Propagation characteristics of one-dimensional photonic crystal slab waveguides and radiation loss

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We present a type of slab waveguide structure, which is composed of one-dimensional photonic crystal. We calculated the dispersion relations and radiative loss ratio for air-bridge and SiO_2 cladding waveguide structures. The calculations show that the dispersion relations of the proposed waveguide are greatly different from those of the usual index-guided waveguide structure, and then predict the existence of small-group velocity modes. Although the small-group velocity modes are above the light line, the numerical results indicate that they have a small radiation-loss rate for large slab thicknesses, even above the light line of cladding material.

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For photonic integrated circuits, an essential building block is the optical waveguide structure. Planar photonic crystal (PC) waveguides, or PC slabs, have been extensively investigated in view of the realization of integrated optical interconnects. These structures have been studied extensively by experiment and also by numerical simulations.[1] So far, a dispersion curve lying within the gap region below the light line has been thought to be necessary to ensure low-loss propagation.

In this paper, we present theoretical results for the slab waveguide structure which has in-plane one-dimensional photonic crystal structures.[2] Figure 1 shows the in-plane dielectric distribution of a waveguide. The structure has a periodically changing refractive index region in only the y direction, and there is no periodic index variation along the propagation direction. An electromagnetic wave is assumed to propagate in the z direction. The one-dimensional PC structure works as the guide region of waveguide instead of the generally investigated two-dimensional PC structure. In an ordinary two-dimensional PC waveguide structure, the large periodic index contrast creates a strong distributed feedback, which leads to a large dispersion and severely limits the bandwidth. However, in the proposed waveguide, there is no periodical structure in the propagation direction. This means a broad bandwidth can be achieved. Yeh *et al.* studied waveguides extensively using one-dimensional periodic structures.[3] Although such waveguides have interesting propagation modes peculiar to band-gap-guided modes, they cannot be used in a chip or an optical circuit, because the confinement is only in one dimension. Therefore, they are not practical. In-plane confinement in a two-dimensional PC slab waveguide is thought to be promissing for practical use. However, the radiation loss of the mode above the light line is very large, so that only the mode under the light line can be used. Therefore, the peculiar feature of the band-gap-guided mode in the small wave-vector domain could not be used. The one-dimensional PC slab structure proposed here is a slab version of the waveguide proposed by Yeh *et al.*, and it has an in-plane confinement and can be used in an optical circuit. In the proposed waveguide, it is expected that the out-of-plane radiation loss is small and that the unusually small wave-vector domain above the light line can be used, since the structure is uniform in the propagation direction. In this research, we perform numerical computations of the radiation loss of leaky modes above the light line and prove the usefulness of the one-dimensional PC-slab waveguide structure. This is an attempt at numerical calculations of the radiation loss of a slab PC waveguide structure.

The physical reasoning underlying our design is best illustrated by comparing the dispersion relation of a conventional index-guided waveguide with that of a photonic band-gap guided waveguide. Let b be the normalized propagation constant and v the normalized frequency. For conventional waveguides, the b-v characteristics do not depend on structure parameters, such as the refractive index and the width of the core region, whereas for band-gap guided waveguides, they do. In the analysis, the refractive index of the periodic structure is assumed to be 3.5/1.5, respectively. The widths d_a and d_b are $0.3a$ and $0.7a$, respectively. The normalized frequency of the electromagnetic wave for the PC-guiding

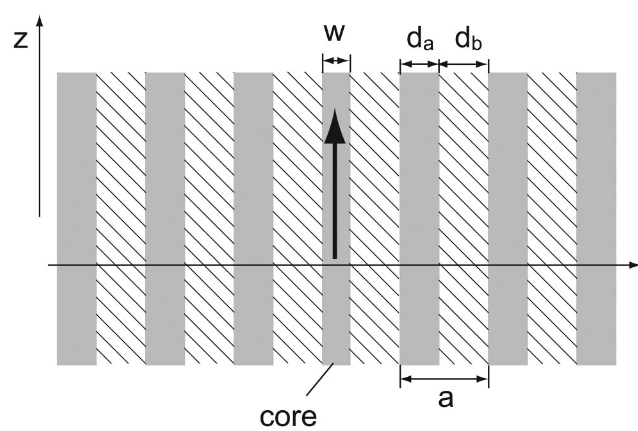

FIG. 1. Schematic view of the in-plane dielectric distribution of the PC waveguide.

