

Reducing the out-of-plane radiation loss of photonic crystal waveguides on high-index substrates

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Two-dimensional photonic crystal linear defect waveguides on semiconductor substrates are studied. It is predicted that the out-of-plane radiation loss can be reduced by shifting one side of the photonic crystal cladding by one-half period with respect to the other along the propagation direction. © 2004 Optical Society of America

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Since the invention of artificially engineered photonic bandgap materials,^{1,2} photonic crystal defect waveguides have been the subject of active research because of their potential to be a basic building block for densely integrated optics. Finite-thickness two-dimensional photonic crystal defect waveguides have been the primary research subject because of their relative ease of fabrication. So far, low-loss transmission in photonic crystal defect waveguides has been demonstrated in suspended membrane³ and low-index bottom cladding structures^{4,5} but with a narrower bandwidth in the latter case. Recently, there were also reports of finite-thickness two-dimensional photonic crystal defect waveguides formed in both GaAs (Ref. 6) and InP (Ref. 7) material systems with transmission losses as low as 11 and 20 dB/mm, respectively. These values were obtained by increasing the linear defect width to three lines. These structures support multimode transmission at all frequencies within the photonic crystal bandgap, making it more difficult to analyze the field and to control the field excitation, however. The purpose of this Letter is to investigate theoretically the role of the photonic crystal cladding in the out-of-plane radiation loss in deeply etched structures and to present a defect waveguide structure on a semiconductor substrate with improved out-of-plane radiation loss and single-mode transmission over a reasonable bandwidth.

We start with analysis of a conventional single-line defect photonic crystal waveguide formed by removing a single row of holes from a triangular photonic crystal lattice, which is referred to as type A waveguide. All waveguides considered in this Letter were formed by indices of refraction consistent with an $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ epitaxial waveguide grown on a GaAs substrate with thicknesses of 1.0, 1.0, and 6.0, normalized by the lattice constant. The indices of refraction of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and GaAs are taken as 3.0 and 3.4, respectively, in the simulation. Note that the results in this Letter also apply to waveguides formed in the InGaAsP material system. For the waveguides considered here, the photonic crystal extends through the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ lower cladding layer and is shown schematically in the inset of Fig. 1(a). We define the epitaxial growth direction, the same direction in which air holes are perforated, as the $\hat{z}$ direction. The linear defect of the waveguide, which

is created along the Γ – K direction of the photonic crystal lattice, is oriented in the $\hat{y}$ direction.

