Journal of the Optical Society of Korea, Vol. 7, No. 1, March 2003, pp. 38-41

Highly-Dispersive Guided Modes of Two-Dimensional Photonic Crystal Waveguides

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(Received January 22, 2003)

We present an analysis of highly-dispersive guided modes of two-dimensional photonic crystal waveguides. By the plane wave expansion method, band structures and mode profiles of two-dimensional photonic crystal waveguides are obtained. It is found that guided modes have very small group velocities and very large group velocity dispersions in the region near the Γ-point and in the region near the Brillouin zone edge. Especially, the group velocity dispersions are found to be millions of times larger than that of a conventional optical fiber. The contributions of the transverse resonance formed by two photonic band gap reflectors and the standing wave mode formed by periodic structures are discussed. We conclude that the highly-dispersive characteristics originate from the resonator-like aspect of the photonic crystal waveguide.

OCIS codes : 130.3120, 230.3990, 230.7370, 260.2030.

By the presence of the photonic band gap, photonic crystals have the ability to control the propagation of light [1]. If we introduce a point or line defect in the photonic crystal, we can achieve an optical resonator or waveguide in wave-length-scale. Thus, photonic crystal devices are good candidates for the photonic integrated circuit. The photonic crystal waveguide has attracted great interest because its guiding mechanism is different from that of a conventional dielectric waveguide. Due to the difference, photonic crystal waveguides have unique features not provided by conventional waveguides. To utilize the features, various structures of photonic crystal waveguides have been considered. For example, a sharp bend [2], a waveguide branch [3] and a channel drop filter [4] have been proposed and investigated. Another considerable feature of the photonic crystal waveguide is its dispersion characteristics. Automatically, photonic crystal waveguides have extremely large group velocity dispersions in some frequency range [5,6]. These are not easily seen in conventional optical waveguides. Using this feature, we can achieve an effective dispersion compensator in a compact size. For more active applications, understandings of large group velocity dispersions are necessary. We discuss the physical origins that provide large group velocity dispersions to photonic crystal waveguides.

In this paper, we calculate mode profiles and band structures of two-dimensional photonic crystal waveguides by using the plane wave expansion method. The photonic crystal is a triangular lattice of air holes in a dielectric medium. The refractive index of the dielectric medium is 3.4 and the radius of the air hole is $0.35a$, where a is the lattice constant. The triangular lattice structure of air holes has a larger photonic band gap for TE modes than that for TM modes. Through this paper, we consider the TE modes of photonic crystal waveguides and their profiles of the z-component of the magnetic field. Two possible geometries of photonic crystal waveguides are shown in Fig. 1(a) and (b). The type-(a) waveguide is formed by removing a row of air holes in ΓK-direction. It is symmetric with respect to the center line along ΓK-direction. The type-(b) waveguide is formed by modifying the type-(a) waveguide to be dephased by a half of the lattice constant. In regular photonic crystals, the type-(a) is more common than the type-(b). Therefore, we consider the type-(a) waveguide first. And the type-(b) waveguide will be discussed as an intermediate structure to understand the type-(a) waveguide.

Generally, a guided mode of a waveguide is represented by the wave vector, k, along the propagation direction. For the waveguide that has a uniform dielectric structure along the propagation direction, modes of different wave vectors are independent. And modes of the waveguide are represented by wave vectors in

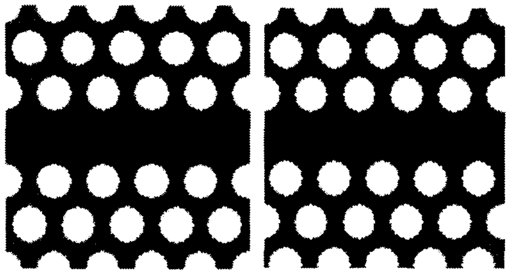
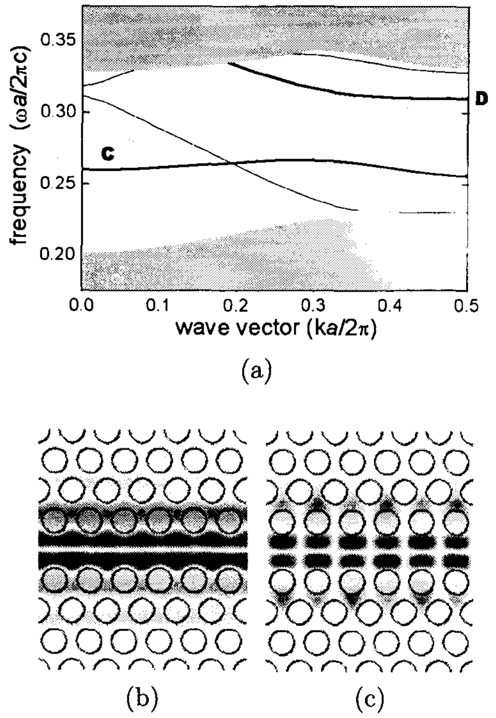

(a) (b)

FIG. 1. (a) Type-(a) photonic crystal waveguide. It is formed by removing a row of holes in ΓK-direction. (b) Type-(b) waveguide. It is formed by modifying the type-(a) to be dephased by a half of the lattice constant.



