Taper structures for coupling into photonic crystal slab waveguides

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We present an adiabatic taper design in three dimensions for coupling light into photonic crystal defect waveguides in a square lattice of circular dielectric rods. The taper is a two-stage structure in which the first stage makes the transition from a dielectric waveguide to a coupled-cavity waveguide. The second stage subsequently transforms the waveguide mode from an index-guided mode to a band-gap-guided mode. We discuss differences between the two-dimensional device and its three-dimensional slab version. © 2003 Optical Society of America

OCIS codes: 060.1810, 130.3120, 230.7370.

1. INTRODUCTION

Photonic crystals are very interesting candidates for the realization of photonic integrated circuits because of their ability to confine light, guide it around tight bends and perform a wealth of other optical functionality such as filtering and add–drop multiplexing.[1–3]

The ultimate confinement of light can be realized only in full three dimensional (3D) photonic crystals, which are still very hard to fabricate. However, for short- to medium-term applications, two-dimensional (2D) photonic crystal slabs offer an interesting alternative.[4] In these structures, the horizontal confinement is provided by an in-plane, 2D, photonic crystal, while a slab waveguide structure takes care of the vertical out-of-plane confinement. Provided the index contrast is high enough, lossless guided modes can exist in these structures.

The practical use of these structures for photonic integrated circuits is limited if there are no good approaches to coupling light into them efficiently. It is the aim of this paper to present adiabatic coupling structures for photonic crystal slab waveguides in the form of square lattices of dielectric pillars in air. To the best of our knowledge, coupling into these structures has never been thoroughly investigated. There have been reports of coupling into 2D photonic crystal waveguides,[5] but these did not capture the out-of-plane aspect. Other papers did take into account full three dimensionality, but dealt with

crystal structures consisting of a triangular lattice of air holes in a dielectric.[6,7] We want to focus here on the dual structure of dielectric pillars in air because in these systems, it is easier to achieve a monomode operating regime, and because scattering losses due to sidewall roughness might be lower. Moreover, rather than employing an *ad hoc* gradual transition, in this paper we exploit the existence of an explicit adiabatic theorem for periodic systems.[8] Given the simple constraints imposed by this theorem, we thus demonstrate the design of a 3D structure that has an *a priori* guarantee of high transmission for a sufficiently gradual taper.

The rest of this paper is structured as follows. In Section 2 we describe the parameters of the waveguide structure we use. The design of the coupling structure is then started in Section 3 using a 2D model. Many of the issues involved in the taper design are already present in two dimensions, which allows us to get a qualitative insight into the device physics using a model with lower computational demands. In Section 4 we draw on these insights to design a full 3D coupling structure. We show that the 3D version of this structure is not a straightforward application of the 2D design, but that additional modifications need to be made.

2. WAVEGUIDE STRUCTURE

The structure under study consists of a layer of GaAs ($n = 3.37$) of thickness 830 nm over a 1500-nm alumi-
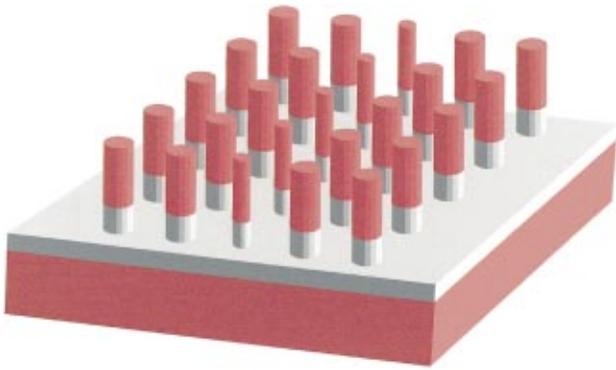
Fig. 1. Photonic crystal slab based on a square lattice of dielectric rods in air.
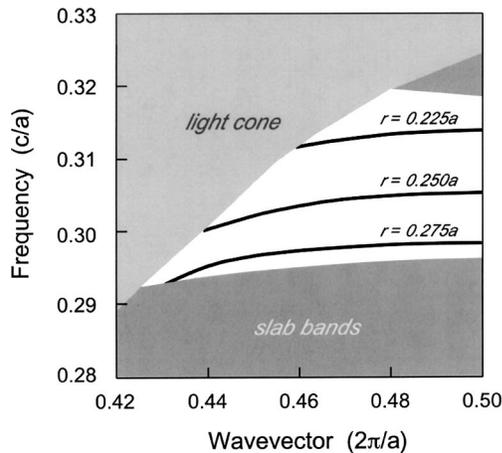

