Efficient Waveguide Bend Design in Photonic Crystals

Rumen Iliew, Christoph Etrich, Ulf Peschel, and Falk Lederer,
Institut für Festkörpertheorie und Theoretische Optik,
Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany
Rumen.Iliew@uni-jena.de

By interpreting line defects in photonic crystals as strongly coupled point defects we predict basic properties of the waveguide modes from the properties of the point defects and compare the results with rigorous calculations.

Keywords: guided-wave optics, photonic crystals, periodic structures, waveguide modes

The realization of efficient sharp and compact waveguide bends is still a challenging task in microoptics. With the introduction of photonic crystals (PCs) major interest has also focused on the issue of efficient waveguide bends embedded in PCs. There are various proposals for bend design in order to minimize losses. Examples are smoothening the sharp bends [1], introducing cavities or intermediate straight sections [2] or placing smaller holes around the bend [3]. To inhibit the modal mismatch at a Y splitter [4] an additional hole has been added at the bend. On the other hand, it has been shown that a coupled-defect waveguide (CDW) composed of a chain of point defects in a PC can also have a very high transmission for a certain wavelength range at sharps bends [5] when the single defect is single moded. In that case it can be shown that for the single point defect in a square or hexagonal lattice this mode is invariant under all symmetry operations of the C_{4v} or the C_{6v} point group of the underlying crystal, respectively.

The aim of this contribution is to put forward an efficient tool for bend optimization. In our approach we start from the localized modes of a single point defect (e. g. a removed rod or a filled air hole) in a photonic crystal lattice at frequencies within the bandgap. Grouping such defects separated by a few lattice constants into a chain leads to the well-known CDW whereby it is assumed that the modal field of the single defect is not changed significantly and hence the properties of the modes in the arising miniband are determined by the properties of the single defect. This is validated by the good agreement of coupled-mode description and rigorous treatment.

Here we apply this approach to strongly coupled defects where the spacing is one lattice constant and arrive at a W1 line defect waveguide. The complete electromagnetic fields of the waveguide in Fourier domain are again written by means of a superposition of the modal fields of the single point defect located at the individual defect sites l and modified with a complex amplitude a_{kl}:

$$\mathbf{E}(\mathbf{r},\omega)=\sum_{k,l} a_{kl}(\omega)\,\mathbf{e}_k(\mathbf{r}-\mathbf{R}_l),\quad \mathbf{H}(\mathbf{r},\omega)=\operatorname{sgn}(\omega)\sum_{k,l} a_{kl}(\omega)\,\mathbf{h}_k(\mathbf{r}-\mathbf{R}_l) \tag{1}$$

Here $\mathbf{e}_k$ and $\mathbf{h}_k$ denote the orthogonal electric and magnetic field of the k-th mode of the single defect, respectively and $\mathbf{R}_l$ is the l-th defect site. For a wave-like excitation $a_{kl}=a_{k,0}\exp(ilKa)$ (K…Bloch wave vector, a…lattice pitch) for the case where we have a twofold degenerate point defect mode we get two decoupled minibands as solutions for the defect chain. This fact we identify as one cause of reduced bend transmission due to coupling to the respectively other mode at the bend.

When instead we have only one point defect mode, that necessarily then bears the full symmetry of the underlying lattice there occurs only one miniband with the following dispersion relation obtained from coupled mode analysis (CMA) for only nearest neighbor interaction describing the relation between the excitation frequency ω and the Bloch vector *K*:

$$\omega(K)=\frac{1+2\beta\cos(Ka)}{1+\frac{1}{2}\gamma_0+(2\beta+\gamma_1)\cos(Ka)} \tag{2}$$

with $\beta, \gamma_0, \gamma_1$ being overlap integrals of the electric field of the single point defect with the spatial distribution of the dielectric constant for the line defect. For describing bends sections of line defect waveguides must be put together at different angles and additional terms in the equations for the coefficients occur [5] modifying the transmission characteristics.

Plane-wave calculations [6] of the line defect reveal that for square or hexagonal lattices inside the occuring miniband the field structure is still mainly given by the superposition of the field of the single defects shifted by the defect distance. This is also confirmed by the good agreement of the dispersion relation of the miniband obtained from rigorous planewave calculations and from equation (2) as shown in Figure 1 for a sample structure composed of a two-dimensional hexagonal array of dielectric (semiconductor) cylinders in air with removed cylinders as defects and for TM polarization of the electromagnetic field.

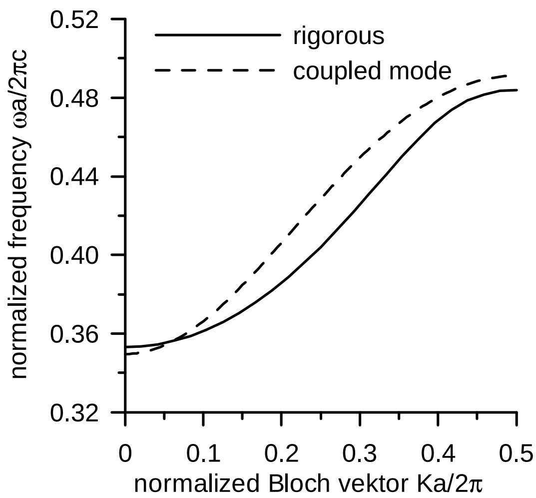

Figure 1. Comparison of the dispersion relations obtained from rigorous (planewave) and coupled mode calculations for a line defect in the TM example structure.

