Out-of-plane scattering losses in 1D photonic crystal slabs.

Wim Bogaerts, Peter Bienstman, Dirk Taillaert, Roel Baets
Ghent University - IMEC, Department of Information Technology (INTEC),
Sint-Pietersnieuwstraat 41, 9000 Gent, BELGIUM

In photonic crystal slabs an in-plane photonic crystal is combined with a slab waveguide. Light is then confined in plane by the photonic crystal and out-of-plane by the slab waveguide. The etched structures will cause light to scatter out of the waveguide plane. We studied the out-of-plane scattering losses of these holes using a 2D approximation of this 3D structure, with etched slots instead of holes. Our simulation techniques included mode expansion with PML. We show that the losses increase with higher index contrast, but that with very high index contrasts light can be coupled into lossless Bloch modes.

One of the most promising applications of photonic crystals today is the use of two-dimensional crystal structures (e.g. air holes in a large index material) in combination with a layered waveguide to confine light in the third dimension [1, 2]. One can then use a channel waveguide to guide light in the plane of the crystal [3], but then the light can be scattered out of the waveguide plane in the air holes etched through the waveguide core. Understanding these scattering losses could allow us to treat 2D photonic crystals slabs as a pure 2D problem, substituting the air holes by a complex refractive index [5].
Two approaches have been suggested to reduce scattering losses. One is to use as low contrasts as. As suggested by Bénisty et al. [1, 5], losses increase with the square of $\Delta\varepsilon$, where $\Delta\varepsilon = n_{core}^2 - n_{clad}^2$, n_{core} and n_{clad} being the refractive index of the slab's core and cladding respectively.
Another approach is to maximize the index contrast of the slab waveguide, even to a limit where semiconductor is suspended in air. This high index contrast allows for structures with Bloch modes below the light line without radiation losses [6, 5].
We studied the losses of a 2D approximation of the full 3D structure. Figure 1 shows a 3-layer slab waveguide with intersecting air slots. We will show here that by raising the refractive index contrast of the waveguide structure, losses will increase as predicted [1, 5], but that these losses can drop again once a lossless Bloch mode is excited.

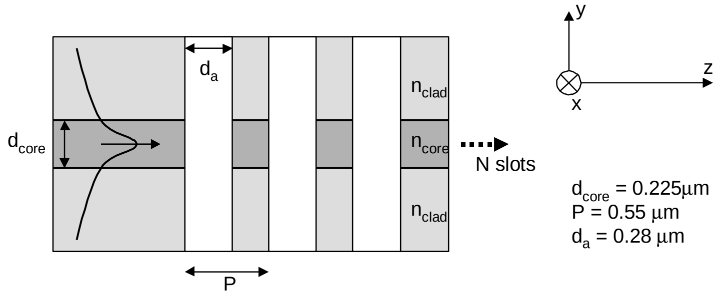

Figure 1*: The simulated structure. A symmetric 3 layer slab waveguide periodically intersected with air slots*

Simulation tools and structures

For this study we used our simulation tool CAMFR [8], a vectorial eigenmode expansion tool with perfectly matched layer (PML) boundary conditions. The structure is divided into sections with a constant refractive index profile along the propagation axis, where the field is expanded into the eigenmodes of that section. The continuum of radiation modes is approximated by placing the structure between two perfectly conducting metal walls coated with PML to eliminate the parasitic reflections. At the interfaces between different waveguide sections, mode matching is used to decompose the field into the eigenmodes of the new section, resulting in a scattering matrix describing the entire structure. We can calculate reflection and transmission of finite structures, but also band structures for infinite periodic structures using Bloch boundary conditions in the propagation direction. FDTD was used for verification.

We tried to approach common semiconductor heterostructures, today the most popular material for 2D photonic crystal slabs. We opted for a three-layer slab waveguide with a core thickness d_{core} of 0.225µm and a refractive index n_{core} of 3.5. The slab waveguide is single mode at a wavelength of 1.55µm for all values of n_{clad}. We then vary the waveguide cladding index n_{clad} to study its behavior for different values of $\Delta\varepsilon$. This change in index contrasts obviously alters the dispersion relation of this waveguide and also the band structure of a periodic structure etched into the waveguide.