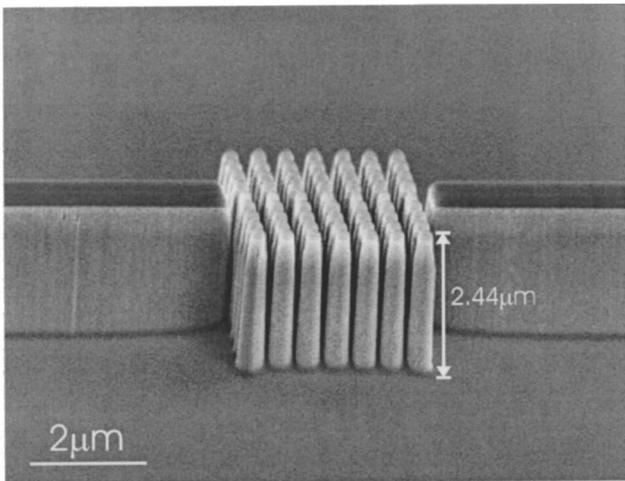Fig. 2.   Band diagram of defect modes in photonic crystal slab structure of Fig. 1 for different defect radii.

Fig. 3.   Experimental prototype of photonic crystal slab structure.

num oxide cladding layer (n = 1.61).   Below the oxide layer is a GaAs substrate. This slab waveguide structure provides vertical confinement in a high-index GaAs core sandwiched by low index air and oxide claddings.   By etching these layers, we create a lattice of circular dielectric rods with a lattice constant of a = 500 nm.   The rod radius is $0.30a$.   The etch depth (or height of the pillars) is 1430 nm, meaning that we etch 600 nm into the oxide layer.

A line-defect, TM-like waveguide is created by reducing the rod radius of a row in the photonic crystal (Fig. 1). Figure 2 shows the band structure of such waveguides for varying radii of the defect.   Using a radius of $0.25a$ results in a mode that is located in the center of the usable bandgap below the light line.

Figure 3 also shows a scanning-electron micrograph of a preliminary structure consisting of a bulk crystal in GaAs with conventional input and output waveguides.

3. TWO-DIMENSIONAL COUPLING ANALYSIS

A. Untapered Waveguides

We will first study a 2D version of this structure, not because it will give quantitative results directly applicable to the 3D case, but because it will allow us to identify qualitatively many of the issues in the coupler design early at lower computational cost.   In two dimensions the bandgap extends from 0.235 to 0.300 (in normalized frequency units c/a).   If we choose a defect radius of $0.20a$ (instead of the r = $0.25a$ used in three dimensions), we create a defect mode extending in frequency from the lower band edge to 0.270.

As input waveguide, we will consider a narrow-dielectric-ridge waveguide (photonic wire) with the same width as the defect diameter.   Coupling from a broad-ridge waveguide to such a photonic wire is easily achieved by standard tapers and is not the focus of this paper.

