISBN: 978-0-691-12456-8 (acid-free paper)

1. Photons. 2. Crystal optics. I. Joannopoulos, J. D. (John D.), 1947- II. Title.

QC793.5.P427 J63 2008

548'.9-dc22

2007061025

British Library Cataloging-in-Publication Data is available

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To Kyriaki and G. G. G.

To see a World in a Grain of Sand,
And a Heaven in a Wild Flower,
Hold Infinity in the palm of your hand
And Eternity in an hour.

— *William Blake, Auguries of Innocence (1803)*

PREFACE TO THE SECOND EDITION

We were delighted with the positive response to the first edition of this book. There is, naturally, always some sense of trepidation when one writes the first text book at the birth of a new field. One dearly hopes the field will continue to grow and blossom, but then again, will the subject matter of the book quickly become obsolete? To attempt to alleviate the latter, we made a conscious effort in the first edition to focus on the fundamental concepts and building blocks of this new field and leave out any speculative areas. Given the continuing interest in the first edition, even after a decade of exponential growth of the field, it appears that we may have succeeded in this regard. Of course, with great growth come many new phenomena and a deeper understanding of old phenomena. We felt, therefore, that the time was now ripe for an updated and expanded second edition.

As before, we strove in this edition to include new concepts, phenomena and descriptions that are well understood—material that would stand the test of advancements over time.

Many of the original chapters are expanded with new sections, in addition to innumerable revisions to the old sections. For example, chapter 2 now contains a section introducing the useful technique of perturbation analysis and a section on understanding the subtle differences between discrete and continuous frequency ranges. Chapter 3 includes a section describing the basics of index guiding and a section on how to understand the Bloch-wave propagation velocity. Chapter 4 includes a section on how to best quantify the band gap of a photonic crystal and a section describing the novel phenomenon of omnidirectional reflectivity in multilayer film systems. Chapter 5 now contains an expanded section on point defects and a section on linear defects and waveguides. Chapter 6 was revised considerably to focus on many new aspects of 3D photonic crystal structures, including the photonic structure of several well known geometries. Chapters 7 through 9 are all new, describing hybrid photonic-crystal structures consisting, respectively, of 1D-periodic dielectric waveguides, 2D-periodic photonic-crystal slabs, and photonic-crystal fibers. The final chapter, chapter 10 (chapter 7 in the first edition), is again focused on designing photonic crystals for applications, but now contains many more examples. This chapter has also been expanded to include an introduction and practical guide to temporal coupled-mode theory. This is a very simple, convenient, yet powerful analytical technique for understanding and predicting the behavior of many types of photonic devices.

Two of the original appendices have also been considerably expanded. Appendix C now includes plots of gap size and optimal parameters vs. index contrast for both 2D and 3D photonic crystals. Appendix D now provides a completely new description of computational photonics, surveying computations in both the frequency and time domains.

The second edition also includes two other major changes. The first is a change to SI units. Admittedly, this affects only some of the equations in chapters 2 and 3; the “master equation” remains unaltered. The second change is to a new color table for plotting the electric and magnetic fields. We hope the reader will agree that the new color table is a significant improvement over the old color table, providing a much cleaner and clearer description of the localization and sign-dependence of the fields.

In preparing the second edition, we should like to express our sincere gratitude to Margaret O’Meara, the administrative assistant of the Condensed Matter Theory Group at MIT, for all the time and effort she unselfishly provided. We should also like to give a big *Thank You!* to our editor Ingrid Gnerlich for her patience and understanding when deadlines were not met and for her remarkable good will with all aspects of the process.

We are also very grateful to many colleagues: Eli Yablonovitch, David Norris, Marko Lončar, Shawn Lin, Leslie Kolodziejski, Karl Koch, and Kiyoshi Asakawa, for providing us with illustrations of their original work, and Yoel Fink, Shan-hui Fan, Peter Bienstman, Mihai Ibanescu, Michelle Povinelli, Marin Soljacic, Maksim Skorobogatiy, Lionel Kimerling, Lefteris Lidorikis, K. C. Huang, Jerry Chen, Hermann Haus, Henry Smith, Evan Reed, Erich Ippen, Edwin Thomas, David Roundy, David Chan, Chiyan Luo, Attila Mekis, Aristos Karalis, Ardavan Farjadpour, and Alejandro Rodriguez, for numerous collaborations.

Cambridge, Massachusetts, 2006

PREFACE TO THE FIRST EDITION

It is always difficult to write a book about a topic that is still a subject of active research. Part of the challenge lies in translating research papers directly into a text. Without the benefit of decades of classroom instruction, there is no existing body of pedagogical arguments and exercises to draw from.

Even more challenging is the task of deciding which material to include. Who knows which approaches will withstand the test of time? It is impossible to know, so in this text we have tried to include only those subjects of the field which we consider most likely to be timeless. That is, we present the fundamentals and the proven results, hoping that afterwards the reader will be prepared to read and understand the current literature. Certainly there is much to add to this material as the research continues, but we have tried to take care that nothing need be subtracted. Of course this has come at the expense of leaving out new and exciting results which are a bit more speculative.