Results

First we studied the scattering of a single air slot. This can be looked upon as the incoherent limit where each slot radiates independently, and losses of individual slots are accumulated. This way we can verify our result with the model proposed by Bénisty et al [1]. Figure 2 shows the losses of a single slot with a width d_a of 0.28µm. We see that for low index contrasts the out-of-plane scattering increases quadratically with $\Delta\varepsilon$. For higher refractive index contrasts the losses level out. So when one operates in the region of low to medium index contrast it might be beneficial to keep the refractive index contrast as low as possible, for a small increase in n_{clad} might yield a considerable drop in losses. For high refractive index contrasts a change in refractive index of the cladding is far less important from the viewpoint of out-of-plane scattering losses.

Treating the losses of each air hole incoherently seems overly simplistic when working with photonic crystals. As shown in [4, 5], a 2D periodic structure can have lossless Bloch modes, when the scattering of all holes interfere destructively. Our simulations show that 1D periodic structure can support a similar guided lossless Bloch mode. For this study, we used a period P of 0.55µm and an air slot width d_a of 0.28µm. Figure 3 shows the band structure of this infinite 2D structure for different values of $\Delta\varepsilon$. The shaded region bounded by the light line indicates the continuum of the radiation modes. The out-of-plane scattering losses are plotted in figure 4 as a function of $\Delta\varepsilon$. To eliminate the fluctuations caused by working with a finite periodic structure, we took the average of the losses of the periodic structures with 30 to 50 periods. For high contrasts the structure quickly changes between 4 distinct regimes.

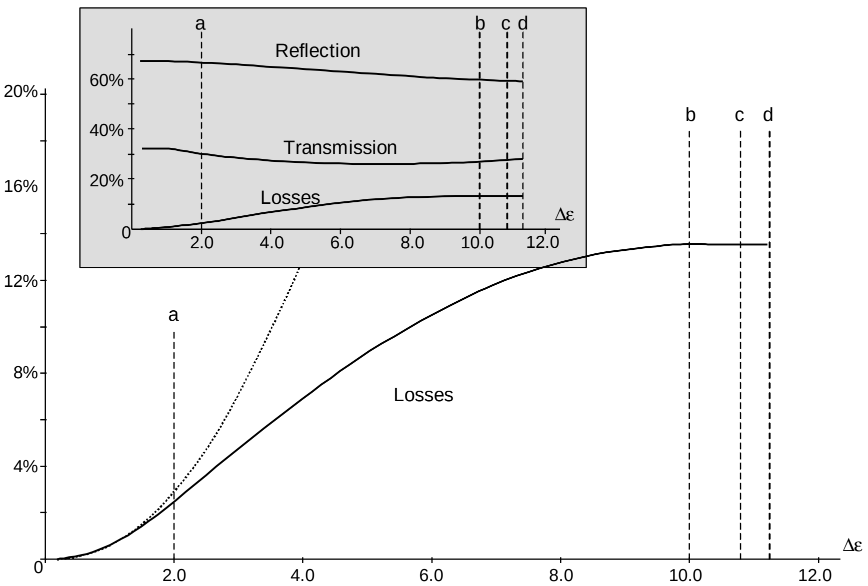

Figure 2: *Out-of-plane scattering losses for a single air slot.*

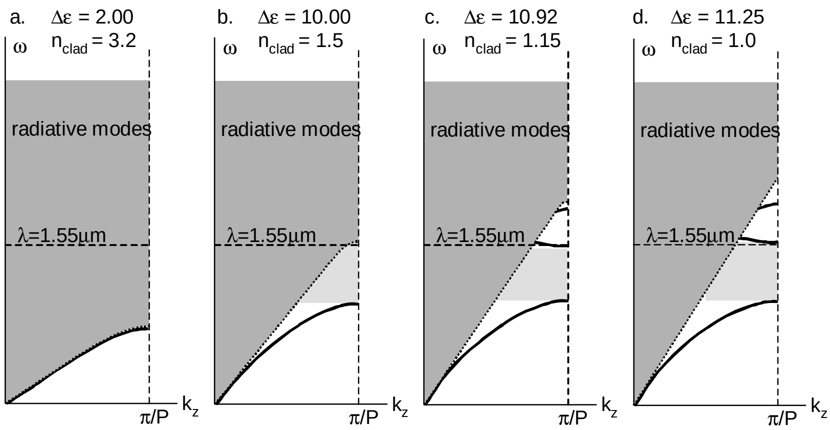

Figure 3: *Band structures of the structure in figure 1 for different* $\Delta\varepsilon$.