Figure 4 shows the transmission through the untapered structure for a photonic crystal waveguide length of 8 periods.   These simulations were done with a frequency-domain model based on vectorial eigenmode expansion[9] and a staircase approximation of the index profile with a resolution of 20 pixels per period.   This modeling tool CAMFR is freely available from the Internet.[10]

Although there are frequencies for which the untapered structure achieves unity transmission, this phenomenon is entirely due to Fabry–Perot resonances, in which a parasitic cavity is formed by reflections from the input and output facets.   As a further illustration of this effect, we also plot in Fig. 4 transmission through a photonic crystal waveguide with a different length (10 periods). The peaks are shifted because of the different cavity length.

Figure 4 clearly shows that there is an imperfect conversion of the optical mode from the dielectric waveguide to the photonic crystal waveguide.   One of the main reasons it is hard to achieve good coupling is the fundamental difference in guiding mechanism and field profile between these two waveguides.

In the dielectric waveguide, the waveguide mode consists entirely of forward-propagating field components. The waveguide mode in the photonic crystal is, of course, a forward-propagating Bloch mode, but because of the strong scattering inside the crystal, this Bloch mode (with net forward energy flux) consists of both forward- and backward-propagating field contributions (Fourier components).   Another way of looking at this is to note that the ratio between the electric and magnetic field (related to an effective "impedance") will be very different for these two waveguides.
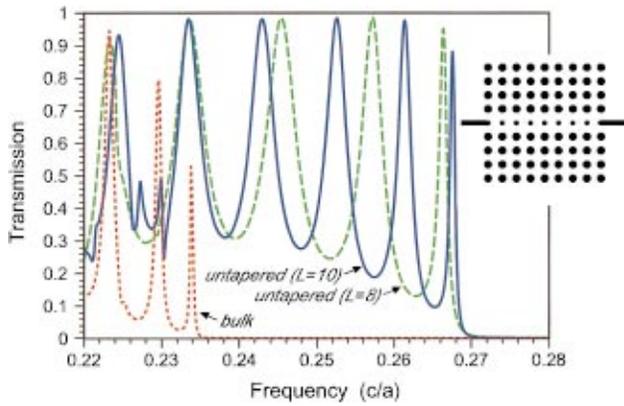
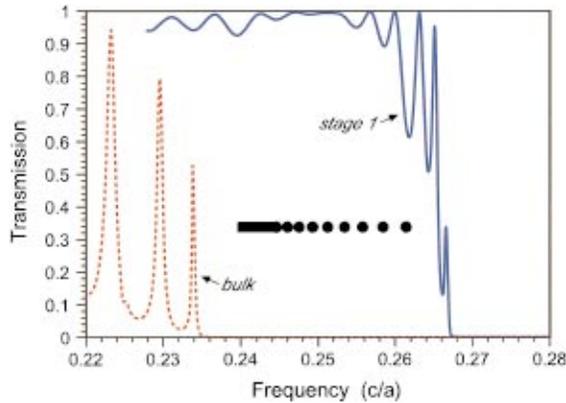Fig. 4. Transmission through bulk crystal and two untapered waveguides of different lengths.

Fig. 5. Transmission through a stage I input coupler (geometry shown in the inset), a 20-period coupled-cavity waveguide (not shown in inset), and a stage I output coupler (mirror image of the inset).

In the dielectric waveguide, the mode is guided by classical total internal reflection in which the field is concentrated in a region having a higher refractive index than its surroundings. In the photonic crystal waveguide, the effective index of the line defect is lower than that of its surroundings because the radius of the defect rods is smaller than that of the bulk rods. In this case, the guiding mechanism is that light in the defect is channeled by two perfect mirrors formed by the adjacent bulk photonic crystal.

Thus, to increase the coupling efficiency, we need to address these two issues. For that reason, we propose a two-stage coupling structure in which stage I converts the forward dielectric mode into a mode with both forward and backward components and stage II makes the transition from high-effective-index guiding to low-effective-index guiding.

