MAS and MMP Simulations of Photonic Crystal Devices

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Abstract

We present a new technique for the computation of transmission and reflection coefficients of waveguide discontinuities in photonic crystals (PhCs). This technique is based on the Method of Auxiliary sources (MAS) and uses a special complex origin source for an optimal excitation of the mode in the input port and a reflection compensation scheme for handling the reflections at the output ports. In order to validate the results, we use a rather rigorous approach, based on a combination of the Multiple Multipole Program (MMP) with Mode Matching Technique (MMT). Good agreement is obtained for various applications, such as waveguide bends, filtering T-junctions, and coupling of a slab waveguide to a PhC waveguide.

Introduction

The Method of Auxiliary Sources (MAS) [1] and the Multiple Multipole Program (MMP) [2] are both efficient and accurate boundary methods that are very promising for the study and optimization of demanding structures such as waveguide discontinuities and other structures in PhCs [3, 4]. Such structures are currently of high interest because they are very promising for high-density integrated optics [5] as well as in the microwave regime. Since design rules are missing for PhC devices, most of the promising structures were designed rather intuitively and supported by some numerical simulations. We have demonstrated that numerical optimizations allow us to drastically improve the properties of an intuitive design [6, 7]. For such optimizations, field solvers are required that are not only efficient, but also accurate and reliable at the same time. Since inaccuracies heavily disturb the optimization process, we focus on boundary methods with exponential convergence, namely MAS and MMP. For MMP, a sophisticated technique for waveguide discontinuities had been developed many years ago. This technique can also be applied to discontinuities of waveguides in PhCs [2]. It consists of the following steps: 1) Computation of the waveguide modes. 2) Packing each waveguide mode in a "connection". 3) Matching of the connections with a truncated model of the discontinuity [2]. As a consequence, small truncated models become available with very small undesired reflections of evanescent waves that were neglected in the output ports. The MAS technique avoids the tricky computation of the waveguide modes as will be demonstrated in the following section.

MAS computation of waveguide discontinuities

The mode matching at the ports of waveguide discontinuities in the MMP approach requires the computation and insertion of the waveguide's eigenmodes into the discontinuity model. For doing this, a rather sophisticated code, such as MaX-1 [8] is required. Many software packages can solve scattering problems but have no options for solving demanding eigenvalue problems such as the computation of the PhC waveguide's eigenmodes. When one wants to avoid the implementation of the computation of waveguide modes, one cannot apply the mode matching technique (MMT) at the input and output ports. One then must find reasonable techniques for truncating the ports, for exciting the wave in the input port, for computing the undesired reflections at the truncated output ports, and for either minimizing or compensating the undesired reflections.

In the MAS scheme, one essentially approximates the electromagnetic field in any domain by a set of auxiliary sources (monopoles in 2D applications) that are placed along auxiliary lines outside the boundaries of the domain. In 2D models, the auxiliary lines may be obtained from conformal mapping and other methods. Monopoles are well known as sources of electromagnetic waves that radiate uniformly in all directions. One can easily generalize these sources by introducing complex origins, leading to a beam-like radiation pattern istead. The direction of the beam and the beam width are determined by the imaginary part of the complex origin. Such monopole beams are almost perfect for the excitation of the fundamental modes in a PhC waveguide, i.e., by an optimal placement of the complex origin monopole, one can excite the fundamental waveguide mode almost without exciting higher order evanescent modes. We call such an optimized complex origin monopole the Imitating WaveGuide Aperture (IWGA) source.

In order to measure the reflection of waves at an output port of a conventional waveguide, one can observe the standing wave pattern along the waveguide and compute the reflection coefficient from the Standing Wave Ration (SWR). Although a PhC waveguide is periodic rather than cylindrical, the propagation of the fundamental mode along a line in the center of the waveguide is very close to the propagation of waves in cylindrical waveguides. Therefore, we also can use the SWR technique to compute the reflection coefficient at any waveguide port in a PhC while introducing appropriate observation lines, as illustrated in Figure 1. Thus, we know how to evaluate the reflection caused by the model truncation at any waveguide port that supports a single, fundamental waveguide mode.

