Reducing Out-of-Plane Scattering Loss in One-Dimensional Photonic Crystal Slabs Using a Simplified Mode-Matching Technique

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Abstract

A method for reducing out-of-plane scattering loss in photonic crystal (PC) slabs is examined. FDTD simulations of light propagation through two-dimensional, PC slab, cross-sections reveal that matching vertical mode profiles between the slab and the lattice holes is an effective method for reducing scattering loss. Moreover, a simplified structure having only limited mode-matching is also shown to significantly reduce scattering loss. The PC slabs used in the simulations contain resonant defects, which provide an effective means for evaluating our method.

Keywords: Photonic crystal slabs, integrated optics, guided waves, vertical mode-matching, scattering loss.

1. Introduction

Fabricating three-dimensional (3-D) photonic crystals with submicron features has proven to be a formidable challenge [1], [2]. In response to this difficulty, the PC slab has become a favored alternative [3], [4]. This type of PC uses a 2-D lattice of air holes etched through a step-index waveguide to replicate the properties of the full 3-D PC structure. The PC slab reduces fabrication complexities and can be more easily integrated with conventional, planar, optical devices.

However, despite these advantages, PC slabs have a notable drawback – out-of-plane scattering loss [5], [6], [7]. For example, a simple line defect waveguide in a PC slab, in comparison to a similar high-index channel waveguide, exhibits more propagation loss [8], [9]. These losses are due in part to the lack of complete vertical confinement in the slab geometry. In other words, the lack of confinement within the lattice holes leads to diffraction-induced scattering at the slab-hole interface [4]. As a result, several methods have been proposed to decrease out-of-plane scattering loss based on vertical confinement through the use of waveguiding within the holes [10], [11], [12]. In this paper we further analyze these techniques using one-dimensional PC slab structures with single and multiple defects and compare structures that provide varying degrees of vertical confinement.

2. Vertical Mode-Matching

The most general form of a PC slab is shown in cross-section in figure 1. The structure may consist of six different materials. If the structure is vertically symmetric, a horizontal symmetry plane will bisect the core guiding region which can then be used to classify the guided modes as even or odd [3], [4]. This requires that $n_{1a} = n_{1c}$ and $n_{2a} = n_{2c}$. Furthermore, for the structure to be waveguiding, n_{1b} must be larger than n_{1a} and n_{1c}. These conditions are most easily met with a membrane structure where $n_{1a} = n_{1c} = n_{2a} = n_{2b} = n_{2c} = 1$. Alternatively, a heterostructure (e.g. SOI) with $1 < n_{1a} = n_{1c} < n_{1b}$, and $n_{2a} = n_{2b} = n_{2c} = 1$ can satisfy the necessary conditions. Light, nevertheless, can be scattered in either case as there is no mechanism to vertically confine light within the holes. This lack of confinement allows coupling of the guided wave to the radiation modes within the cladding. Ideally a loss-less Bloch mode operating below the light line may propagate in the PC slab if the structure has high, vertical, refractive index contrast [6]. However, this is true only for infinitely extended structures with perfect periodicity, which would exclude important devices such as defect waveguides with sharp bends. Therefore, in practice, out-of-plane scattering loss is a major obstacle to the development of PC slab-based devices.

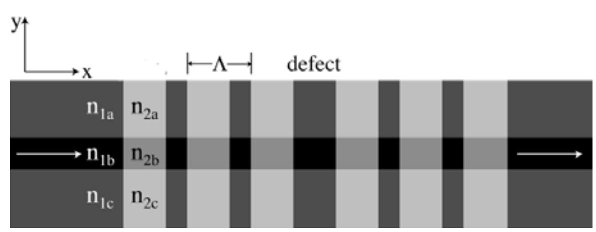

Fig. 1: General form of the PC slab structure, shown in cross -section.

To use refractive index guiding within the lattice holes, the inequality n_{2a}, $n_{2c} < n_{2b}$ must be satisfied. If the refractive indices are chosen properly, the vertical mode profile of the slab will perfectly match that of the holes as determined by the overlap integral

$$\Theta = \frac{\left|\int E_1(y)E_2(y)dy^2\right|}{\left|\int E_1^2(y)dy\left|E_2^2(y)dy\right|\right|}, \quad (1)$$

where E_1 (y) is the vertical mode profile in the slab and E_2 (y) is the vertical mode profile in the hole. When $\Theta = 1$ there is perfect vertical mode-matching, while when $\Theta = 0$ there is no mode-matching. The goal then is to maximize Θ.

