Sidewall Roughness in Photonic Crystal Slabs: A Comparison of High-Contrast Membranes and Low-Contrast III-V Epitaxial Structures

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We have simulated sidewall roughness in photonic crystal slabs. Structures with a low vertical index contrast (like III-V waveguides) are shown to be more prone to scattering at sidewall roughness than membranes or SOI-like structures.

Keywords: photonic crystals, scattering, roughness, silicon-on-insulator

Introduction

Today's photonic crystal slab waveguides are limited in their performance by propagation losses. A large fraction of these losses can be attributed to out-of-plane scattering. While in-plane scattering in photonic crystal slabs is prevented by the photonic bandgap effect, in the vertical direction the light is only bound by a vertical index contrast. Most photonic crystal structures consist of a lattice of holes etched into a slab waveguide structure. These holes break the vertical confinement, allowing the light to radiate to the top or bottom cladding. Evidently, the amount of scattering is highly dependent on the refractive index profile of the layer structure in which the photonic crystals are fabricated. One can use a conventional III-V grown layer structure in the GaAs or InP material system. These structures have a low index contrast between the guiding core and the cladding. Alternatively, photonic crystals can be made in a layer structure with a high index contrast, like silicon-on-insulator (SOI) or semiconductor membranes. Both systems have their merits, but exhibit a drastically different behaviour with respect to out-of-plane scattering losses.

Out-of-plane scattering accounts for a large fraction of the losses in photonic crystals. Current state-of-the-art single-mode photonic crystal waveguides have losses of 6dB/mm in SOI [1], and 11dB/mm in III-V materials [2]. These losses are orders of magnitude larger than those of classical waveguides. To reduce these losses, good management of out-of-plane scattering is needed.

Intrinsic Out-of-Plane Scattering

Out-of-plane scattering in photonic crystal slabs has a number of different causes. Even in perfect photonic crystal slabs light is not necessarily confined vertically, and can leak away gradually as it propagates through the structure. This is true for modes located above the light line in the dispersion diagram. These modes extend into the top and bottom cladding and have a radiation component. As is discussed in [3] and [4], these losses increase strongly with the index contrast between core and cladding. Therefore, III-V semiconductors with a low index contrast are a good material system to keep these losses low. On the other hand, when the photonic crystal waveguide modes are located below the light line, they propagate without loss as long as the periodicity is not disturbed. However, it is only possible to construct such a photonic crystal when it has a cladding with a low refractive index and therefore a light line with a steep slope. This implies a high vertical refractive index contrast, as found in SOI or semiconductor membranes.

To reduce intrinsic losses one can either use a low refractive index contrast, so the intrinsic losses are kept low (but not zero) or use a high refractive index contrast, designing a waveguide with a guided Bloch mode. However, in the latter case, careful engineering is needed for defects, as these might cause large scattering losses [3].

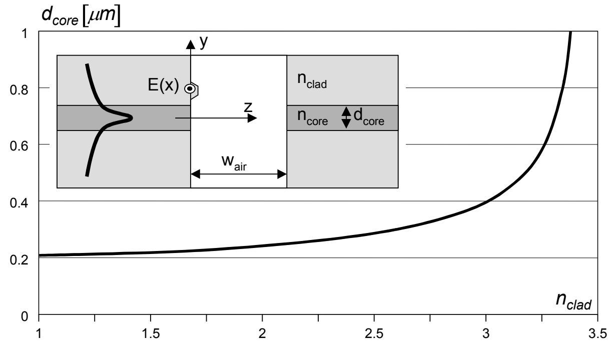

Figure 1: 3-layer slab waveguide with air slot. To guarantee single-mode behaviour, the thickness of the slab core is dependent on the refractive index of the cladding.

Out-of-Plane Scattering at Sidewall Roughness

Although one can design photonic crystal waveguides that are intrinsically lossless, this will never be the case for fabricated structures. The most common fabrication technique for photonic crystals consists of high-resolution lithography combined with dry etching. Although the quality of this technology is improving steadily, a certain amount of roughness due to the etching process is unavoidable. These irregularities, mostly located on the sidewalls of the holes, can scatter light and give rise to losses. Again, we expect the vertical index profile to play a role.

To model the out-of-plane scattering caused by sidewall roughness, we used a 2-D approximation of a photonic crystal slab: 1-D air slots etched into a slab waveguide (Figure 1). We then modelled the scattering roughness by a dipole excited by the incident electromagnetic field, i.e. the mode of the slab waveguide. Because the scatterer radiates in all directions, a fraction of the light will be recaptured by the slab waveguide core. This fraction is of course dependent on the index profile of the slab waveguide and the position of the roughness on the sidewall. We calculated a measure for the losses by averaging over position y of the irregularity on the sidewall:

$$L_{tot} \sim \int_y P(y) L(y) dy , \tag{1}$$

with $P(y)$ the power radiated by the dipole and $L(y)$ the fraction not recovered by the slab waveguide core. We calculated this using CAMFR [5][6], a vectorial eigenmode expansion tool with PML absorbing boundary conditions. Along the propagation axis, the structure is cut into sections with a constant index profile, in which the electromagnetic field is expanded into the local eigenmodes. Radiation modes are supported through PML absorbing boundary conditions. At the interface between sections, mode matching is used to decompose the field into the eigenmodes of the new section. This way, a scattering matrix describing the entire structure is obtained.

