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K. Busch, S. Lölkes , R. B. Wehrspohn, and H. Föll

Photonic Crystals

Advances in Design, Fabrication, and Characterization

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and H. Föll (Eds.)

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Coverpicture
(Main picture) Simulation of field distribution in a photonic crystal (PhC) waveguide with integrated beam splitter. (Background) SEM picture of an electrochemically etched 3D PhC with a full photonic bandgap in the IR. (Foreground) Emission spectrum of a PhC laser.

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Contents

Preface

The semiconductor revolution, that began in the late 1940's, enabled profound and unanticipated improvements in our standard of living. These artificial electronic materials, that control the flow of electrons on a microscopic scale, remain a centerpiece of today's micro-electronics industry. Likewise, the invention of the laser in the early 1960's, inspired the development of artificial materials that mold the flow of light. The photonics industry has irrevocably enhanced the way we transmit information, through the replacement of electronic signals in wires, with laser pulses in optical fibers. Along this course of scientific and technological progress, it is tempting to ask whether there exists a photonic analogue of the electronic semiconductor micro-chip. This requires the design and fabrication of practical photonic materials that can localize light and mold its flow on an equivalently microscopic scale. The collection of articles in this book describes significant research developments in Germany towards this objective.

Photonic band gap (PBG) materials are a novel class of photonic crystals that carry the concept of molding the flow of light to the most microscopic level allowed by the laws of physics. Consisting of dielectric microstructures with periodicity of roughly half the wavelength of light, PBG materials scatter photons in a manner similar to the scattering of electrons by the crystalline array of atoms in a semiconductor. The resulting gap in the electromagnetic spectrum provides a unique environment in which unwanted pathways for electromagnetic wave propagation are removed and desired ones can be selectively engineered, through defects in the photonic crystal lattice. In this way, a PBG material provides a robust platform for the integration of passive optical circuitry and active light emitting devices onto a compact optical micro-chip. Moreover, the electromagnetic density of states on the optical micro-chip can be engineered through suitable crystal defect architectures. This enables highly frequency selective changes in the rate of spontaneous emission of light from atoms whose resonance frequency lies within the engineered electromagnetic vacuum. This provides a new frontier in the field of quantum optics. The possibilities outlined above have inspired a worldwide effort to design, fabricate, and characterize a variety of different types of photonic crystals.

Research efforts in Germany have played a leading role in the worldwide effort to realize the promise of photonic band gap materials. These include the fabrication of two-dimensional and three-dimensional photonic crystals of unprecedented aspect ratio, in single crystal semiconductors such as silicon, using photo-electrochemical etching. These crystals have provided a platform for pioneering optical experiments both within Germany and internationally. Other novel photonic band gap architectures may soon be achieved through direct optical "writing" using two-photon absorption and holographic lithography in a polymer-based template, followed by replication (inversion) of the template with polycrystalline semiconductors. On the theoretical side, efficient modeling of electromagnetic wave propagation in complex defect architectures is an essential prerequisite to the design and fabrication process. This prominent role for theory is made possible through the essentially perfect applicability of Maxwell's equations to the optical properties of photonic crystals, without additional complicating interactions such as electron-electron and electron-phonon interactions that arise in the electronic properties of solids. Nevertheless the complex geometries of photonic crystal defect architectures and their concomitant light localization effects, call for the development of novel computational approaches. One of these, described in this book, is the introduction of Wannier functions (the optical analogue of localized atomic orbitals in solid state physics) as the basis functions for electromagnetic wave propagation. These localized basis functions may be indispensable for efficiently describing optical propagation within optical circuit architectures of three-dimensional PBG materials. Finally, a number of practical applications of photonic crystals is beginning to appear. Two particularly interesting and unique developments are the use of photonic crystals as mirrors and couplers for practical III-V semiconductor based lasers and the integration of a number of such lasers within a photonic crystal micro-chip.

It is clear from the above illustrations that photonic crystal research in Germany has provided a number of important, first-of-its-kind in the world, achievements. This book provides the reader with a valuable introduction to a number of these developments and an overview of a number of other emerging research directions.

Sajeev John

Toronto, December 2003

About the editors

Kurt Busch has been an Associate Professor at the Department of Physics and the School of Optics: CREOL & FPCE at the University of Central Florida (Orlando, USA) since January 2004. He received his undergraduate (Dipl.-Phys.; 1993) and postgraduate training (Dr. rer. nat.; 1996) at the University of Karlsruhe (Germany) and partly at the Iowa State University (Ames, USA). His professional experience included working at Iowa State University (Ames, USA), the University of Toronto (Canada; 1997-1999) and leading a junior research group within the Emmy-Noether program of the Deutsche Forschungsgemeinschaft at the University of Karlsruhe (Germany; 2000-2003). His research interests lie in light-matter interactions and wave propagation in strongly scattering materials and Photonic Crystals.

Stefan Lölkes graduated in semiconductor physics at the Technical University of Munich, Germany, in 2000. In 2001, he started his Ph.D. thesis on "Electrochemical etching of Photonic Crystals" at the Chair for General Materials Science at the Christian-Albrechts-University of Kiel, Germany. In parallel, he co-organized already several national symposia on Photonic Crystals in the framework of the DFG priority program 1113 "Photonic Crystals".

Ralf B. Wehrspohn received his diploma degree in physics at the University of Oldenburg in 1995. He then carried out a Ph.D. at the Ecole Polytechnique in France about thin film technology and electrochemistry. In 1998 he joined the Philips Research Laboratories in Redhill, U.K., to work on thin film transistors for AMLCD. From end of 1999 to March 2003 he has been responsible for the activities on photonic crystals and self-ordered porous materials at the Max-Planck-Institute of Microstructure Physics in Halle. Since April 2003 he is full professor in experimental physics at the University of Paderborn where he leads the activities on nanophotonic materials. R. B. Wehrspohn has been awarded with the Heinz Maier-Leipnitz award of the DFG and the TR100 innovation price of the MIT in 2003.

Helmut Föll received his Ph.D. degree in Physics in 1976 from the University of Stuttgart in conjunction with the Max-Planck-Institute for Metal Research in Stuttgart. After postdoctorial work at the Department of Materials Science and Engineering at Cornell University and a position as guest scientist at the T.J. Watson Res. Center of IBM in Yorktown Heights, he joined Siemens in 1980, working in the newly founded Solar Energy Department of Central Research in Munich. After various senior positions in microelectronics development, in 1991 he accepted an offer of the Christian-Albrechts-University of Kiel to become the founding dean of the newly established Faculty of Engineering, where he also holds the Chair for General Materials Science. Since 1998 he is back to research, with particular interest in solar cell technology and the electrochemistry of semiconductors. He is one of the pioneers in the field of porous semiconductors and has coauthored more than 150 papers and 20 patents.

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