This paper is organized as follows 1) we analyze the case where there is perfect mode overlap and 2) we analyze a simplified structure where there is only partial overlap. In both cases, we compare our structures to a reference structure having constant refractive index holes. All structures are analyzed through simulation based on transmission through a single PC defect with three or four "mirror" periods on each side as illustrated in figure 1.

Our studies are valid for 1-D PC structures in 2-D slab cross-section geometry, and serve as an approximation to the more useful 2-D PC structure in the fully 3-D slab geometry. In the case of holes without vertical confinement, our 2-D computational geometry overestimates the out of plane scattering loss (as in the 2-D slab PC, light can flow around the holes), but will provide qualitative estimation of the diffraction losses within the holes [5].

3. Simulation Results

All of the calculations are performed using a 2-D TE (electric field along the z-axis) FDTD code. We use a uniform spatial grid with $\Delta x = \Delta y = 15$ nm. The time stepping is $\Delta t = 25$ *a*s and perfectly-matched layer boundary conditions are used [13].

3.1. The Ideal Structure

In the first set of simulations, perfect vertical mode-matching is created between the slab and the holes by filling the holes with materials of appropriate refractive indices such that $n_{1b}^2 - n_{1a}^2 = n_{2b}^2 - n_{2a}^2$ [12]. This creates a common waveguide mode in the vertical direction (i.e. $\Theta = 1$). As an example, the following materials are used for matching: $n_{1a} = n_{1c} = 2.84$, $n_{1b} = 3.4$, $n_{2a} = n_{2c} = 1.45$ and $n_{2b} = 2.366$. The core thickness is 0.25 μm in the slab and holes allowing for a single TE mode to propagate with effective indices of 3.093 and 1.899, respectively. The cladding thickness is 3 μm.

The 1-D resonator illustrated in figure 1 is simulated using the aforementioned parameters. The resonator consists of three periods of quarter-wave width on both sides of a half-wave defect. The calculated transmission spectrum is shown in figure 2 a). At 1550 nm the transmission peak reaches 100%. For comparison, the same structure is simulated with a uniform refractive index in the holes equal to the effective refractive index of the mode-matched structure's holes, i.e. $n_{2a} = n_{2b} = n_{2c} = 1.899$. As shown in figure 2 b), without vertical confinement, the transmission peak drops from 100% to 36.9%.

Next we analyze these two structures as a function of the number of "mirror" periods on each side of the defect. This provides information regarding how well the defect is able to store energy, thereby indicating the level of loss in the defect cavity. This information is contained in the parameter called the quality factor, Q, defined as the center wavelength divided by the bandwidth. Figure 3 a) shows the transmission for the mode-matched structure and a structure with uniform index holes as a function of mirror periods. The