B. Stage I Coupler
In Fig. 5 we simulate a structure which makes an adiabatic transition from a dielectric waveguide to a (albeit rather strongly coupled) coupled-cavity waveguide also called coupled-resonator optical waveguide)[11] and then back to a dielectric waveguide. In such a coupled resonator optical waveguide, the waveguide mode is, in fact, a Bloch mode with both forward- and backward-

propagating field components. By gradually decreasing the distance between the resonators (in this particular example, by reducing the period by 10% each period), it is obvious that they will eventually merge to become a traditional dielectric waveguide in which the mode has only a forward-propagating field component.

As Fig. 5 shows, the transmission through such a structure (both input and output coupler) can be practically 100% over a large bandwidth. As an aside, we also want to point out that not just any gradual geometric transition which causes the rods to merge would give rise to 100% transmission. For example, keeping the period fixed and making the rods gradually more elliptical until they merge would not give a high transmission, at least not in regions near the band edge of the coupled-cavity waveguide. This is because the guided mode would leave the gap and no longer be guided, which is a necessary condition for the adiabatic theorem for photonic crystals to hold.

Finally, we want to point out that the stage I structure is already useful in its own right (i.e., without the pres-
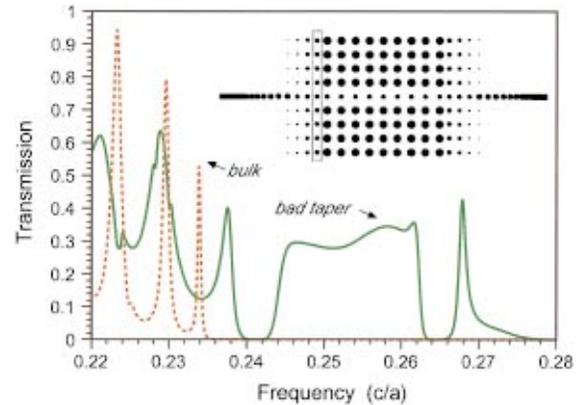

Fig. 6. Transmission through a "bad" taper structure in which the cladding rods are varied in diameter in stage II.
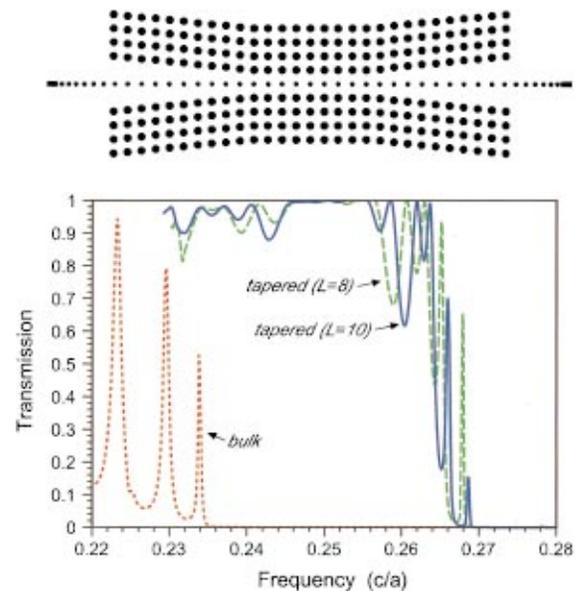