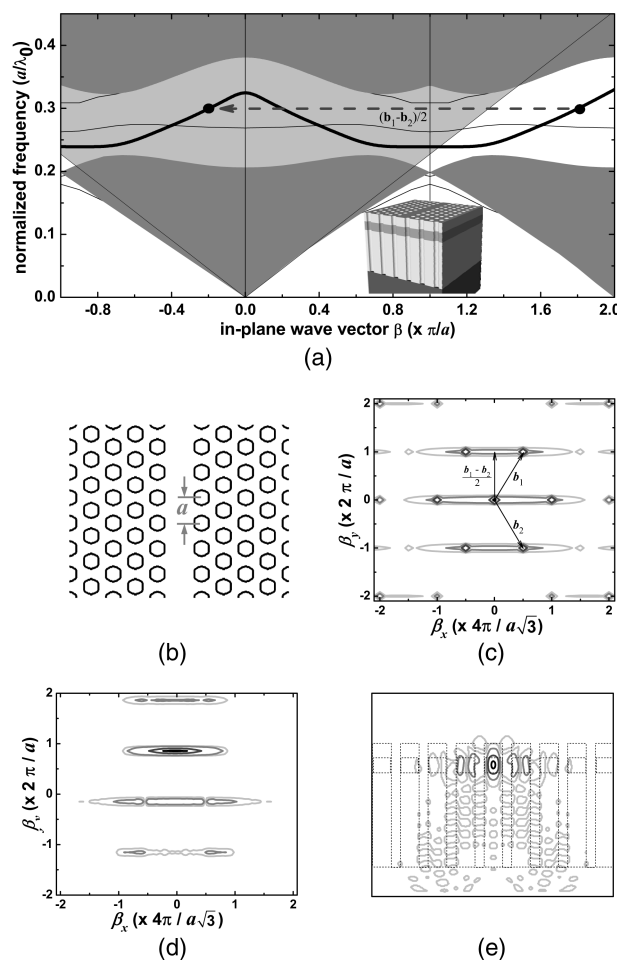


Fig. 1. (a) Photonic band diagram for a type A single-line photonic crystal defect waveguide in an extended Brillouin zone scheme. The defect mode analyzed for out-of-plane radiation loss is marked by the thick curve. (b) In-plane dielectric distribution of the waveguide and (c) its Fourier transform. (d) Fourier transform of H_z at the midplane for the defect waveguide mode at $\beta_y = 0.2\pi/a$, and (e) H_z^2 shown in the cross section of the same mode with waveguide dielectric distribution overlaid by dotted lines. All contours are in gray scale; the darker, the higher the magnitude. The adjacent gray levels differ in magnitude by a decade.

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Figure 1(b) shows the in-plane dielectric distribution of a type A waveguide, and Fig. 1(c) shows its Fourier transform. The presence of the missing row of holes causes spatial Fourier components that would not be present in a bulk two-dimensional triangular lattice. In particular, there are Fourier components along the waveguide direction, Γ - K , at $(\mathbf{b}_1 - \mathbf{b}_2)/2$, where $\mathbf{b}_1$ and $\mathbf{b}_2$ are unit vectors of the reciprocal lattice. From the discrete translational invariance of the waveguide along the propagation direction and the Fourier transform of the lattice, we can write the electric field in the waveguide as

$$\mathbf{E}(x, y, z, t) = \sum_n c_n^{(A)} \mathbf{f}_\beta^{(A)}(x, z) \times \exp\left(i\left[\omega t - \left[\beta + n\left(\frac{\mathbf{b}_1 - \mathbf{b}_2}{2}\right)\right]y\right]\right), \quad (1)$$

where n is an integer, (A) labels this as a type A structure, and β is restricted to the first zone of the reciprocal space. The $n = 0$ term, $c_0^{(A)}$, in this series is inside the radiation cone of the cladding layers and contributes to the radiation loss of the waveguide mode. This term is not large, however, as can be seen from Fig. 1(d), which shows the Fourier transform of the in-plane H_z component for the same propagation constant $\beta_y = 0.2\pi/a$ as the field H_z^2 in Fig. 1(e) obtained from a three-dimensional finite-difference time-domain simulation. Figure 1(d) shows that the dominant component of the field is $c_1^{(A)}$, which is in the second zone. $c_1^{(A)}$ is outside the light cone and does not contribute to the radiation loss of the waveguide mode. $c_1^{(A)}$ and $c_0^{(A)}$ are coupled by the Fourier component of the lattice at $(\mathbf{b}_1 - \mathbf{b}_2)/2$. The $n = 0$ term, $c_0^{(A)}$, in the $c_n^{(A)}$ is illustrated in Fig. 1(a), which shows the waveguide dispersion relation in the extended zone scheme. The vertical radiation light cone due to the bottom $\text{Al}_x\text{Ga}_{1-x}\text{As}$ cladding and transverse radiating region in the photonic crystal are mapped as light gray and dark gray areas, respectively. The defect modes of interest for the out-of-plane radiation loss analysis are marked with a thicker curve in the figure. If the coupling between the $n = 0$ component in the field in Eq. (1) and the $n = 1$ component is reduced by reducing or eliminating the Fourier component of the lattice at $(\mathbf{b}_1 - \mathbf{b}_2)/2$, so is the waveguide radiation loss. This can be accomplished in a type B photonic crystal waveguide, which is formed by removing a single row of holes from a triangular lattice and then shifting one side of the cladding along the direction of the waveguide by half a lattice period. The inset of Fig. 2(a) shows the lattice of a type B waveguide, and the Fourier transform of this dielectric distribution is shown in Fig. 2(b). Figure 2(b) shows that there is no Fourier component of the lattice along Γ - K at $(\mathbf{b}_1 - \mathbf{b}_2)/2$ because of the cancellation of the contributions from each side of the cladding after the half-period shift. Figure 2(a) also shows the dispersion relation of a type B waveguide. The magnetic field component, H_z , of the waveguide mode considered assumes an evenlike symmetry along the center of the waveguide. In type A structures, the