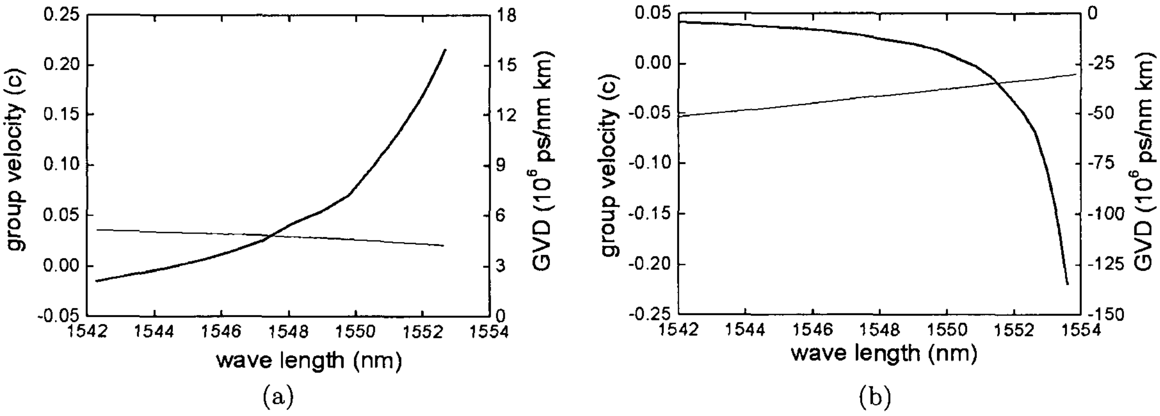
(a)

(b) (c)

FIG. 2. (a) Band structure of type-(a) photonic crystal waveguide. Thick solid lines indicate modes having two anti-nodes in the transverse direction. The region C is near the starting part of the band and the region D is near the Brillouin zone edge. (b), (c) Mode profiles of k=0.0 in the region C and of k=0.5 in the region D, respectively.

the infinite k-space. However, for the waveguide that has a periodic dielectric structure, all wave vectors in the infinite k-space are not necessary for the representation of modes. The Fourier transform of the periodic structure has discrete k-components, $\frac{2\pi}{a}m$, where a is the period and m is an integer. Through the interaction with these Fourier transform components, the mode of k creates modes of $k + \frac{2\pi}{a}m$, and they are not independent any more. Thus, for periodic dielectric structures like photonic crystal waveguides, their modes could be represented by the Bloch wave vectors in the irreducible Brillouin zone, $0 < k < \frac{2\pi}{a}$.

The band structure of the type-(a) two-dimensional photonic crystal waveguide is shown in Fig. 2(a). Gray areas are projected bands of photonic crystal and a white area is the photonic band gap where guided modes are present. Thick solid lines indicate guided modes that have two anti-nodes in the transverse direction [7] as shown in Figs. 2(b) and (c). We focus our attentions on the region C and the region D where the guided bands are flat. The region C represents the starting part of the guided band where modes have wave vectors near the Γ-point. From the band structure, group velocities and group velocity dispersions are calculated as shown in Fig. 3(a). In this calculation, the lattice constant is 405 nm and the corresponding wavelength is about 1550 nm. Here, the group velocity is very small. More interestingly, the



(a) (b)

FIG. 3. (a) Group velocities and group velocity dispersions of modes in the region C with a=405 nm. The thin solid line indicates the group velocity and the thick solid line indicates the group velocity dispersion. (b) Group velocities and group velocity dispersions of modes in the region D with a=482 nm.

