Simulation and Fabrication of Photonic Crystals

J. Zarbakhsh, E. Heissl, C. Hasenfuss, G. Kocher-Oberlehner and K. Hingerl
Christian Doppler Labor für Oberflächenoptische Methoden
Institut für Halbleiter und Festkörperphysik, Universität Linz, Altenbergerstr. 69, A-4040 Linz, Austria

Beginning 2003 the Christian Doppler Laboratory for Surface Science Methods was established at University Linz. The main goal is to bridge the gap between basic research and applied research on the topic of photonic devices. Although it is ultimately planned that also prototypes of these devices are fabricated in the cleanroom, in the first year the main emphasis was laid on novel designs. In this report these novel designs are described which will be fabricated in this year and in the future years experimentally with e-beam lithography resp. nanoimprint lithography.

Introduction

On 1st of January 2003 the Christian Doppler Laboratory for Surface Science Methods (CDLOOM) has been established at the Institute for Semiconductor and Solid State Physics at University Linz. The cooperating industry partner of CDLOOM is Photeon Technologies GmbH, Bregenz, Austria. The main work packages of the CDLOOM are twofold, namely two industrial topics: (1) Simulation of devices based on photonic crystals (PhC), (2) Prototype fabrication and parameter measurements.

CDLOOM has been established as interdepartmental group reporting to the department of semiconductor physics (Prof. Bauer) as well as to the department of solid state physics (Prof. Heinrich), because CDLOOM is using mainly the spatial and organizational infrastructure of the solid state physics department and the technical infrastructure of the semiconductor physics department, especially the clean room. Although it is ultimately planned that also prototypes of these devices are fabricated in the cleanroom, in the first year the main emphasis was laid on novel designs. Furthermore, due to the fact that almost all coworkers have not been at the physics department, within the first year the e-beam or UV lithography, etching, RIE etching, mask preparation, etc. characterization by AFM etc. had to be learned.

Theory

In 2003 the group worked in cooperation with Photeon on the following devices:

Efficient Fiber-High Index Waveguide Coupling by 1D Photonic Crystals

We investigated different technologies to couple light from a silica fiber into a high index waveguide. Finally we came up with a design, which is displayed in Fig. 1, where an omnidirectional Bragg reflector is used to squeeze the light together (Fig. 2 reduction of mode diameter), so that it can be coupled well into an high index waveguide, e.g. a Si waveguide on SOI material.

