Improved Transmission for 60° Photonic Crystal Waveguide Bends

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Abstract

We have investigated and optimized a 60°-waveguide bend that is implemented in a planar photonic crystal (PhC) with triangular lattice symmetry. The in-plane guiding within the planar PhC stucture is based on a W1 defect waveguide (a single line defect acting as a light channel in the G-K-direction) whereas for the vertical light confinement we rely in a slab waveguide formed by the low index contrast material system InGaAsP/InP. To achieve a reasonable bandgap around 1.55 mm the PhC consists of a lattice of holes with a filling factor of 39%. Our simulations are carried out in the frequency domain with the 2D multiple multipole (MMP) method. We show a significant improvement in both the transmission efficiency (up to 96.8%) and the transmission bandwidth by performing an optimization based on a sensitivity analysis. The most promising structure was afterwards simulated with a 3D-FDTD program, where we achieved transmission efficiency that peaks at 66%.

A major drawback of conventional dielectric waveguides is that their bending radii are limited to several millimeters due to the degradation of total internal reflection. Since the guiding of light in a PhC defect waveguides is not given through total internal reflection but the photonic bandgap (PBG) effect they can provide bending within the subwavelength range. Hence, PhC waveguides offer a promising scheme for low loss and ultra-dense optical integration. Instead of the 3D-PhC structures that are difficult to fabricate 2D planar PhC system are widely used [1], where the in-plane guiding is provided by the photonic crystal and the vertical light confining is warranted by a slab waveguide that is formed by the low index contrast material InGaAsP/InP. A PhC possesses a bandgap in which light is not permitted to propagate. By introducing a line defect in the PhC light of certain wavelengths is now allowed to be guided. Since, we want to use an operating wavelength around 1.55 mm our PhC consists of an array of holes with triangular lattice symmetry having a filling factor of 39% (which yields to a r/a ratio of 0.33). The vertical slab structure comprises a multi-layer structure where the InGaAsP (Q=1.22) guiding layer of thickness 434nm is sandwiched between a 200nm cap layer and a 600nm buffer layer, both made of InP. The substrate consists of n^+-doped InP. For the 2D simulations we therefore use an effective index of 3.24 as background material, which is calculated by multilayer effective index method. This 2D PhC supports a photonic bandgap between c/a of 0.203 and 0.35 for TE polarized light. We introduce now a W1 waveguide (a single line defect in the Γ-K-direction), to achieve a dispersion curve in this bandgap region. This dispersion curve extends in the Γ-K-direction from c/a = 0.31 down to 0.233 (Figure 1). We can clearly see the mini-stopband, as already reported in numerous studies.

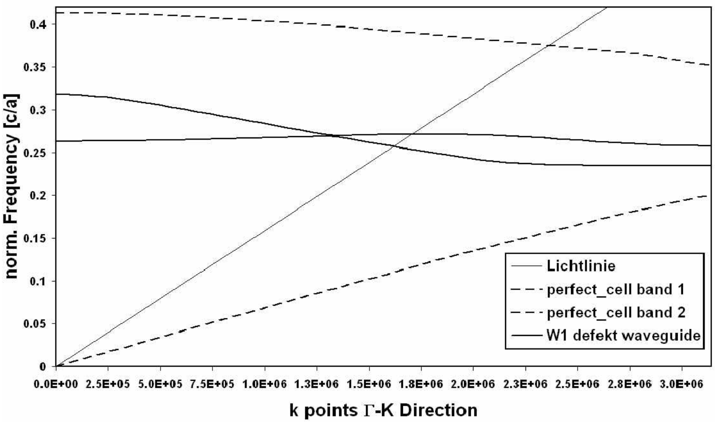

Figure 1: Dispersion curve of the W1 waveguide with a filling factor of 39% and an effective (background) index of 3.24.

Since, phenomenological models [2] have proven to be best suited to bridge the gap between a realistic planar PhC structure and its proper 2D representation 2D modeling has become a powerful mean for the evaluation of PhC device concepts. In order to do so we are using a 2D multiple multipole (MMP) method [3], which allows us to introduce the eigenmodes of the W1 defect waveguide as perfect excitation and matching conditions for the different ports. We start our optimization by first looking at a wavelength scan in the non-optimized case, wherein the original position of the holes remains unchanged (Inset of Figure 2).