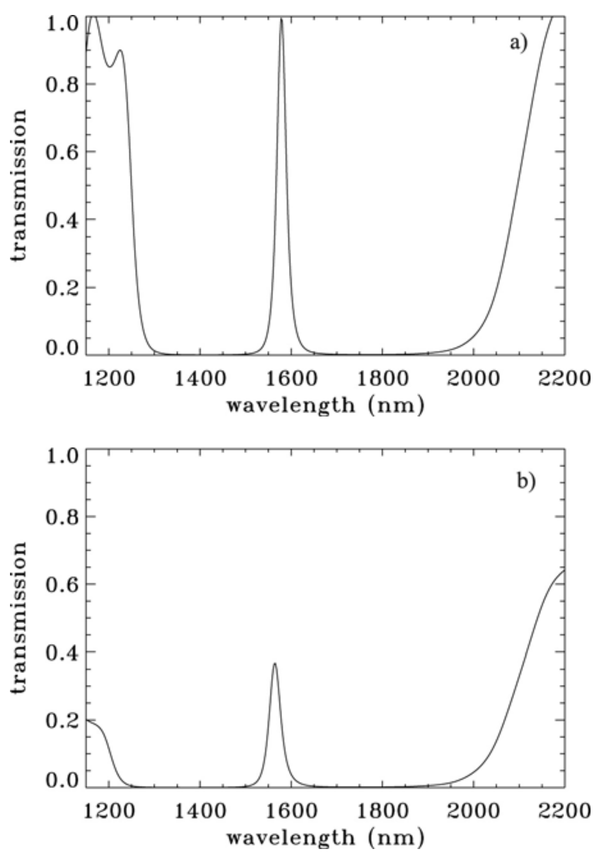

Fig. 2: The calculated transmission spectra for a PC slab with a) mode matching ($n_{1a} = n_{1c} = 2.84$, $n_{1b} = 3.40$, $n_{2a} = n_{2c} = 1.45$, $n_{2b} = 2.37$) and b) with uniform refractive index holes ($n_{1a} = n_{1c} = 2.84$, $n_{1b} = 3.4$, $n_{2a} = n_{2c} = n_{2b} = 1.90$).

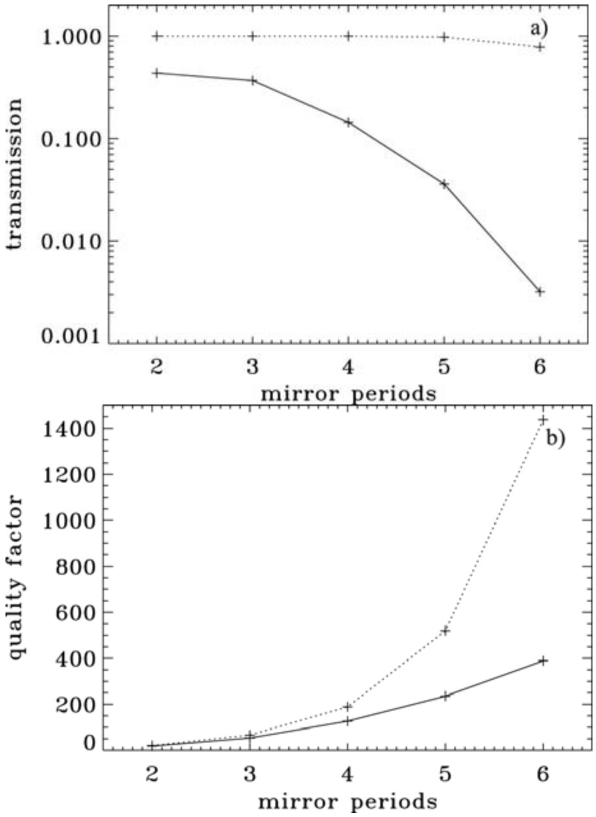

Fig. 3: Calculated a) transmission and b) quality factor plotted as a function of mirror periods on each side of the central resonant defect. The dotted line represents the structure with mode-matching ($n_{1a} = n_{1c} = 2.84$, $n_{1b} = 3.40$, $n_{2a} = n_{2c} = 1.45$, $n_{2b} = 2.36$) and the solid line represent the uniform index holes ($n_{1a} = n_{1c} = 2.84$, $n_{1b} = 3.40$, $n_{2a} = n_{2c} = n_{2b} = 1.90$).

mode-matched structure's transmission starts at 100% and drops to 78% at six periods. This drop can be accounted for by the finite cladding thickness [6]. On the other hand, for the structure with constant index holes, the transmission decreases by two orders of magnitude. Figure 3 b) shows that the quality factor increases exponentially for the mode matched structure as expected [12]. The structure with uniform index holes lacks the ability to confine energy in the resonant defect due to energy leakage in the form of scattering loss. As a result, the increase in quality factor is less significant for this structure.

3.2. Partial Mode-Matching

The mode-matched structure examined up to this point requires four different refractive indices. To create such a structure would require very sophisticated fabrication procedures. Therefore, it is desirable to reduce the complexity of the structure. This can be accomplished by using a common cladding for the slab and hole regions. A structure where only the core refractive index is modified provides, as will be shown, many of the same advantageous properties as the perfectly mode-matched structure, yet is more accessible in terms of fabrication. In fact, this structure only requires an etch depth equal to the thickness of the guiding layer, the same as a membrane PC slab.