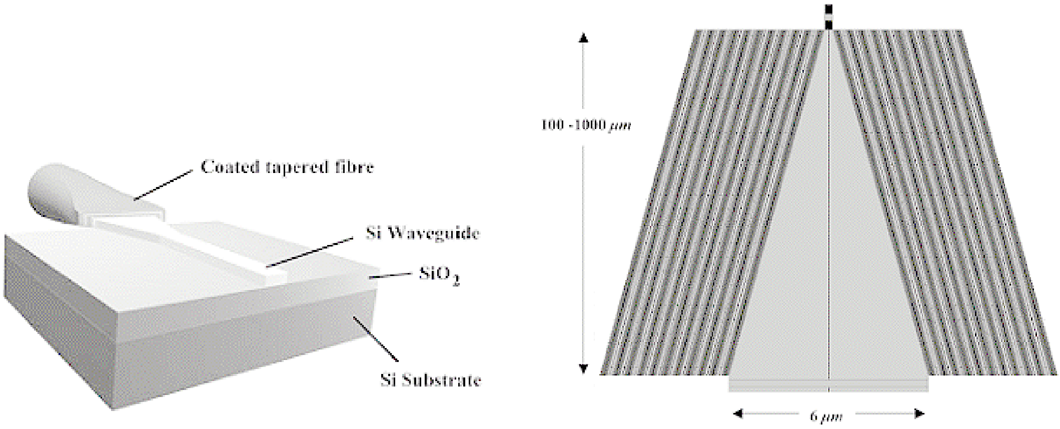

Fig. 1: Schematic drawing of the coupler

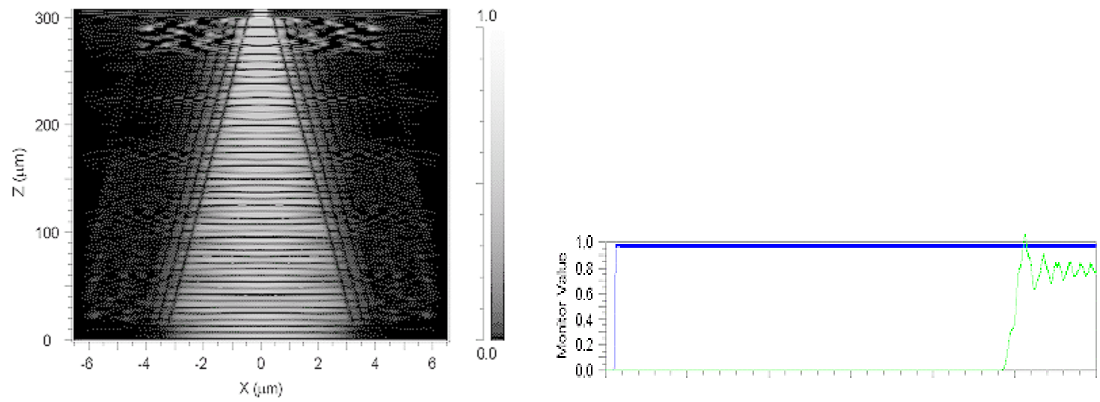

Fig. 2: Calculated efficiency of the coupler for TE modes.

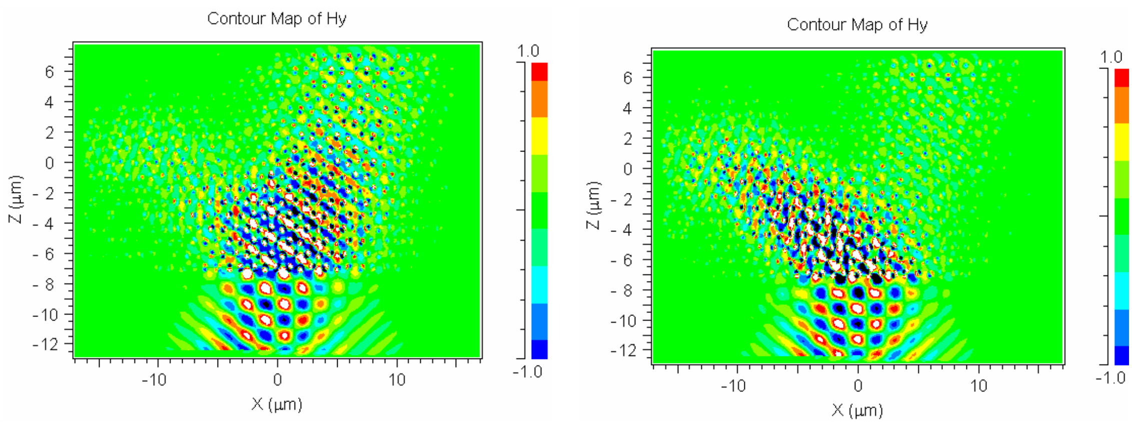

Fig. 3: Superprism effect for (a/λ) =0.58 and (a/λ) =0.585;

Wavelength Demultiplexers Employing the Superprism Effect

Photonic crystals show a very strong dispersion, which can modify the group velocity as well as the propagation direction strongly. The propagation direction can be calculated by calculating $\partial / \partial \vec{k}\ \omega(k)$ and due to the strong dispersion also small wavelength changes can modify the propagation direction enormously. In Fig. 3 2D simulations are shown for holes in Si with a period of 0.58 and neighboring of the free space wavelength, where this phenomenon is displayed. Although the simulation shows that angular deviations up to 90° can be achieved by varying the wavelength less than 1%, the high intensity of backscattered light as well as well as the scattering losses in forward direction exclude device applications.

Nonperiodic and Curvilinear photonic crystals

What we call photonic nonperiodic and curvilinear photonic crystals in this report does not need to possess crystal symmetries nor the rotational and inflational properties of quasicrystals. We apply transformations as e.g. stretching (along one or both dimensions) or shearing (changing the angle between the basis vectors) on the well known quadratic and hexagonal structures. This operations allow to construct rod / hole assemblies, which show on a short range scale a periodic order, however on a scale of the order of 10 lattice constants the (Bravais) lattice type is changed (Fig. 4). Although such a non-periodic system would in principle have no complete band gap (for all directions), for given stretching and shearing parameters not exceeding certain values, each lattice will form, infinitely repeated, a photonic band gap. In the example below (Fig. 4 (a)) we display the case of 2D silicon rods (refractive index n = 3.4), surrounded by air and positioned on circles with radii of 1 – 6 periods (*a*) with a radial and tangential distance of *a*. In the 3rd circle the rods are carved out, leaving a waveguide. Nevertheless, such a structure guides light extremely well, as can be seen in Fig. 4 (b) where for a wavelength of a/λ= 0.4, the power transmission is plotted as a function of time. Recently there have been many efforts to design waveguide bends with high transmission for a broader bandwidth by adding additional holes and moving existing ones in 90 and 60° bends.