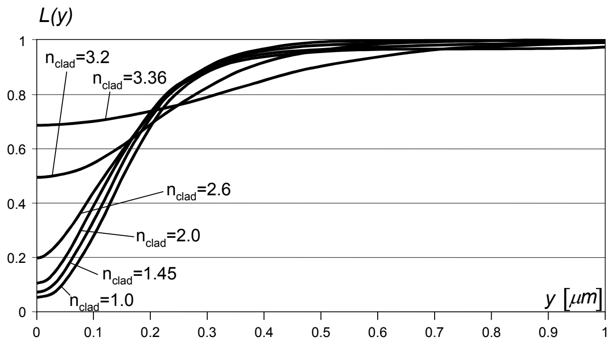

Figure 2: Fraction of light radiated by a dipole in position y that is not recaptured by the waveguide core.

To compare structures with a different refractive index contrast, we defined a slab structure with a constant *v*-number of 2.79. Because the *v*-number depends on the cladding index and core thickness, the core will be thicker for lower cladding index. The core thickness is plotted in Figure 1 as a function of cladding index. For the slab core a refractive index of 3.45 was chosen. The air slots in the slab waveguide are considered to be etched through completely and have a width of 280nm.

Using CAMFR, we then calculated the excitation of the dipole, as well as the fraction of light that can be recovered. This was done in a rigorous way, taking into account the effects of the surroundings on the radiation pattern of the dipole. Because in a photonic crystal, backward and forward propagating light is coupled, we consider the radiated light coupled into the forward and backward propagating mode as *not* lost. Figure 2 plots the lost fraction $L(y)$ of the light as a function position y of the dipole for different values of the cladding index. We see that for low cladding indices (i.e. high vertical index contrast) much light is recovered when the dipole is near the cladding. This can be explained by the fact that a narrow waveguide with high index contrast automatically has a large numerical aperture and can capture much light.

The integrand of equation (1) also contains the power of the radiating dipole. This power depends on two factors: The field strength in position y and the geometry of the roughness on the material-air interface. In a first-order approximation, the incident field strength can be derived from the slab waveguide guided mode. The excitation of the dipole by this incident field is determined by the geometry of the sidewall roughness, as well as by the refractive index contrast along the material-air interface. We can write the radiated power of the dipole $P(y)$ as

$$P(y) = \eta(y)^2 . \frac{E^2(y)}{2.Z_{rad}(y)}, \tag{2}$$

with $E(y)$ the field in position y, $\eta(y)$ describing the effect of the roughness and $Z_{rad}(y)$ the radiative impedance of the environment in position y. The first and last term are easily calculated using CAMFR. To study the effect of the geometry $\eta(y)$ we simulated the scattering of a plane wave incident on an irregularity on a smooth interface between a homogeneous material and air. We did this for different material refractive indices and found that $\eta(y)$ behaves very much like

$$\eta^2 = \gamma.(\Delta\varepsilon_h)^2, \tag{3}$$

with $\Delta\varepsilon_h$ the difference in dielectric constant (i.e. the square of the refractive index) at the interface. If we use this result in our slab waveguide configuration we see that $\eta(y)$ is indeed dependent on the position y, as the index contrast along the interface changes from core to cladding.

Taking into account these results, we can now calculate the integrand in equation (1). $P(y).L(y)$ is

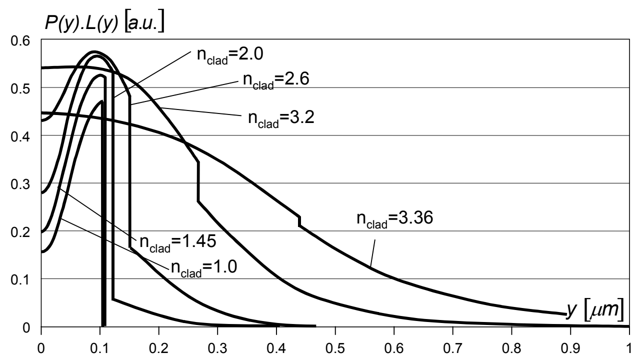

Figure 3: Power lost by radiation caused by an irregularity as a function of position y for different values of the cladding refractive index.

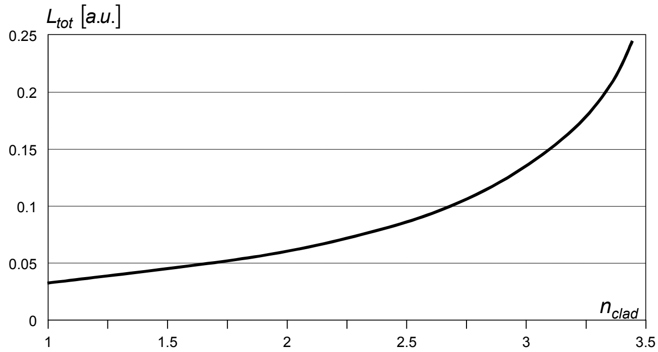

Figure 4: A measure for the average power lost due to sidewall roughness as a function of the refractive index of the slab waveguide cladding.

plotted in Figure 3 for different values of the cladding index. The discontinuity in the curves is caused by the discontinuity in $\eta(y)$ at the core-cladding interface. We see that the amount of scattering is significantly lower for structures with a high refractive index contrast.

Figure 4 plots the measure for scattered light as described in equation (1). We see that for low refractive index contrast, like in III-V, losses due to scattering are considerably higher than in the case of SOI or membranes, and this for a similar amount of sidewall roughness.

Conclusion

Out-of-plane scattering is the major loss mechanism in photonic crystals, and scattering at sidewall roughness can contribute to these losses. Although there are two beneficial regimes for intrinsic losses, i.e. the very high and the very low index contrast, only the high vertical index contrast promises to alleviate these losses for the same level of manufacturing technology.

This advantage with respect to out-of-plane scattering losses might provide an explanation as why photonic crystal waveguides in SOI seriously outperform their III-V competitors [1][2]. Also, these results again show the importance of high-quality fabrication technology. Especially when photonic crystal-based structures are to be commercialised, reproducible mass-fabrication techniques are required.

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