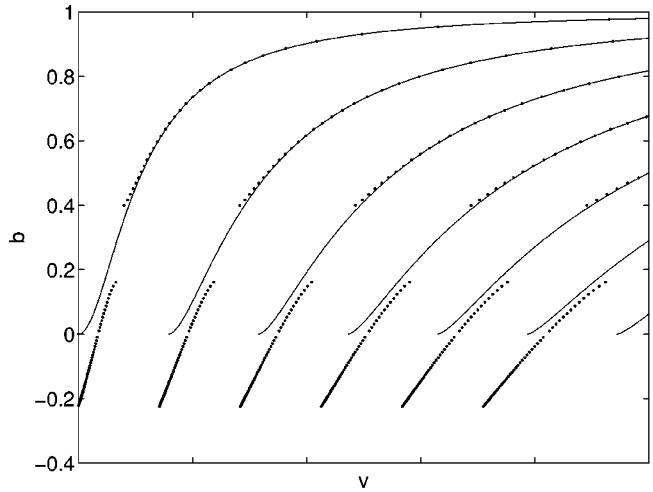

FIG. 2. Calculated dispersion curves of the one-dimensional PC waveguides. The solid lines denote the dispersion of ordinary index-guided waveguides, and the dotted lines denote the dispersion of the one-dimensional PC waveguides.

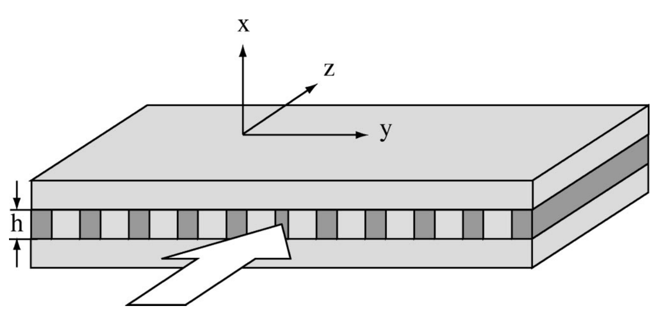

FIG. 3. Model of a one-dimensional photonic crystal slab waveguide structure, showing the periodically varying refractive index in the *y*-direction, which is embedded between uniform cladding layers. The waveguide core is created by introducing a defect.

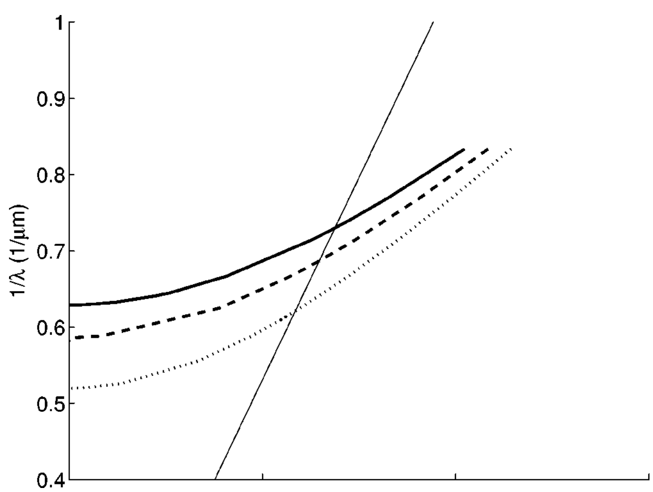

FIG. 4. Calculated dispersion of photonic modes for a waveguide in a SiO_2 cladding waveguide. The slab thickness is 0.2. d_a =0.11, w=0.1, d_b=0.17 (solid line), 0.20 (dashed line), and 0.26 (dotted line).