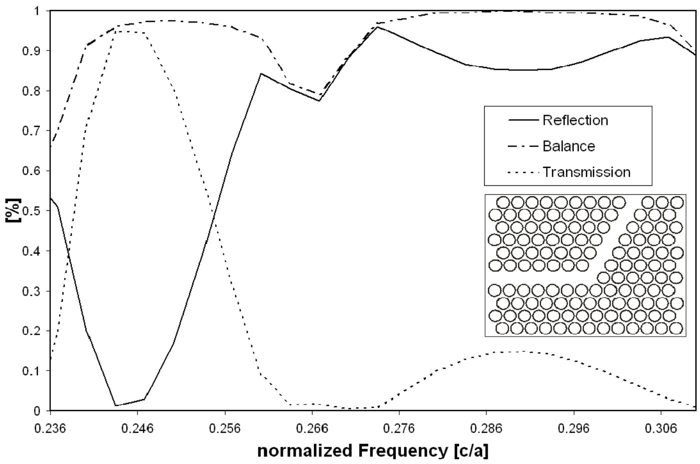

Figure 2: Wavelength scan of the 60°-bend with the original hole position (inset). The maximum of transmission lays around 0.245 and has a bandwidth of about 0.055

One can clearly observe the bend's high transmission efficiency at a normalized frequency around 0.245 providing a bandwidth of about 0.0065, which accords to a wavelength range of 160nm. The drop in the power conservation (balance curve) is due to the mini-stopband shown in figure 1. A sensitivity analysis with respect to small displacements was done for the most critical holes around the proper bending region, in order to shift the maximum of transmission efficiency towards a wider bandwidth. After several optimization steps we finally achieved a best value for the power transmission (Figure 3) of 96.8% (reflection 2.84%) and an overall transmission of more than 86% for a normalized frequency range of 0.02, which corresponds to a wavelength range of 290nm (Figure 4). In the non-optimized case the transmission reached a value of only 14.48% (reflection 85.35%) within this wavelength range.

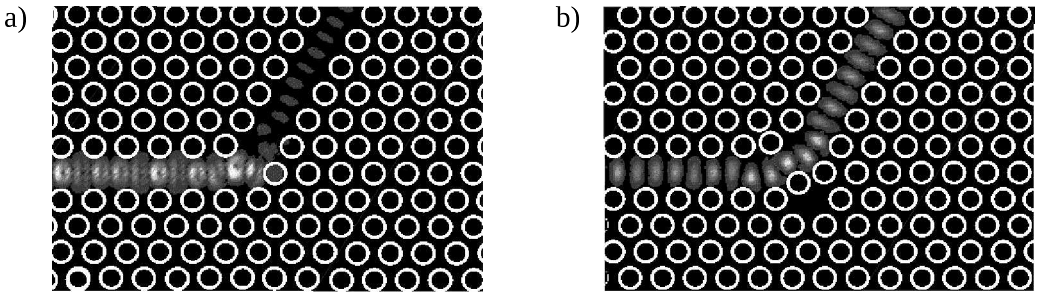

Figure 3: The flow of light is displayed by means of the Poynting vector. For the initial structure (a) the transmission is 14.48% and the reflection 85.35%, whereas for the optimized structure (b) the transmission obtains 96.8% and the reflection 2.84%. Excitation is from left for TE-polarization.

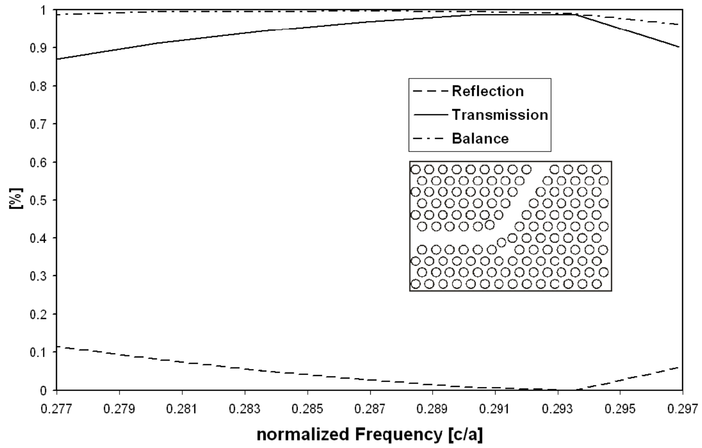

Figure 4: Transmission spectrum of the optimized bend structure (inset). The bandwidth covers a normalized frequency range of 0.02.

In order to validate our 2D structural optimization scenario we perform 3D-FDTD simulations along realistic planar 60°-bends implemented in a low index contrast slab waveguide. Since we want to use this device around 1550nm we calculate the lattice constant to be 430nm and obtain therefore a hole radius of 141.9nm, respectively. The fundamental mode in the PhC waveguide is excited using a few microns long ridge waveguide (2µm etch depth) as feeding structure. To ensure single mode operation we set the ridge waveguide width equal to that of the W1 PhC (i.e. 460nm). Figure 5 shows a qualitatively good agreement between 2D MMP simulation and the 3D FDTD with regard to the distinct spectral features of the non-optimized bend's transmission characteristics.

