Ultra-Refractive Photonic Crystals, Colloidal Opals and Photonic Band Gaps in the THz-Range

A. Öttl[1], P. U. Jepsen and H. Helm

Fakultät für Physik, Universität Freiburg, Herman-Herder-Str. 3, D-79104 Freiburg, Germany
http://frhewww.physik.uni-freiburg.de/
[1] *since March 2002: Institute for Quantum Electronics, ETH Zürich, Hönggerberg HPF D4, CH-8093 Zürich, Switzerland*
http://www.quantumoptics.ethz.ch/home.html
oettl@iqe.phys.ethz.ch

Photonic crystals comprise a completely new class of materials with extraordinary optical properties. They consist of dielectrics with spatially periodic alternating refractive index on the order of a wavelength.

First theoretical work has been done on inhibited spontaneous emission and localization of light in 1987 [1, 2] . Over the last years exact theoretical models in analogy to solid state theory were developed. The most successful method [3] (Plane Wave Expansion Method: PWEM) expands the solutions of a "master equation", which follows directly from Maxwell's equations, in a series of plane waves, employing a Bloch ansatz. The resulting energy eigenvalues are usually expressed as a photonic band structure diagram. For suitable configurations along with a sufficiently high contrast in the dielectric constants, forbidden energy bands, so-called photonic band gaps PBGs form. Another theoretical method [4] (Transfer Matrix Method) discretizes Maxwell's equations for a given crystal and wavelength in space and permits, by calculating the transfer-matrix of the system, the determination of transmission and reflection coefficients. Although a wealth of other models exists (e. g. Finite Difference Time Domain Methods), we only employed these two independent methods in our work to model and design photonic crystals, as well as to verify our experimental results.

In a first project in collaboration with O. Toader and S. John at the University of Toronto we theoretically studied the so-called superprism phenomenon [5], i. e. ultra-refractive effects occurring upon non-normal, non-monochromatic incidence of light on photonic crystals. The results are based on the calculation of dispersion relations of photonic crystals by means of the PWEM, taking into account the classical boundary conditions. They predict extraordinary refraction properties, like multi-refraction, negative index and ultra-refraction for certain crystals which were available for experiments.

Furthermore we present experimental results along with a theoretical analysis for angle-dependent transmission measurements in the visible of colloidal opals. The colloidal crystals consisting of polystyrene spheres ($r = 75\ nm$) in arduous solution self-assembled into an fcc lattice ($a = 480\ nm$) were synthesized and characterized by M. Soddemann and W. Richtering [7]. Due to the low dielectric contrast between PS ($n = 1.6$) and water ($n = 1.3$) only so-called stop bands for certain high symmetry crystal axes are present, as opposed to complete gaps throughout k-space. Rotations of the sample with respect to the probing light shifts the Bragg-peak, i. e. the stop band in frequency and thus reveals insight to the orientation and formation of the crystal within the cell. All features in the UV-vis spectroscopy measurements could be well identified by our numerical calculations.

The last part focuses on the development and characterization of photonic band gap materials for the THz frequency range (100 GHz - 3 THz), carrying on ideas and pre-work done by C. Winnewisser. Since THz-Time Domain Spectroscopy (THz-TDS) is a phase-sensitive measurement method it is well suited to examine the characteristics of photonic crystals. In a single sweep it not only delivers information about the transmission coefficients but also about the phase, i. e. phase-velocity for all frequencies and therefore conclusions on the photonic density of states plus the bandstructure. Furthermore the fabrication of photonic crystals well suited for the near infrared is relatively easy due to the large feature sizes of some tens of micrometers. One structure under study was fabricated at the MPI in Göttingen by M. Stukes group by means of Laser Assisted Chemical Vapor Deposition (LCVD) and consisted of Alumina ($n = 3.25$) rods ($r = 20\ \mu m$) in a woodpile structure ($a = 133\ \mu m$) [6] . The second sample was realized through a rapid prototyping technique by R. Landers at the Freiburger Materialforschugszentrum FMF. It was made of Polyethylen ($n = 1.5$), also in a woodpile structure but with larger feature sizes ($r = 230\ \mu m$, $a = 900\ \mu m$). For both samples the experimental results agreed well with our numerical simulations.

Acknowledgments. The results presented here summarizes the work by A. Öttl in his Diploma thesis [8] which was carried out at the University of Freiburg in the group of H. Helm and partially at the University of Toronto in the group of S. John. He wishes to thank the persons namely mentioned in this abstract who were involved in the progress of his thesis.

[1] S. John, *Phys. Rev. Lett.* **58** 2486 (1987)
[2] E. Yablonovitch, *Phys. Rev. Lett.* **58** 2059 (1987)
[3] K. M. Ho, C. T. Chan and C. M. Soukoulis, *Phys. Rev. Lett.* **65** 3152 (1990)
[4] J. B. Pendry, *J. Mod. Opt.* **41** 209 (1994)
[5] H. Kosaka et al., *Phys. Rev. B* **58** 10096 (1998)
[6] O. Lehmann and M. Stuke, *Science* **270** 1644 (1995)
[7] M. Soddemann, *Diplomarbeit* (Fakultät für Chemie und Pharmazie, Albert-Ludwigs-Universität, Freiburg, 1998).
[8] A. Öttl, *Diplomarbeit* (Fakultät für Physik, Albert-Ludwigs-Universität, Freiburg, 2001).