photonic crystal cladding has even symmetry along the center of the defect. If the photonic crystal is thought of as a perturbation of an epitaxial waveguide structure, the coupling of a laterally even mode and a laterally odd mode under an even symmetry perturbation is zero. However, the perturbation is neither strictly even nor odd in a type B waveguide, resulting in anticrossings at the frequencies where the even and odd modes would intercept. Another distinction for type A and type B band diagrams is at the Brillouin zone boundary. It is important to remember that this Fourier component is only zero along the Γ - K axis as shown in Fig. 2(b) and the Fourier transform of the mode in this waveguide has some spread in the β_x and β_z directions because of the confined transverse mode profile $f_\beta^{(B)}(x, z)$. However, we expect a reduced radiation loss in a type B waveguide because of the elimination of the Fourier component at $(\mathbf{b}_1 - \mathbf{b}_2)/2$, which occurs along the Γ - K axis, where the Fourier transform of the field is peaked. In addition, radiation loss is further reduced because the radiation field under the two waveguide cladding sections is out of phase because of the spatial shift in the lattice leading to a cancellation under the waveguide core. This can be observed in the cross sections of the waveguide modes. Figures 1(e) and 2(c) show the cross section of the H_z^2 of the guided modes in the type A and

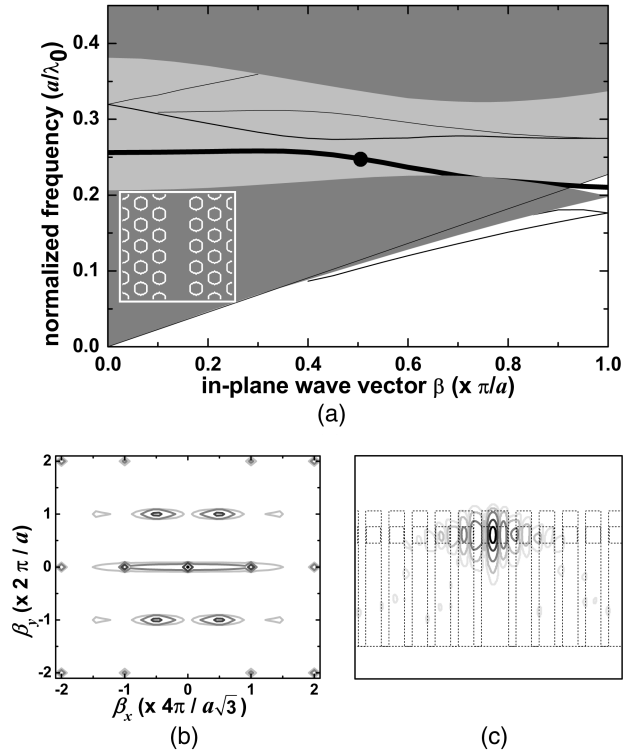


Fig. 2. (a) Photonic band diagram for a type B single-line photonic crystal defect waveguide in a reduced Brillouin zone scheme. The defect mode analyzed for out-of-plane radiation loss is marked by the thick curve. (b) Fourier transform of the in-plane waveguide dielectric distribution. (c) H_z^2 cross section for the defect waveguide mode at $\beta_y = 0.5\pi/a$. The dotted lines outline the waveguide dielectric distribution. The field contour has one additional gray level compared with 1(e) to identify the radiation path.

