Creating large bandwidth line defects by embedding dielectric waveguides into photonic crystal slabs

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We introduce a general designing procedure that allows us, for any given photonic crystal slab, to create an appropriate line defect structure that possesses single-mode bands with large bandwidth and low dispersion within the photonic band-gap region below the light line. This procedure involves designing a high index dielectric waveguide that is phase matched with the gap of the photonic crystal slab, and embedding the dielectric waveguide as a line defect into a crystal in a specific configuration that is free of edge states within the guiding bandwidth. As an example, we show a single mode line defect waveguide with a bandwidth approaching 13% of the center-band frequency, and with a linear dispersion relation throughout most of the bandwidth. [DOI: 10.1063/1.1523637]

Photonic crystal slab structures are constructed by introducing strong two-dimensionally periodic index contrast into a high-index dielectric guiding slab.[1] With sufficient index contrast in the vertical direction, such structures support an in-plane photonic band gap that lies below the light line,[2,3] which allows them to function as a fundamental substrate for large-scale integrated microphotonic circuit applications. For photonic integrated circuits, an essential building block is the waveguide structure. In order to function as an effective information carrying channel, the waveguide should possess several necessary properties: It should have its dispersion curve lying within the gap region below the light line to ensure low loss propagation within the guide and around sharp corners. The waveguide should also be single moded, possess sufficient bandwidth to accommodate the incoming signal, and display minimal dispersion within the signal bandwidth. In a photonic crystal slab, a waveguide is typically created by introducing a line defect into the periodic lattices. These structures have been studied extensively with experiments and three-dimensional simulations.[4–11] However, many of the proposed waveguide structures exhibit relatively small guiding bandwidth and large group velocity dispersion. Developing ways to enlarge the waveguide bandwidth is therefore an important direction of research in photonic crystal structures.[5,7,10]

In this letter, we introduce a general designing procedure that allows us, for any given photonic crystal slab, to create an appropriate waveguide structure that possesses single-mode bands with large bandwidth and low dispersion within the photonic band gap below the light line. The procedure consists of two steps: we first design a conventional dielectric waveguide that is optimally phase matched with the band gap of the photonic crystal slab. We then embed the dielectric waveguide into the photonic crystal in an appropriate way such that the edge states are eliminated and single mode propagation is ensured. (Previously, large bandwidth structures consist of slab waveguides embedded in an array of dielectric rods have been proposed by Johnson *et al.*[4] However, the important role of edge states was not analyzed.) This procedure produces waveguide structures with large bandwidth of single mode and lossless propagation, and creates dispersion relations that are essentially linear over most of the guiding bandwidth.

The underlying physical reasoning of our design is best illustrated by comparing the dispersion relation of a conventional dielectric waveguide with that of a typical photonic crystal waveguide. For concreteness, we consider the wave propagation along the ΓM direction in a photonic crystal with a triangular lattice of holes introduced into a dielectric structure, as shown in the inset in Fig. 1(a). [The M-point has a wave vector of $0.5(2\pi/a)$]. The dielectric structure itself consists of a high-index dielectric layer, with a dielectric constant of 12, sandwiched between two low-index regions with a dielectric constant 2.25. These choices of dielectric constants approximate that of Si or GaAs for the high index region, and SiO_2 or Al_xO_y for the low index regions. The projected band diagram along the ΓM direction for such a crystal is shown as the gray region in Fig. 1(a). There is a large band gap for TE-like modes when the radius of holes $r=0.35a$ and the thickness of the layer $t=0.5a$, where a is the lattice constant.[12] The gap opens up around the M point below the light line and occupies the frequency range between 0.28 and 0.38 c/a.

Within the crystal, a waveguide is created by introducing a line defect. This can be achieved for example, by decreasing the radius of a single row of holes, as shown in the inset of Fig. 1(a).[4] Doing so places single-mode bands into the gap region [Fig. 1(a)]. However, the large periodic index contrast in the vicinity of the line defect creates a strong distributed feedback,[13] which leads to large dispersion and severely limits the bandwidth allowed. In contrast, for a conventional dielectric waveguide structure there is no periodic index variation along the propagation direction [Fig. 1(b)]. Hence, such conventional structures, while not enjoying the presence of in-plane photonic band-gap confinement, nevertheless possess a much larger bandwidth in its single mode region.