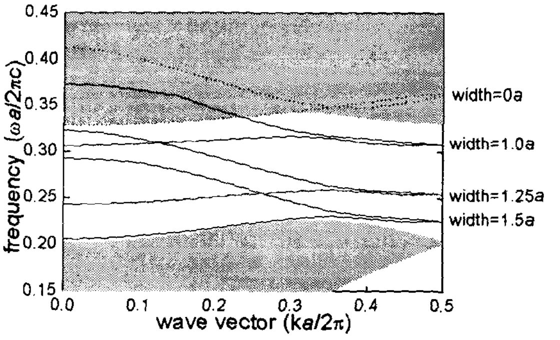


FIG. 4. Band structures of type-(b) waveguides having widths of 0.0 a, 1.0 a, 1.25 a and 1.5 a. The dot line indicates modes of the type-(b) waveguide having the width of 0.0 a, which has the identical dielectric structure to the photonic crystal.

group velocity dispersion is very large on the order of 10^6 ps/(nm·km). Remember that the group velocity dispersion of a conventional optical fiber is less than 20 ps/(nm·km) [8]. The region D represents the Brillouin zone edge. For this region, we calculate the group velocity and the group velocity dispersion as shown in Fig. 3(b), where the lattice constant is 482 nm. Similar to the result observed in the region C, the group velocity is again very small and the group velocity dispersion is even larger on the order of 10^7 ps/(nm·km).

For type-(b) waveguides of various widths, we calculate their band structures as shown in Fig. 4. Here, the width of waveguide is the width of the dielectric material added in the transverse direction from the photonic crystal. For example, the type-(b) waveguide of zero width is identical to the original photonic crystal. As the width increases from zero, the photonic crystal becomes the type-(b) waveguide and the mode of photonic crystal becomes the guided mode of waveguide. Thus, the photonic crystal waveguide tends to inherit its major characteristics from the original photonic crystal.

By the analogy to the mode of photonic crystal, guided modes in the region C of Fig. 2(a) are analyzed. When the wave vector is the Γ-point, the mode of the lowest air band of photonic crystal has a resonance in the transverse direction perpendicular to the ΓK-direction as shown in Fig. 5(a). As the wave vector increases along the ΓK-direction, the transverse resonance is modulated by the wave vector as shown in Figs. 5(b) and (c). From these observations, it is found that the transverse resonance would be dominant in the region C, and the guided modes become highly-dispersive.

It is shown in Fig. 4 that guided bands are folded at the Brillouin zone edge. The folded point represents two guided modes that have the same frequencies and the same wave vectors. However, they propagate in opposite directions. The coupling of these modes creates two standing wave modes. They resonate along the propagation direction within one period of the photonic crystal waveguide. One standing wave mode locates its anti-node at the node position of the other standing wave mode. Unlike the type-(b) waveguide, for the type-(a) waveguide, each standing wave mode has a different anti-node position with respect to the dielectric structure of waveguide. Therefore, guided modes are split at the Brillouin zone edge as shown in region D of Fig. 2. Aided by the effects of standing wave and mode splitting, guided modes can be highly-dispersive near the Brillouin zone edge.

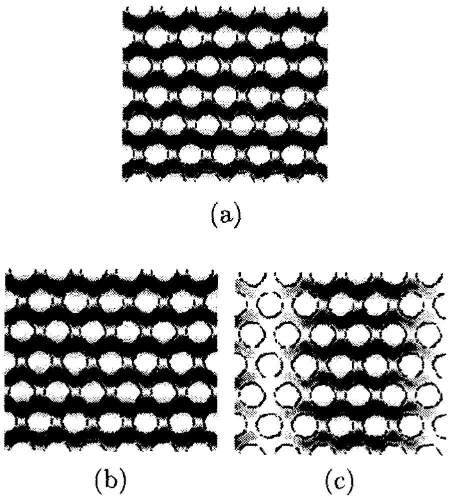

(a)
(b) (c)

FIG. 5. (a), (b), (c) Mode profiles of the lowest air band of two-dimensional photonic crystal with k=0.00, 0.025 and 0.05, respectively.

In the transverse direction perpendicular to the waveguiding direction, the photonic crystal waveguide has the shape of a Fabry-Perot resonator that consists of two photonic band gap reflectors. And along the propagation direction, it has the periodicity following the photonic crystal. The periodic structure can be regarded as an array of identical coupling resonators. Due to their resonator-like aspects, photonic crystal waveguides have highly-dispersive characteristics, and they have very small group velocities and very large group velocity dispersions. These are not easily seen in conventional optical waveguides. The large group velocity dispersion is useful for dispersion compensation. We expect that the photonic crystal waveguide would be an attractive component for dispersion compensation.

In summary, we discussed the physical origin of the highly-dispersive guided modes of the two-dimensional photonic crystal waveguide. Near the Γ-point, the transverse resonance is dominant, supported by the photonic band gap. And near the Brillouin zone edge, two standing wave modes are created. Therefore, guided modes become extremely dispersive. For example, the group velocity dispersion is millions of times larger than that of a conventional optical fiber. Finally, we argue that the resonator picture for the photonic crystal waveguide helps us understand the highly-dispersive characteristics.

ACKNOWLEDGEMENTS

The authors would like to thank Se-Heon Kim for his valuable assistance and discussion. This work is supported by the National Research Laboratory Project of Korea.

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