Since the reflections at the ports are caused by model truncation, we must either design the truncation in such a way that the reflection becomes negligible or we must compensate the reflected wave by adding an appropriate wave at the output port that annihilates the reflection. This may be done by a so-called balancing IWGA source as outlined in Figure 1 for a discontinuity with a single output port. From the computation of the field excited by the feeding IWGA source at the input port, we obtain a solution with some undesired reflection at the output port. The reflected wave will be reflected at the input port again. As a result, we obtain a superposition of multiply reflected waves. When we now replace the IWGA source at the input port by the so-called balancing IWGA source at the output port, we again obtain a superposition of multiply reflected waves. When we now add the two solutions together with an appropriate amplitude of the balancing IWG source, we can compensate all reflections at the output port and obtain a solution without any reflection at the output port. Finally, the reflection at the input port is obtained then from the SWR measurement along L_{in}.

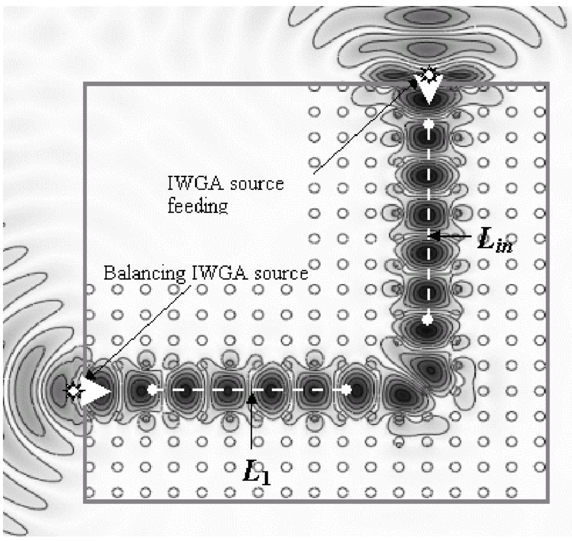

Figure 1. MAS simulation of the 90° W1 defect waveguide bend. The gray rectangle outlines the truncation boundary of the finite PhC model. The underlying PhC consists of a square lattice with $a/\lambda = 0.416$, $\varepsilon = 11.56$, and $r/a = 0.18$. (i) MAS simulation; relative error estimate: 0.3%; transmission 91.15%; reflection 8.58%. (ii) MMP simulation; relative error estimate: 0.45%; transmission 91.26%; reflection 8.56%.

Results

Because of the fundamental discrepancies between standard waveguides and photonic crystal waveguides and since the IWGA source does not perfectly match the field of a waveguide mode, a comparison with a more rigorous approach is required. We therefore compared our MAS results with MMP-MMT results. As one can see from Figures 1 and 2, the agreement for the 90 degree bend in a single mode photonic crystal bend is excellent not only for a single frequency but also over the entire frequency range within the bandgap where the waveguide mode exists.

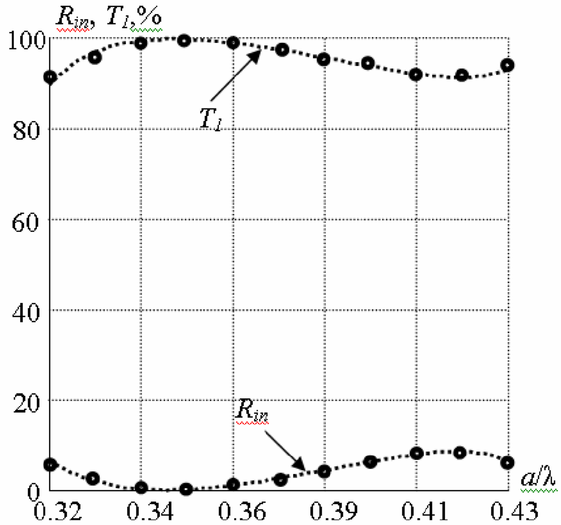

Figure 2. Comparison of the MAS (circles) and MMP (dashed lines) model for a 90^o W1 defect waveguide bend as a function of the normalized frequency a/λ within the first bandgap. The discrepancy is less than 1% for all frequencies.

In order to demonstrate that accuracy of the MAS technique, we have computed more complicated models, namely a filtering T-junction that consists of a T-shaped waveguide with an input and two output ports. Therefore, two compensating IWGA sources are required here. For obtaining the filtering characteristics, this configuration contains three rods in each output ports. The radii and locations of these rods were optimized in order to obtain the desired filtering properties. The corresponding values are rather critical, i.e., high accuracy is required at least near these rods. Depending on the frequency, the light is either transmitted mainly to the left or to the right output port. As one can see, almost no light is transmitted to one of the ports for some frequencies. Since the corresponding transmission coefficients are rather small, a high accuracy of the field computation is required for obtaining a good estimate of these coefficients.