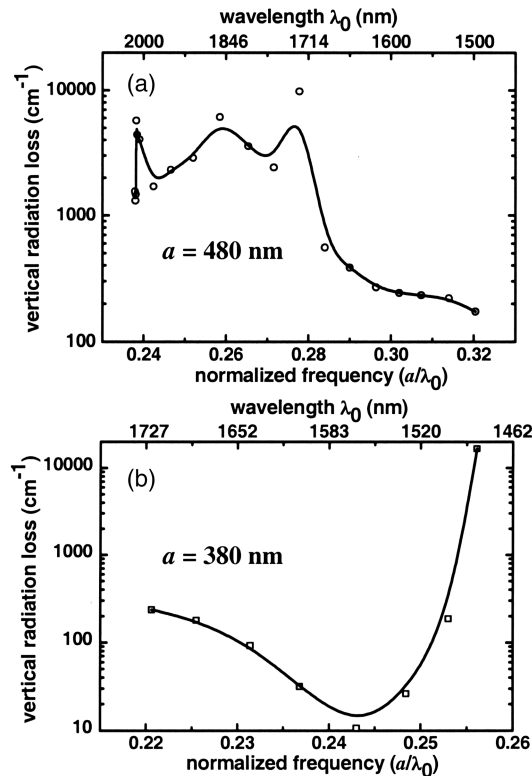


Fig. 3. Out-of-plane radiation loss as a function of normalized frequency for the photonic crystal defect slab waveguides modeled in this work. The lattice constant $a = 480$ nm is assumed for a type A deeply etched waveguide (a) and 380 nm for type B (b). Points are calculated values and curves are B-spline curve fits.⁹

type B waveguides at $\beta_y = 0.2\pi/a$ and $\beta_y = 0.5\pi/a$, respectively. Their location in the band diagram is also marked. This will be shown below to be the point with the lowest out-of-plane radiation loss for the band considered. It is clear that not only does the field in type A waveguide leak through the photonic crystal cladding but also the mode actually has strong vertical propagation directly beneath the waveguide core that contributes to the out-of-plane radiation loss. For a type B waveguide the vertical propagation beneath the linear defect is absent. Radiation loss underneath each of the cladding sections remains but is reduced.

The out-of-plane radiation loss as a function of normalized frequency for type A and type B photonic crystal single-line defect slab waveguides is shown in Fig. 3. This loss is calculated with the three-dimensional finite-difference time-domain method detailed in Ref. 8. The lattice constant, a , for the type A defect waveguide is chosen to be 480 nm. This waveguide is predicted to have a minimum out-of-plane radiation loss of 174 cm^{-1} . The operation range, in which this loss is predicted to be $<300\text{ cm}^{-1}$ when centered at 1550 nm, spans a wavelength range of 134 nm. This range corresponds to the modes near the vicinity of the Brillouin zone center in the reciprocal space. However, for a type B defect waveguide, the lowest radiation loss is predicted to be 10.7 cm^{-1}

when we choose lattice constant $a = 380$ nm. This is more than an order of magnitude reduction in radiation loss compared with the type A structure. The lattice constant for the type B structure is chosen so that the lowest-loss transmission band is also centered at 1550 nm. The in-plane wave vector of the least lossy mode is $\beta = 0.5\pi/a$ for a type B waveguide and is near $\beta \sim 0.2\pi/a$ for a type A waveguide. The bandwidth for type B waveguide modes with low out-of-plane radiation loss ($<30\text{ cm}^{-1}$) is 68 nm and is limited by anticrossing with the immediately higher waveguide mode and interaction with the photonic dielectric band edge.

It should be noted that the defect waveguide described in this Letter may not be the optimal type B structure for low-loss transmission but does serve to illustrate a method for reducing the radiation loss of waveguides on high-index substrates. Neither will it preserve rotation symmetry when turning 60° and 120° corners. For that purpose, it is better to create a dual-line modified defect waveguide where both rotation symmetry and single-mode operation are satisfied. The reason to consider a single-line defect waveguide here is to conduct a fair comparison with a type A waveguide.

In summary, we have shown that the out-of-plane radiation loss of the photonic crystal defect waveguide can be reduced by an order of magnitude by shifting the photonic crystal claddings one-half period with respect to each other along the propagation direction. Although the resulting waveguide is still predicted to have a larger loss than a suspended membrane or low-index bottom cladding waveguide, it brings us closer to an applicable structure for integrated photonic circuitry.

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