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

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Photonic crystal slabs combine a slab waveguide with an in-plane photonic crystal. 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 using a 2D approximation of this 3D structure, with etched slots instead of holes. Our simulation techniques include mode expansion with PML absorbing boundary conditions. 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 for instance, use a channel waveguide to guide light in the plane of the crystal [3], but light could 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 [6].
Two approaches have been suggested to reduce scattering losses. One is to use as low contrasts as possible. As suggested by Bénisty et al. [1, 6], losses increase with the square of $\Delta\varepsilon$, where $\Delta\varepsilon = n^2_{core} - n^2_{clad}$, n_{core} and n_{clad} being the refractive index of the slab's core and cladding.
A different approach is to maximize the index contrast, even to membranes suspended in air. This high index contrast can allow for Bloch modes below the light line without radiation losses [6].
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 index contrast of the structure, losses will increase but that these losses can drop again once a lossless Bloch mode is excited.

Simulation tools and structures

For this study we used our simulation tool CAMFR [7], 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 for the entire structure.
In our layer structure, we tried to approach semiconductor heterostructures, using a three-layer slab waveguide with a core thickness of 0.225µm and a refractive index n_{core} of 3.5. We then vary the waveguide cladding index n_{clad} to study its behavior for different values of $\Delta\varepsilon$.

Results

For this study, we used a period P of 0.55µm and an air slot width d_a of 0.28µm. Figure 2 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 3 as a function of $\Delta\varepsilon$. To eliminate the fluctuations caused the finite periodic structure, we averaged the losses of the structures with 30 to 50 periods. For high

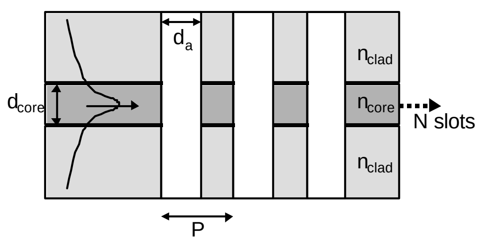

Figure 1: *The simulated structure.*

contrasts the structure quickly changes between 4 distinct regimes.

In figure 2a ($\Delta\varepsilon$ = 2.0) we are above the light line, and losses increase with increasing $\Delta\varepsilon$, since light easily couples to the radiative continuum. At $\Delta\varepsilon$=10.00 (figure 2b) the periodic structure has a region below the light line for high values of k_z. However, no guided mode is present in this region. At a slightly higher contrast of $\Delta\varepsilon$=10.92 (figure 2c) there is a guided mode below the light line at 1.55μm. In the bulk of the structure, this mode has no radiation losses. We see that overall losses drop sharply, with increased transmission. Most of the loss in this regime is transition loss at the boundaries of the structure. For even higher refractive indices (figure 2d) there are again no propagating lossless modes, 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.

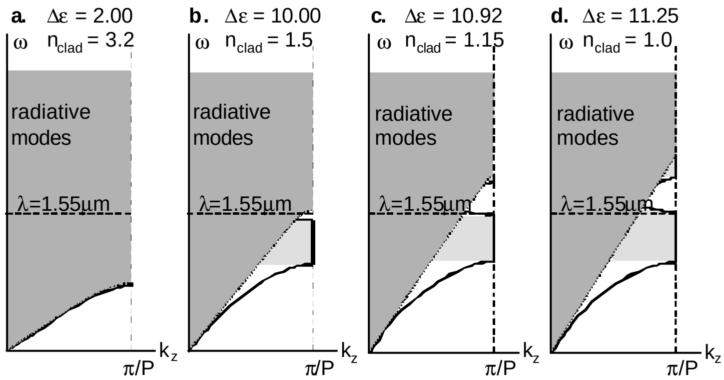

Figure 2: *Band structures for different refractive index contrasts.*

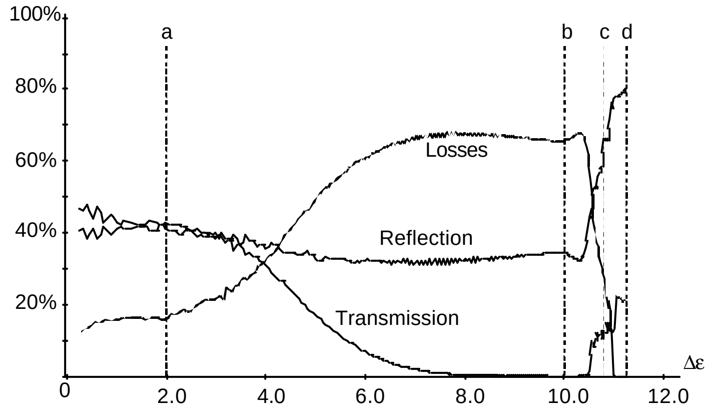

Figure 3*: Reflection, Transmission and out-of-plane scattering loss averaged over a structure with 30 to 50 periods.*

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. 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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