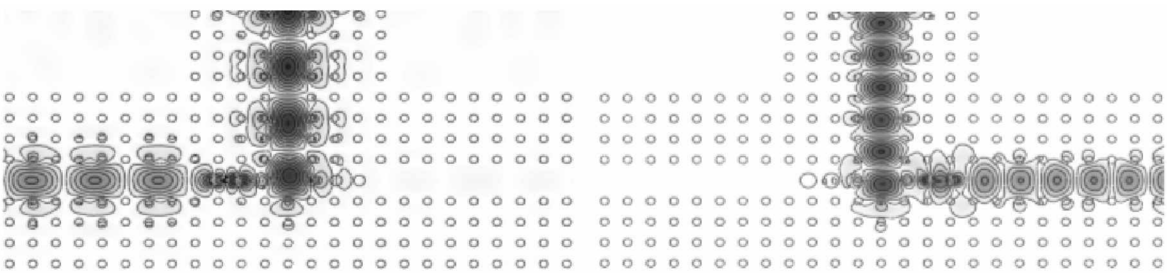

Figure 3. $a = 1\mu m$; for right propagation $a/\lambda = 0.41$; for left propagation $a/\lambda = 0.346$

MAS: $R_{left}^{up} = 36.38\%; T_{left} = 63.71\%; T_{right} = 0.42\%$; $R_{right}^{up} = 36.02\%; T_{left} = 0.11\%; T_{right} = 63.76\%$

MMP: $R_{left}^{up} = 35.37\%; T_{left} = 63.38\%; T_{right} = 0.41\%$; $R_{right}^{up} = 36.51\%; T_{left} = 0.11\%; T_{right} = 63.28\%$

As a third test case, we consider the coupling of a fundamental mode in a slab waveguide to a defect waveguide in a photonic crystal. As one can see from Figure 4, one obtains a rather smooth transition. The power transmission of the un-optimized waveguide interface is around 69%, optimized structures easily reach values larger than 90%. Once more, the agreement with the MMP-MMT results is good.

Conclusions

For all test cases, very accurate results were obtained with the MAS technique using IWGA sources and the power reflection compensation at the output ports. These techniques are not restricted to the MAS. They can be added to all kind of field solvers for handling waveguide discontinuities in photonic crystals as well as traditional waveguide discontinuities. However, the current implementation is limited to single-mode waveguides. For multi-mode waveguides, both the IWGA source and the SWR evaluation of the reflection coefficient would have to be improved.

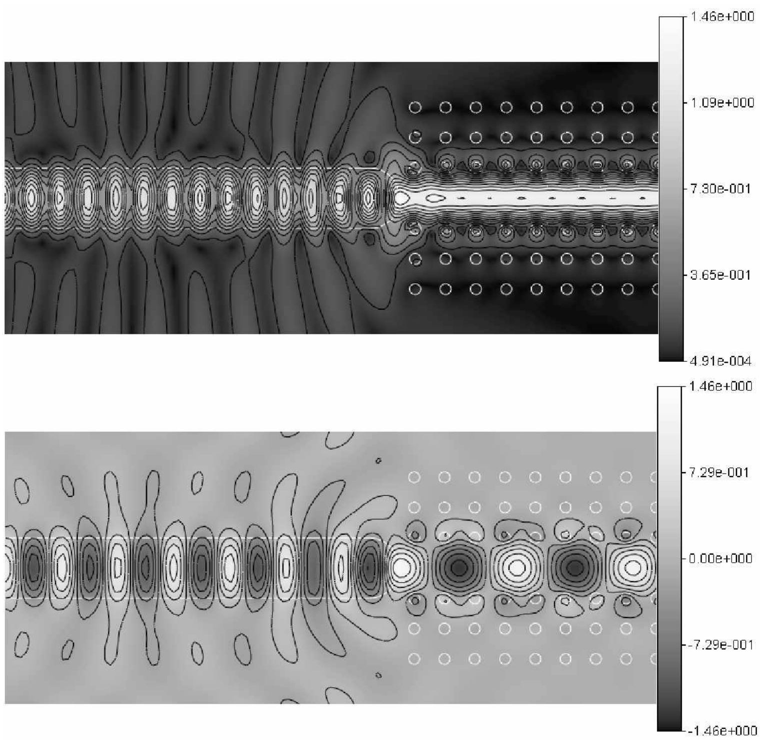

Figure 4. Coupling of a slab waveguide into a PhC waveguide at relative frequency fa/c=0.38; h(diel_WG)= 3.379; h(PC)= 1.644; SWR_WG(MAS)= 1.718; SWR_WG(MMP)=1.656.

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