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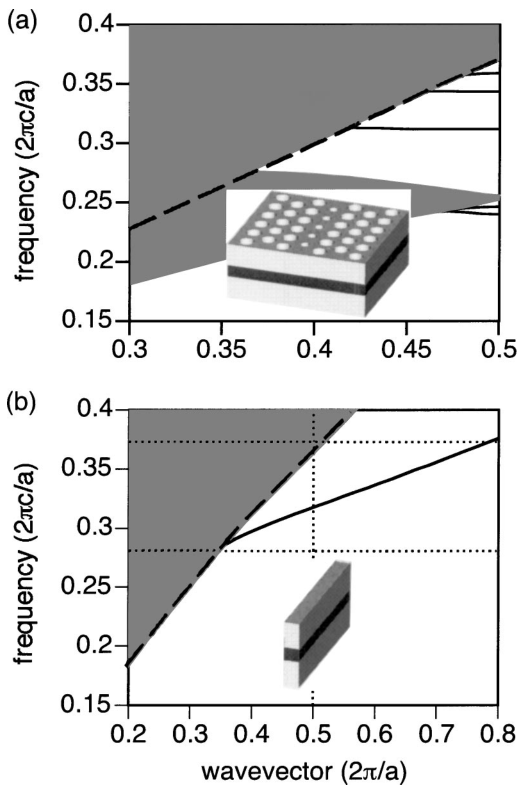

FIG. 1. Each panel is the corresponding band diagram for the dielectric structure shown in the inset. For the insets, the dark gray region and light gray regions represents high or low index materials, respectively. For the band diagrams, the thick dashed lines are the light lines. The gray regions represent the continuum of extended modes: (a) band diagram of a line defect in the photonic crystal slab. The crystal, shown in the inset, consists of a triangular array of air holes with a radius of $0.35a$ introduced into the dielectric media. The line defect is created by reducing the radius of one row of holes from $0.35a$ to $0.20a$. (b) Band diagram of a conventional dielectric waveguide. The structure, surrounded by air, has the width of $0.6a$. The vertical dotted line represents the value of the wavevector for the M point. The two horizontal dotted lines indicate the lower and upper frequencies of the gap in the photonic crystal shown in (a) with the same thickness $0.5a$ for the high dielectric layer.

The motivation of our approach, therefore, is to try to combine the presence of an in-plane photonic band gap with the benefits of the larger bandwidth that is inherent in the conventional structures. We accomplish this by creating a line defect comprising a high index conventional dielectric waveguide. Since the gap for the photonic crystal slab is incomplete, the dispersion of the conventional guide has to be chosen to match the gap of the photonic crystal in terms of both the frequencies and the wave vectors. In other words, the gap and the dispersion of the dielectric waveguide must be phase matched. For the ease of fabrication, we will fix the waveguide to have the same thickness as the crystal slab, the only free parameter left then is the width w of the guide and a choice of $w=0.6a$ indeed creates a dispersion relation that is phase matched with the gap [Fig. 1(b)].

We now proceed to consider the dispersion relation of the crystal structure with a line defect comprising the dielectric waveguide designed above. The defect region is created by bisecting the crystal with an air trench, and by placing the dielectric waveguide inside the trench (Fig. 2). (Importantly, the basic periodicity of the crystal is not disturbed in this procedure.) Since the width of the dielectric guide is fixed already by phase-matching constraints, the only free parameter is the width of the air slit w_a. The dispersion relation for a structure with $w_a=1.2a$ (in which case the truncation is located in the dielectric region between the air holes), is shown in Fig. 3(a). In this case, in addition to the states that are associated with the dielectric waveguide, the presence of the interfaces between the air region and the periodic crystal introduce edge states into the gap. These edge states have most of the intensity localized at the interfaces between the air trench and the periodic region [Fig. 3(b)]. In contrast, the states associated with the dielectric waveguide is largely localized within the high index region at the center of the structure [Fig. 3(c)].

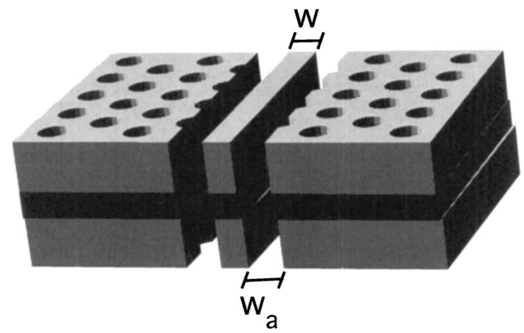

FIG. 2. Line defect structure with a high index waveguide embedded in a photonic crystal slab.

To design a single mode waveguide, it is thus critically important to remove the edge states from the wavelength range of the guided modes of the dielectric waveguide. Since the edge states are largely confined at the interfaces, they are sensitive to the dielectric configurations at the boundaries between the air trenches and the periodic region. Therefore the properties of these states can be systematically tuned by