To investigate the simplified structure, we perform simulations with $n_{1a} = n_{1c} = n_{2a} = n_{2c} = 1.45$, $n_{1b} = 3.4$, and the hole core index n_{2b} is varied between 1.542 and 2.518. In figure 4 a), the transmission spectra is plotted for the simplified structure with three and four mirror periods. As n_{2b} approaches larger values, the transmission approaches 100%. This is due to the increasing level of mode overlap. The % overlap is indicated on the dotted line style.

The quality factor is plotted in figure 4 b). The degradation of the quality factor due to scattering loss can be characterized by expressing the overall quality factor as two constituent terms,

$$\frac{1}{Q} = \frac{1}{Q_I} + \frac{1}{Q_L}, \qquad (2)$$

Here Q_I is the intrinsic quality factor due to the coupling coefficients of the cavity "mirrors", and Q_L is

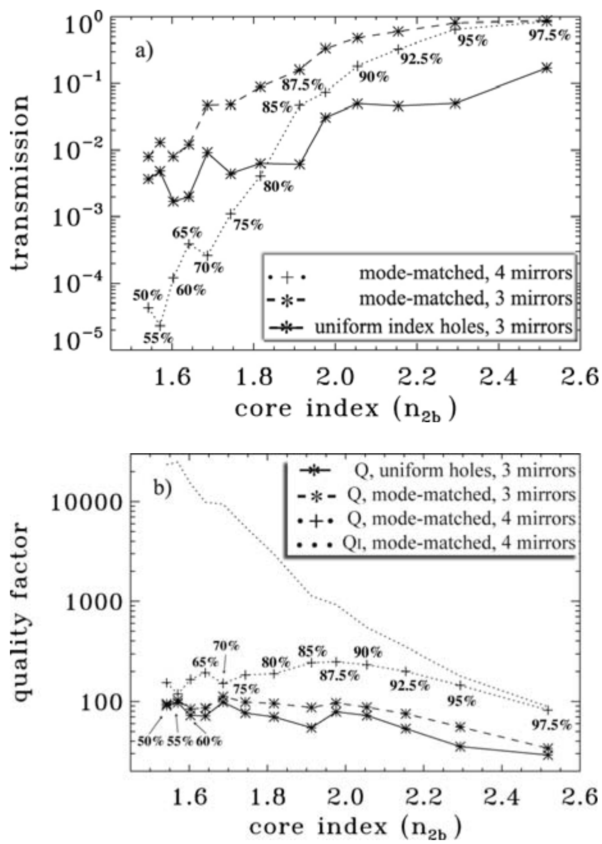

Fig. 4: Calculated a) transmission and b) quality factor as functions of n_{2b}. The intrinsic quality factor Q_I is also plotted in b). The mode overlap is shown by %.

the loss-limited quality factor. For a loss-less structure $Q_L = \infty$, meaning that $Q = Q_I$. Therefore, any deviation of Q from Q_I indicates that loss exists in the system. The intrinsic quality factor can be directly calculated given the transmission and total quality factor, $T = (Q / Q_I)^2$ [14].

The intrinsic quality factor has an inverse relationship with n_{2b} as seen in figure 4 b). High values of n_{2b} create low in-plane contrast and, consequently, a lower Q_I. On the other hand, low values of n_{2b} increase the out-of-plane scattering which lowers Q_L and the transmission. Therefore there is a tradeoff between Q_I and Q_L and there exists an optimum value of n_{2b} that maximizes the overall quality factor. In figure 4 b) for the case of four mirror periods on each side of the defect, that value is approximately 1.98; however, the transmission at this optimal value is relatively low at 34%.

For constant index holes the transmission is reduced by about an order of magnitude, and the quality factor drops due to an exorbitant amount of loss. The lower transmission and quality factor illustrate the advantage of using even imperfect mode-matching.

4. Conclusion

In this paper we examined a method to reduce out-of-plane scattering loss in PC slabs. Through the simulation of a 1-D PC slab with a resonant defect, we demonstrated that vertical mode-matching can greatly reduce scattering loss. In particular, it was shown that even in an imperfect mode-matching scheme, where only the refractive index of the core layer is changed, there is reduced loss compared to a similar PC slab with constant index holes. While there is a tradeoff between mode overlap and in-plane contrast, reasonable transmissions can be retained with higher quality factor resonances (by increasing the number of mirror periods). This suggests that a simplified mode-matching structure may offer a fair compromise between fabrication complexity and performance.

5. References

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