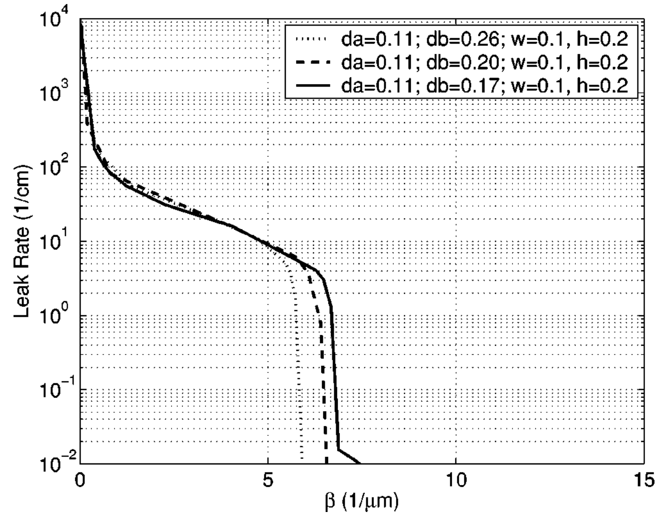

FIG. 5. Calculated radiation loss of photonic modes for a waveguide in a SiO_2 cladding waveguide. Solid, dashed, and dotted lines are for d_b of 0.17, 0.2, and 0.26, respectively.

waveguide ω=1.5(c/a) is used. The calculated results for *b*-*v* characteristics are shown in Fig. 2. For this type of PC-guided waveguide, the relations are dependent on the frequency. In this calculation, confinement in the *x* direction was ignored.

The dispersion lines for the photonic band-gap-guided waveguide show a gap when the normalized propagation constant *b* is around 0.3, which corresponds to the Bloch propagation modes for the periodic structure. The electromagnetic wave within this region radiates outside of the core and cannot propagate through the waveguide. The most important point regarding this result is as follows. For ordinary index-guiding waveguides, the propagation constant should be positive. However, in Fig. 2, the propagation constant for the band-gap-guided waveguide is negative. The negative normalized propagation constant means that the effective in-

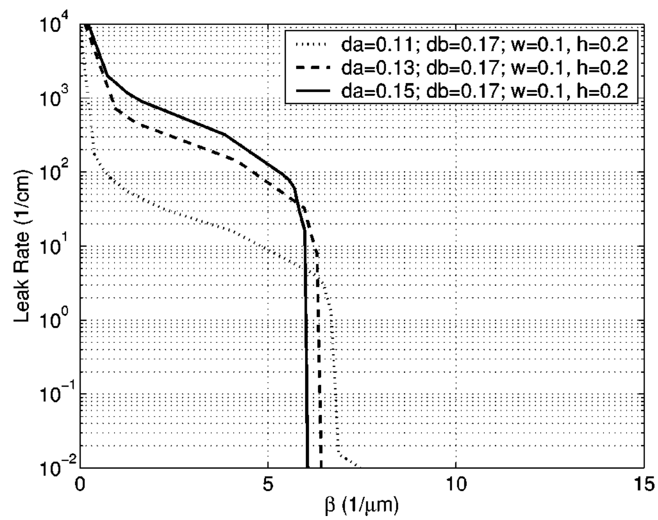

FIG. 6. Calculated radiation loss of photonic modes for a waveguide in a SiO_2 cladding waveguide. The solid, dashed, and dotted lines are for d_a of 0.15, 0.13, and 0.11, respectively.

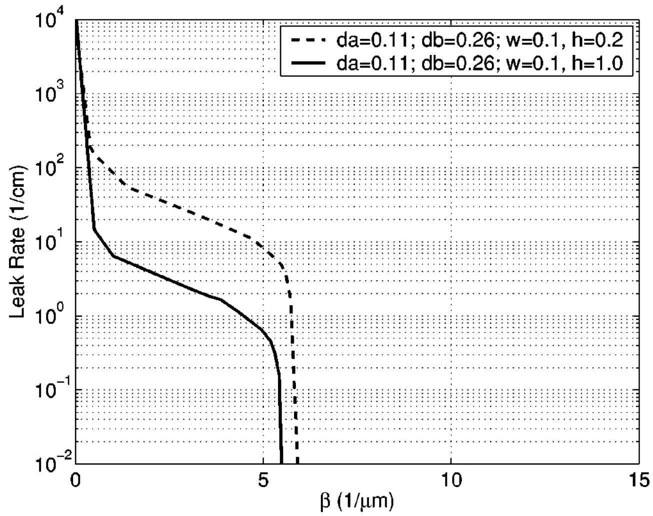

FIG. 7. Calculated radiation loss of photonic modes for a waveguide in a SiO_2 cladding waveguide. The solid and dotted lines are for h of 0.2 and 1.0, respectively.