Fig. 7. Transmission through the two-stage input coupler, a waveguide of 8 or 10 periods length, and the output coupler.
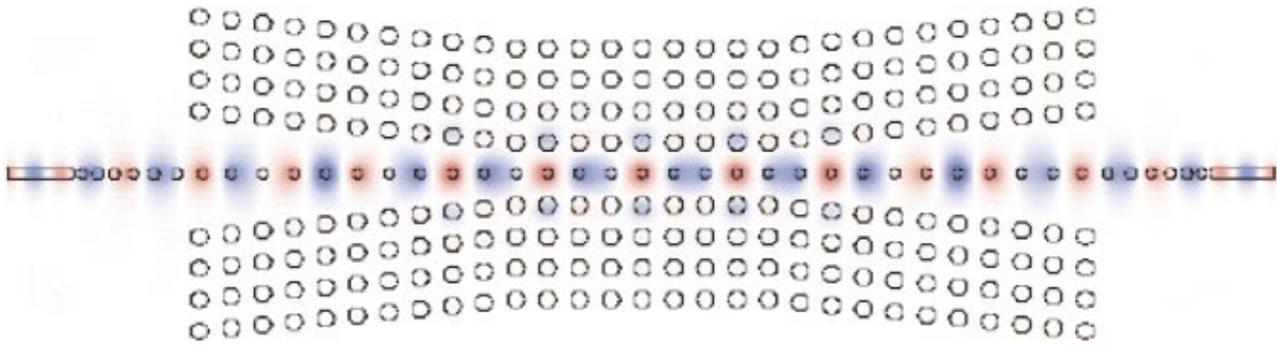
Fig. 8.   Time snapshot of the electric field in the taper structure.   Only the top half of the structure is shown.

ence of stage II), e.g., when coupling to coupled-cavity waveguides.

C. Stage II Coupler

When the adiabatic transition in stage I reaches the value of the lattice constant, the input coupler can be seen as a photonic crystal defect waveguide, but without the bulk photonic crystal cladding.   So the cladding needs to be introduced in stage II of the coupler, thereby transforming the mode from high-index guiding to low-index guiding (gap guiding).   One obvious approach to achieve this is to change the cladding rod radius gradually from zero to its final value (see Fig. 6).   Such an approach was tried with reasonable success for crystal structures based on air holes in a dielectric[6]; however, there it was used in a different context, namely to couple photonic crystal waveguides of different widths.   For coupling to the dielectric input waveguide, an abrupt transition was used, which yielded acceptable transmission because the waveguide was rather wide (and therefore multimode, which also makes tapering more difficult).

In this paper, we want to achieve adiabatic tapering, not only to couple photonic crystal waveguides of different widths, but to make the transition from index guiding to gap guiding.   For this purpose, the gradual variation of cladding radius does not work, as we can see in Fig. 6. The reason for this is that the taper goes through an intermediate state (the box in the inset of Fig. 6) in which the core and cladding rods have the same diameter.   This section is a bulk crystal which also has a band gap and therefore reflects the incoming radiation.   So, when designing a taper structure, one should ensure that each intermediate stage has a guided mode and does not couple to the radiative continuum.[8]   We should point out that this reflection and–or scattering from an intermediate stage is not due solely to some geometric coincidence, but is a fundamental issue which arises from the fact that by "turning on" the bulk crystal, we pull the radiative continuum down until it lies below the guided mode.   So inevitably there will always be an intermediate stage at which the waveguide mode crosses the continuum and is no longer guided.

The right way to achieve reflectionless adiabatic tapering is to keep the radius of the rods fixed, but to decrease gradually the distance between the cladding and the line defect (see Fig. 7), in this case by $0.1a$ per period.   In this way, reflections do not occur from an intermediate stage
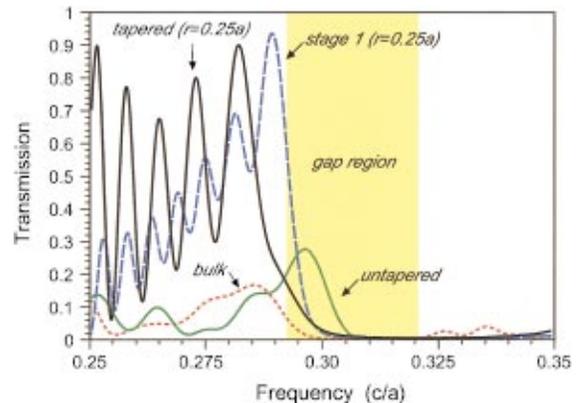