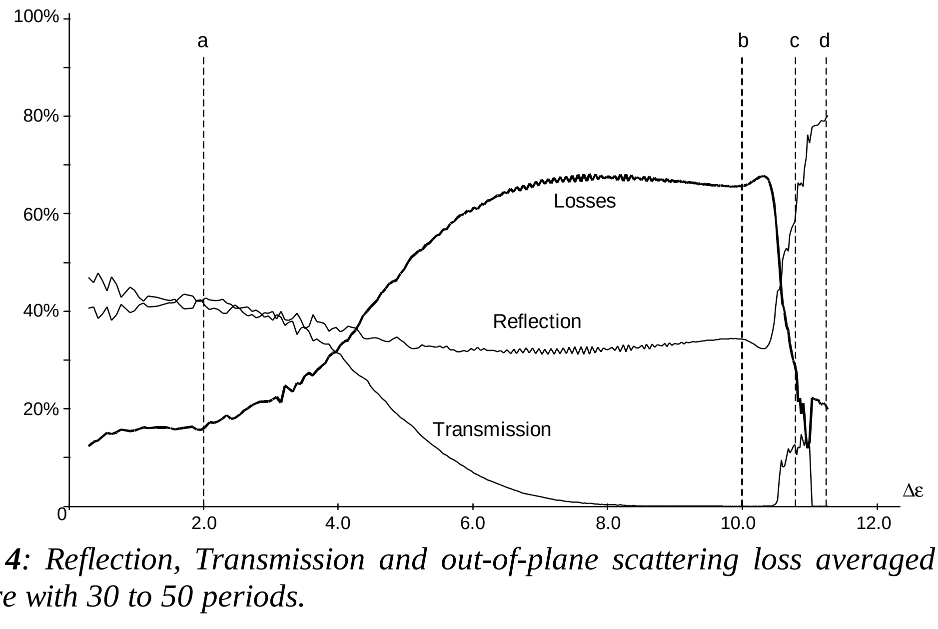

Figure 4: *Reflection, Transmission and out-of-plane scattering loss averaged over a structure with 30 to 50 periods.*

In figure 3a ($\Delta\varepsilon$ = 2.0) we are working above the light line, and out-of-plane scattering losses increase with increasing index contrast, since the light easily couples to the radiative continuum. At an index contrast of $\Delta\varepsilon$=10.00 (figure 3b) the infinite periodic structure has a region below the light line for high values of k_z. However, there is no guided mode present in this region. At a slightly higher index contrast of $\Delta\varepsilon$=10.92 (figure 3c) there is a guided mode below the light line at the operating wavelength. For an infinite structure, this mode would have no radiation losses. Here this is only true for the bulk of the structure. We see that losses have dropped sharply in this region, with dramatically increased transmission. Most of the loss in this regime is transition loss at the boundaries of the structure. For even higher refractive indices (figure 3d) there are again no propagating lossless modes at the operating wavelength, instead there is a bandgap. Most of the incident light is now reflected in the first few periods and losses are quite low, again mainly due to transition losses at the boundary of the structure.

Conclusions

In the design of photonic crystal slabs, care should be given to the proper layer structure to keep out-of-plane scattering losses within reasonable bounds. When treating the losses of each hole independently, they increase with the square of $\Delta\varepsilon$ for low index contrasts, while for higher index contrasts they level out.

For a periodic structure, we can distinguish 4 different regimes. For low refractive index contrasts, losses also increase with increasing $\Delta\varepsilon$. For high contrasts losses will be very high unless one excites a lossless Bloch mode. If one operates in a bandgap below the light line, losses will also be low because light cannot penetrate the crystal.

From the perspective of out-of-plane scattering, two regimes seem to be favorable to reduce undesired losses. For applications with many defects close to each other, one should choose a low index contrast. For few and/or widely separated defects, a lossless Bloch mode and therefore a high refractive index contrast is preferable.

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