dex of the waveguide is smaller than that of the cladding material. In other words, the phase velocity of the waveguide mode is faster than that of the cladding material. This situation cannot be achieved in an ordinary index-guided waveguide. In this negative b region, group velocities of photonic modes are very low. However, for finite-thickness waveguide structures, i.e., slab structures, the $b<0$ region is above the light line, where the radiative loss is generally thought to be large. Even in this region, light propagation is guided horizontally by the photonic band gap of the one-dimensional PC. This means that a quantitative estimation of radiation loss is necessary prior to use in practical applications.

The light-line problem represents an intrinsic limit for the application of PC slabs to integrated photonics. It is therefore important to quantify the level of intrinsic losses and to know their dependence on the structure parameters.[4] One way to estimate the radiation losses of slab photonic crystal waveguides is to use the finite-difference time-domain method, which is rather computationally intensive and time consuming. In this work, we adopt an approximate analytic technique based on the discrete spectral index (DSI) method, which is used for the analysis of ridge waveguide structures.[5] To analyze the light propagation and intrinsic radiation loss in the vertical direction, we use a modified DSI method.

The slab waveguide structure considered in this study is shown in Fig. 3. Light is confined by the index difference in the vertical direction and by the photonic band gap in the horizontal direction. A sinusoidal function is normally assumed in DSI formulation, but this assumption is not adequate for this kind of structure. In the first step of the analysis, the entire structure is divided into vertically uniform horizontal layers, such as cladding layers and the photonic slab layer. For a given wave vector, Maxwell's equation is solved analytically for the periodic index variation structure with defects in the slab layer. The transfer matrix method[3] is used for this calculation. For the cladding layers, the field is expanded in a Fourier series. Either a sine or cosine function, depending on whether the field is symmetric or asymmetric, is considered. The expansion coefficients in each layer are determined to fullfil boundary conditions at the interfaces between neighboring layers. This numerical method is not limited to symmetrical structures, and it takes into account the semi-infinite thickness of the cladding layers. The variational boundary condition at the interface is assumed to be the regular DSI method. This calculation is performed iteratively for different wave vectors until we obtain the physically correct propagation mode of the structures, which means that the field does not diverge at infinity. The radiation loss is calculated from the imaginary part of the propagation constant β.

For simplicity, we assume a vertically symmetric waveguide structure, where the slab structure is between cladding layers of the same material. The refractive index of the slab layer is 3.5/1.5, and that of the cladding region is 1.5. The refractive index of the core region is 3.5. The dispersion curves for several waveguide structures are shown in Fig. 4, where the slab thickness h is 0.2 μm. The thin straight line indicates the light line of cladding material. The radiation loss was calculated for these slab structures with a SiO_2 cladding waveguide. Figure 5 shows the radiation loss for d_b of 0.26, 0.20, and 0.17 as a function of β. Although radiation loss is negligible below the light line, an abrupt increase of radiation loss has been reported for the frequency above the light line for ordinary slab-PC waveguide structures.[6] The loss rate does not depend on d_b. The β where the leak rate abruptly increases corresponds to the light line, and it varies with d_b because of the blueshift of the dispersion curve for smaller d_b. Figure 6 shows the radiation loss for d_a of 0.11, 0.13, and 0.15. The radiation loss greatly increases with increasing d_a. For $d_a=0.11$, the propagation mode has a wide distribution horizontally because of the small difference between w and d_a. However, the propagation mode has a narrow distribution for $d_a=0.15$. This change of the mode spread causes changes in the vertical radiation loss rate. This radiation loss decreases for large h as shown in Fig. 7.

In summary, we have investigated the characteristics of slab waveguide structures that use a one-dimensional photonic crystal as a horizontal guiding region. We found that a very low-group velocity mode is obtained by these structures. We also found that, although this low-group velocity condition lies above the light line, a sufficiently small radiation loss can be achieved for appropriately designed structures.

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