Fig. 9.   3D transmission through bulk crystal, untapered waveguide (both 8 periods long), stage I taper (with the same length as the full taper, but with the bulk crystal cladding removed), and full taper.
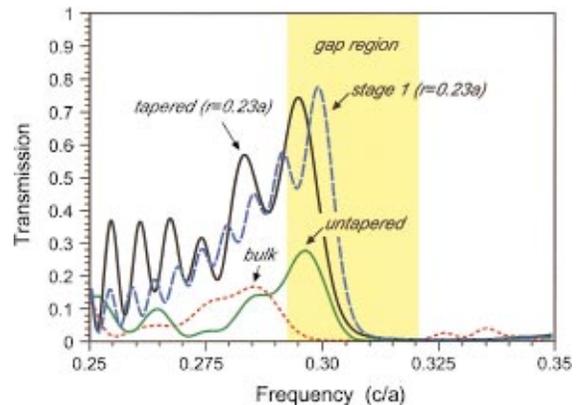

Fig. 10.   Same as Fig. 9, but this time with a stage I taper having a defect radius of $0.23a$ instead of $0.25a$.

because the lower-band continuum always exists below the guided mode and only its local density of states is altered.

As can be seen from Fig. 7, the transmission of the entire taper (stage I and stage II) is very close to 100% and has a significant bandwidth.   As in Fig. 4, we also plot the transmission for two different waveguide lengths.   In the range 0.245–0.255 the transmission does not vary from its near unity value, indicating very good modal conversion.   For other frequencies, there are some shifts, but in general the transmission is much better than in the un-

tapered case. Once again, the adiabatic theorem guarantees that we can accomplish this transition arbitrarily by making the taper gradual enough.

In Fig. 8, we plot the field distribution in the entire structure. It is obvious that there are differences in field profiles in the dielectric waveguide, stage I, stage II, and the photonic crystal waveguide. However, it is clear that the taper structure provides a gradual transition between these profiles.

4. THREE-DIMENSIONAL COUPLING ANALYSIS

Let us now go back to the 3D case and the geometry described in Section 2. We use 3D finite-difference time-domain methods and a resolution of 20 pixels per period to model the structures. Following the strategy of Section 3 to create a taper does not give rise to any transmission inside the bandgap, as plotted in Fig. 9. This is because the 3D defect mode has a much smaller bandwidth compared with the 2D case. A similar observation is true for stage I of the taper. The narrow pass bands of stage I and the waveguide mode do not overlap in this case, which explains the lack of transmission inside the gap in Fig. 9. This is remedied by slightly changing the rod radius in stage I from $0.25a$ to $0.23a$, which shifts the pass band of stage I into the bandwidth of the waveguide mode (Fig. 10). In this case taper transmission is 75%, compared with 30% for the untapered case.

The adiabatic theorem guarantees that it should be possible to achieve 100% transmission. However, for this the taper needs to be significantly more gradual than our computational resources allow us to study. In the 3D case the group velocity is much lower and so is the k-vector phase mismatch with the reflected wave (because we operate near the edge of the Brillouin zone). Both factors have a detrimental influence on the required taper length.[8]

Additionally, because of resolution limitations, it is uncertain if $0.23a$ is really the optimal value for the stage I taper radius, i.e., the one that gives the best alignment between the two stages. This also means that fabrication tolerances will be rather stringent. Experimental verification is currently in progress.

5. CONCLUSIONS

We have presented novel two-stage taper designs which allow efficient coupling from a dielectric waveguide to a coupled-cavity waveguide or to a line-defect waveguide in a photonic crystal slab of dielectric pillars in air. In two dimensions these structures have nearly 100% transmission and a very good bandwidth. For the design of the 3D structures, special care needs to be taken to adjust the parameters of the two stages to have overlapping pass bands. In three dimensions, despite the lower group velocities in the waveguide and the lower bandwidth of the taper ($0.005\,c/a$ instead of $0.015\,c/a$ as in two dimensions), the transmission can still be up to 75% with good control of the fabrication process.

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