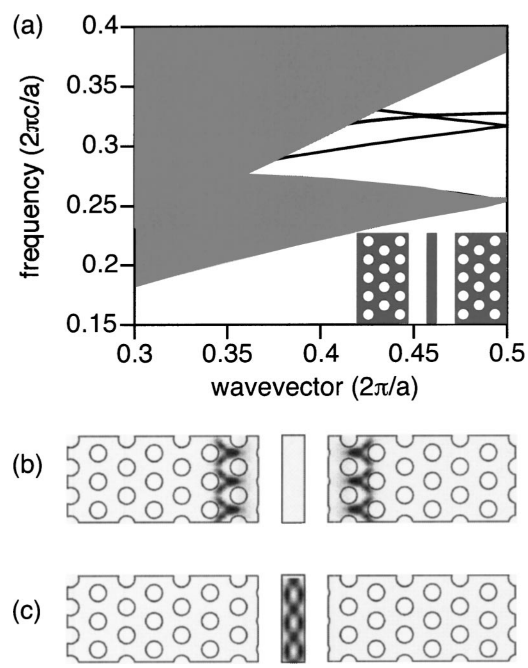

FIG. 3. (a) Dispersion relation for a line defect structure, with the width of the air slit at $1.2a$. The inset shows the top view of the structure; (b) cross-sectional view of the intensity in the electric field for the mode at the band edge with a frequency of 0.327 ($2\pi c/a$). (c) cross sectional view of the intensity in the electric field for the mode at the band edge with a frequency of 0.316 ($2\pi c/a$). In both (b) and (c), the colors white and dark gray represent low and high intensity, respectively.

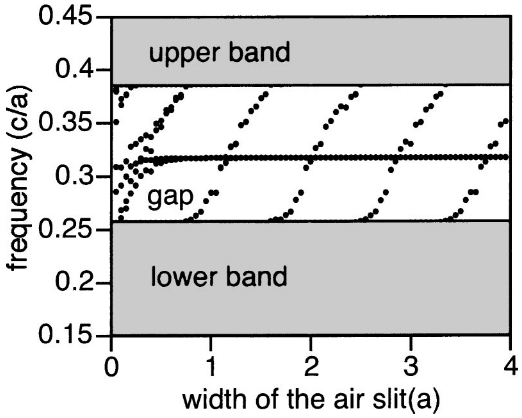

FIG. 4. Frequencies of modes at the *M* point as a function of width of the air slit for the line defect structure shown in Fig. 2. The gray region represents the frequency range of the extended states. The white region is the band-gap region.

simply changing the width w_a of the air slit. Moreover, the strong index contrast at the interfaces flattens the dispersion relation of the edge states (Fig. 3). For design purposes we can therefore systematically study the effect of truncations by plotting the frequencies of confined modes at the *M* point as a function of w_a, as shown in Fig. 4. Except for the region of strong edge–waveguide interaction at $w_a < 0.5a$, the frequency of the edge states varies periodically as a function of w_a. The period, $0.866a$, corresponds exactly to the lattice constant of the crystal along the direction perpendicular to *M*. The two modes that are associated with the dielectric waveguide itself, on the other hand, are relatively insensitive to the interface conditions and have the frequencies remain approximately constant at the center of the gap when w_a is sufficiently large. By choosing a truncation that corresponds to $w_a = 0.8a$ (Fig. 5, inset) the edge states are completely

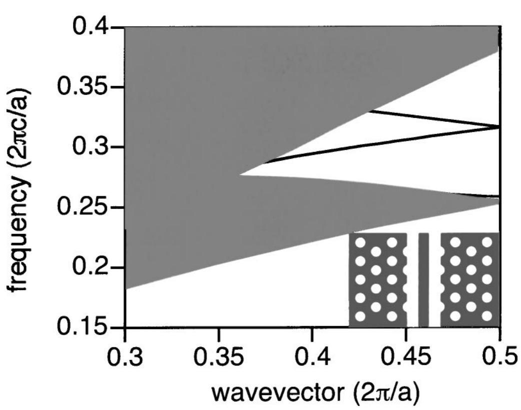

FIG. 5. Dispersion relation for an optimized line defect structure, with width of the air slit at $0.8a$. The inset shows the top view of the structure. Note that the truncations of the crystal cut across the air holes.

removed from the guiding bandwidth. For such a structure, the dispersion relation indeed exhibits single (folded) guided mode with a large bandwidth extending from 0.29 to 0.33 c/a (Fig. 5).

We note that, in the optimized structure the size of the air slit $w_a = 0.8a$ represents the distance between the edges of the dielectric guide and the periodic region of less than a quarter of the free space wavelength. Thus one expects that the electromagnetic field propagating within the guide should be strongly confined by the photonic band gap. On the other hand, the frequency splitting between the two modes at the *M* point is $\sim 0.0001(2\pi c/a)$. Hence the dispersion of the line defect within the gap largely resembles that of a stand-alone conventional dielectric waveguide with a large linear dispersion region. Therefore, in terms of dispersion properties, this design combines the best features of both photonic crystals and conventional dielectric waveguides. In addition, our design does not alter the basic underlying periodicity of the crystal, and does not require minimum feature sizes that are smaller than what is necessary to construct the crystal itself. These structural features are beneficial for design and fabrication purposes. Thus, we believe that this work will be significant for the future developments of integrated microphotonic circuits in photonic crystals.

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