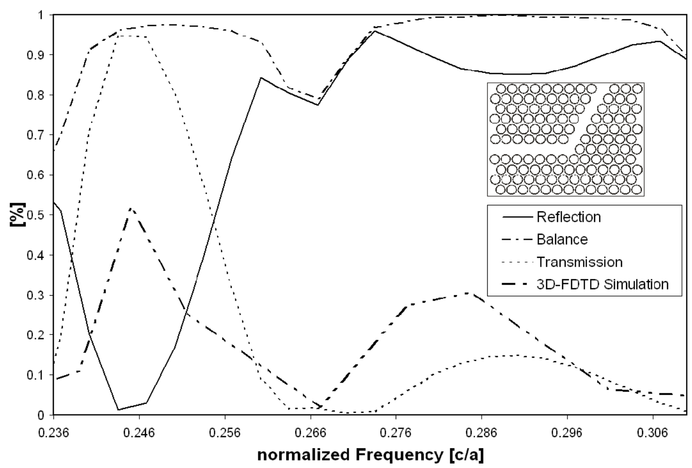

Figure 5: Comparison of bend simulation with 2D MMP method and 3D FDTD. Both simulations show a good characteristic agreement.

As a next step we use the bend topology that has been provided by the 2D optimization scenario for a subsequent 3D simulation. Here we achieve an improvement in transmission efficiency of more than 40%, which yields to overall power transmission values larger than 60% for the W1 60° waveguide bend as shown in Figure 6 (b).

a) b)

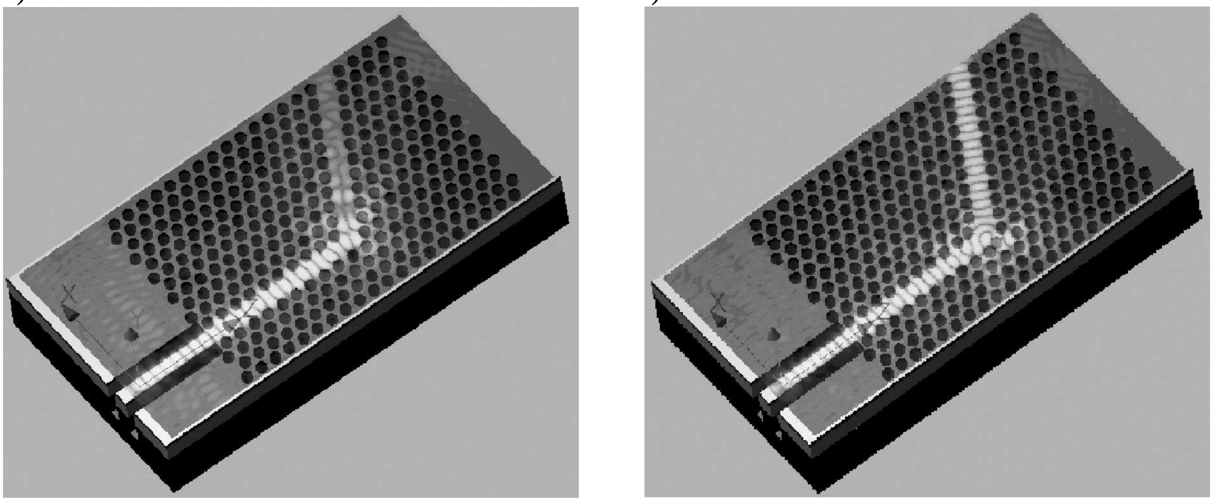

Figure 6: 3D FDTD simulation of the H_z-field for a (a) non-optimized bend and (b) an optimized bend. The TE-mode is injected using the ridge waveguide on the left bottom. We achieve an improvement in transmission efficiency of about 40% leading to power transmission values of larger than 60% for the optimized bend.

In conclusion, we performed the analysis and optimization of a planar PhC 60°-bend for a low index contrast InGaAsP/InP waveguide system. We used a 2D representation of the planar PhC structure to setup a sensitivity analysis with regard to the most critical holes in the proper bending region. This optimization step has resulted in a 2D PhC bend that shows a power transmission of at least 86% over a wavelength range of 290nm.

Based on the qualitative agreement between 2D and 3D simulations an optimal planar PhC 60°-bend has been proposed. The resulting bend shows an improved transmission efficiency of more than 60%. This result may provide additional confidence with respect to a proximate device fabrication.

References:

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