We will utilize this knowledge for designing efficient waveguide bends by following the idea that a point defect mode with the full symmetry of the point group will have the same coupling strength into all equivalent lattice directions. For instance, for point defects arranged in ΓK direction in a hexagonal lattice this would mean there are six equivalent directions for coupling to a second point defect. Exploitation of this idea leads us to a geometry of hexagonally arranged dielectric rods with a double bend where we expect a high transmissivity within a reasonable wavelength range. The result of a two-dimensional finite-difference time-domain (FDTD) calculation of this double bend for a continuous wave excitation at the left end is shown in Figure 2.

In Figure 3 we show the result of the respective FDTD transmissivity calculation for the interesting wavelength range confirming the expected high efficiency of the bend. If we have instead a doubly degenerate point defect mode with a twofold symmetry both of the point defect modes have two different coupling constants to the modes of neighboring defects, depending whether it is a straight line or a bend. Additionally, it will couple to both modes of the next defect resulting in mode mixing and hence to reduced transmission into the original mode of the waveguide.

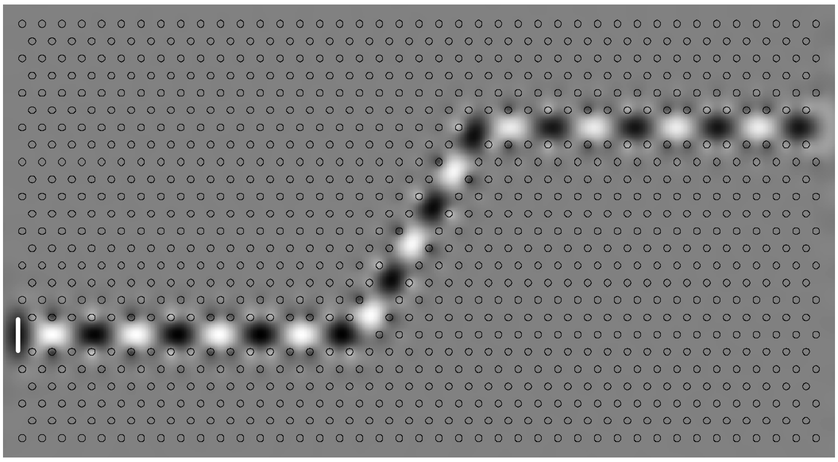

Figure 2. Image plot of the *z* component of the electric field of a W1 waveguide double bend realized in a 2D photonic crystal for TM polarization. The excitation is shown as a white line in the left part.

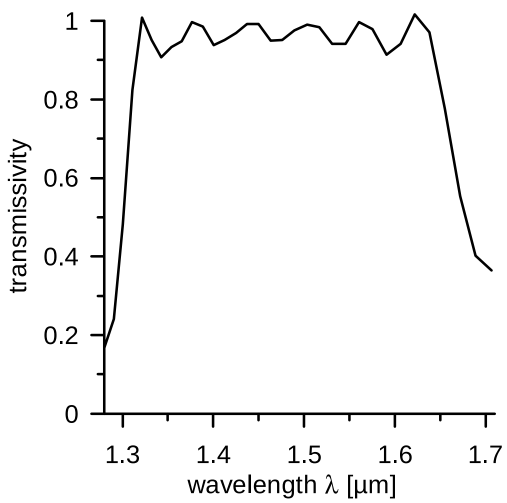

Figure 3. Transmissivity (intensity transmission) obtained for the structure in Fig. 2 from 2D FDTD calculations.

In our paper we will predict the bending performance of W1 line defect waveguides in PCs from the behavior of the single defect for different geometries and compare with FDTD calculations. We will explore the reliability of quantitative predictions based on a CDW description for different geometries.

References

[1] J. Moosburger, M. Kamp, A. Forchel, S. Olivier, H. Benisty, C. Weisbuch, U. Oesterle, “Enhanced transmission through photonic-crystal-based bent waveguides by bend engineering,” *Appl. Phys. Lett.* **79**, 3579-3581, 2001.

[2] S. Olivier, H. Benisty, C. Weisbuch, C. J. M. Smith, T. F. Krauss, R. Houdré, and U. Oesterle, "Improved 60° Bend Transmission of Submicron-Width Waveguides Defined in Two-Dimensional Photonic Crystals," *J. Lightwave Technol.* **20**, 1198-1203, 2002.

[3] A. Talneau, Ph. Lalanne, M. Agio, and C. M. Soukoulis, "Low-reflection photonic-crystal taper for efficient coupling between guide sections of arbitrary widths," *Opt. Lett.* **27**, 1522-1524, 2002.

[4] S. Boscolo, M. Midrio and T. F. Krauss, "Y junctions in photonic crystal channel waveguides: high transmission and impedance matching," *Opt. Lett.* **27**, 1001-1003, 2002.

[5] U. Peschel, A. L. Reynolds, B. Arredondo, F. Lederer, P. J. Roberts, T. F. Krauss, and P. J. I. de Maagt, "Transmission and Reflection Analysis of Functional Coupled Cavity Components," *IEEE J. Quantum Electron.* **38**, 830-836, 2002.

[6] S. G. Johnson and J. D. Joannopoulos, "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," *Opt. Express* **8**, 173-190, 2001.