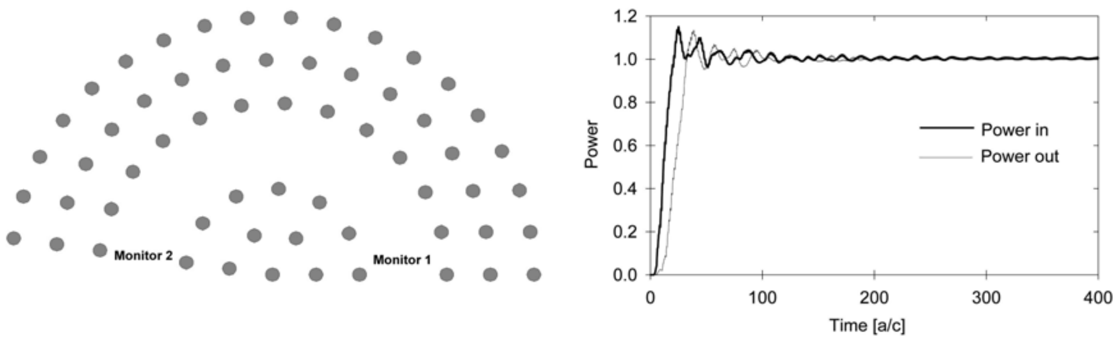

Fig. 4: (a) Nonperiodic (curvilinear) PhC; (b) Loss less propagation in the displayed curvilinear defect.

In our ring structure, which obviously allows coupling light out in any angle, such a procedure is not necessary. The question arises, why a non-periodic structure can localize light so well. The main underlying physics is the localization criterion applied for periodic systems. If the light frequency ω_0 is within a forbidden bandgap with band edge ω_c, the penetration depth $\lambda_{envelope}$ of the field into the photonic crystal can be calculated in a good parabolic approximation as $\lambda_{\text{envelope}} = \sqrt{\alpha / (\omega_c - \omega_0)}$ with the inverse effective photonic mass $\alpha = \partial^2 \omega / \left| \partial k^2 \right.$ where $\mathrm{k_c}$ is the wavevector at the Brillouin zone boundary.

For our almost hexagonal / almost quadratic rod structures even for the worst case (quadratic Γ- M direction) the field penetration depth is less than 0.75*a*. This finding opens up the possibility to design new devices as e.g. circular resonators, whispering gallery mode devices and point defect structures in PhQCs.

Conclusion

The above examples, as well as conventional waveguides, are currently fabricated in the cleanroom on Silicon on Insulator (SOI) materials, which have a slab thickness of 300 nm. The following processing steps are used: resist spinning, e-beam lithography (Jeol and since recently Zeiss LEO), RIE etching, atomic force microscopy, partially metallization and dielectric coating. Furthermore, in October last year an industrial PhD thesis from an employee of EVG Schärding started, where nanoimprint technologies for the fabrication of 3D photonic crystals are evaluated.

Acknowledgements

Christian Doppler Gesellschaft

References

[1] B. Lehner, K. Hingerl, “The Finite Difference Time Domain Method as a Numerical Tool for Studying the Polarization Optical Response of Rough Surfaces” Thin Solid Films, in press.

[2] Javad Zarbakhsh, Frank Hagmann, Sergei F. Mingaleev, Kurt Busch, Kurt Hingerl, “Arbitrary angle waveguiding applications of 2D curvilinear-lattice photonic crystals”, submitted to Appl. Phys. Lett.

[3] (together with Photeon) K. Hingerl, L. Mao, V. Rinnerbauer, J. Schermer, V. Holý, “Reflection and Transmission of Finite 2D Photonic Crystals” European Conference on Optical Communication, Ravenna, 2003.

[4] (Patent) J. Zarbakhsh, K. Hingerl, “Anordnung von dielektrischen Strukturen innerhalb eines Mediums”, Pat. No. 17243.0-P832-54, filed by PHOTEON Technologies GmbH (2003).