If we have succeeded in these tasks, it is only because of the assistance of dozens of colleagues and friends. In particular, we have benefited from collaborations with Oscar Alerhand, G. Arjavalingam, Karl Brommer, Shanhui Fan, Ilya Kurland, Andrew Rappe, Bill Robertson, and Eli Yablonovitch. We also thank Paul Gourley and Pierre Villeneuve for their contributions to this book. In addition, we gratefully thank Tomas Arias and Kyeongjae Cho for helpful insights and productive conversations. Finally, we would like to acknowledge the partial support of the Office of Naval Research and the Army Research Office while this manuscript was being prepared.

Cambridge, Massachusetts, 1995

Photonic Crystals

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1

Introduction

Controlling the Properties of Materials

Many of the true breakthroughs in our technology have resulted from a deeper understanding of the properties of materials. The rise of our ancestors from the Stone Age through the Iron Age is largely a story of humanity's increasing recognition of the utility of natural materials. Prehistoric people fashioned tools based on their knowledge of the durability of stone and the hardness of iron. In each case, humankind learned to extract a material from the Earth whose fixed properties proved useful.

Eventually, early engineers learned to do more than just take what the Earth provides in raw form. By tinkering with existing materials, they produced substances with even more desirable properties, from the luster of early bronze alloys to the reliability of modern steel and concrete. Today we boast a collection of wholly artificial materials with a tremendous range of *mechanical* properties, thanks to advances in metallurgy, ceramics, and plastics.

In this century, our control over materials has spread to include their *electrical* properties. Advances in semiconductor physics have allowed us to tailor the conducting properties of certain materials, thereby initiating the transistor revolution in electronics. It is hard to overstate the impact that the advances in these fields have had on our society. With new alloys and ceramics, scientists have invented high-temperature superconductors and other exotic materials that may form the basis of future technologies.

In the last few decades, a new frontier has opened up. The goal in this case is to control the *optical* properties of materials. An enormous range of technological developments would become possible if we could engineer materials that respond to light waves over a desired range of frequencies by perfectly reflecting them, or allowing them to propagate only in certain directions, or confining them within a specified volume. Already, fiber-optic cables, which simply guide light, have revolutionized the telecommunications industry. Laser engineering, high-speed computing, and spectroscopy are just a few of the fields next in line to reap the

benefits from the advances in optical materials. It is with these goals in mind that this book is written.

Photonic Crystals

What sort of material can afford us complete control over light propagation? To answer this question, we rely on an analogy with our successful electronic materials. A crystal is a periodic arrangement of atoms or molecules. The pattern with which the atoms or molecules are repeated in space is the crystal **lattice**. The crystal presents a periodic potential to an electron propagating through it, and both the constituents of the crystal and the geometry of the lattice dictate the conduction properties of the crystal.

The theory of quantum mechanics in a periodic potential explains what was once a great mystery of physics: In a conducting crystal, why do electrons propagate like a diffuse gas of free particles? How do they avoid scattering from the constituents of the crystal lattice? The answer is that electrons propagate as waves, and waves that meet certain criteria can travel through a periodic potential without scattering (although they will be scattered by defects and impurities).

Importantly, however, the lattice can also prohibit the propagation of certain waves. There may be **gaps** in the energy band structure of the crystal, meaning that electrons are forbidden to propagate with certain energies in certain directions. If the lattice potential is strong enough, the gap can extend to cover all possible propagation directions, resulting in a **complete band gap**. For example, a semiconductor has a complete band gap between the valence and conduction energy bands.

The optical analogue is the *photonic* crystal, in which the atoms or molecules are replaced by macroscopic media with differing dielectric constants, and the periodic potential is replaced by a periodic dielectric function (or, equivalently, a periodic index of refraction). If the dielectric constants of the materials in the crystal are sufficiently different, and if the absorption of light by the materials is minimal, then the refractions and reflections of light from all of the various interfaces can produce many of the same phenomena for *photons* (light modes) that the atomic potential produces for *electrons*. One solution to the problem of optical control and manipulation is thus a **photonic crystal**, a low-loss periodic dielectric medium. In particular, we can design and construct photonic crystals with **photonic band gaps**, preventing light from propagating in certain directions with specified frequencies (i.e., a certain range of wavelengths, or “colors,” of light). We will also see that a photonic crystal can allow propagation in anomalous and useful ways.

To develop this concept further, consider how metallic waveguides and cavities relate to photonic crystals. Metallic waveguides and cavities are widely used to control microwave propagation. The walls of a metallic cavity prohibit the propagation of electromagnetic waves with frequencies below a certain threshold frequency, and a metallic waveguide allows propagation only along its axis. It would be extremely useful to have these same capabilities for electromagnetic