General methods for designing single-mode planar photonic crystal waveguides in hexagonal lattice structures

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Abstract: We systematically investigate and compare general methods of designing single mode photonic crystal waveguides in a two-dimensional hexagonal lattice of air holes in a dielectric material. We apply the rather general methods to dielectric-core hexagonal lattice photonic crystals since they have not been widely explored before. We show that it is possible to obtain single mode guiding in a limited portion of the photonic bandgap of hexagonal lattice structures. We also compare the potentials of different photonic crystal lattices for designing single-mode waveguides and conclude that triangular lattice structures are the best choice.

OCIS codes: (230.7370) Waveguides; (130.2790) Guided waves

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1. Introduction

Recently, photonic crystals [1-2] have inspired much interest due to their potential for controlling the propagation of light. In particular, many studies have been devoted to the possibilities of using line defects in photonic crystals as optical waveguides. Many interesting properties such as efficient guiding of light through sharp bends has been recently proposed [3] and demonstrated at microwave [4] and optical [5-6] frequencies. In these studies, the PBG waveguides were generally constructed by removing one row of either air columns or dielectric rods, which usually results in multimode guiding. Single mode waveguides, however, are more desirable for practical applications. We recently studied [7] a more general type of PBG waveguide, which consists of a dielectric slab placed between two PBG mirrors. Such a PBG waveguide can be made single mode by choosing an appropriate thickness for the dielectric slab. However, the adjustment of the slab thickness generally perturbs the lattice symmetry of the photonic crystals and renders the design of waveguide bends difficult. The centers of the air holes in a single-mode waveguide for practical applications (e.g., all-optical circuits) must be on the same lattice, which is not the case for these single-mode waveguides. To address this problem, we recently proposed another method for designing single mode photonic crystal waveguides which involves increasing the radii of the air holes next to the guiding region [8]. This method is based on the observation that the propagation of the guided modes of a PBG waveguide is mainly controlled by the two rows of air holes next to the guiding region [7,9,10].

Three types of two-dimensional photonic crystal lattices that are of practical interests are square lattice, triangular lattice, and hexagonal lattice. Although the first two cases have been widely investigated, there have been only a few reports regarding hexagonal lattice structures [11-12]. These existing reports are focused mostly on the hexagonal lattice of dielectric rods in air. For planar waveguiding applications, it is more appropriate to use the two-dimensional photonic crystals formed by etching air cylinders in a planar dielectric medium, since guiding in the third dimension (perpendicular to the plane of periodicity) can be achieved by total internal reflection. In the search for an optimum PBG waveguide design, it is necessary to include the case of dielectric-core hexagonal lattice PBG waveguides in our considerations, which will be investigated in details in this paper. In particular, we demonstrate in this paper that it is possible to design a hexagonal PBG waveguide with only one guided mode in the photonic bandgap. We study and compare two different methods for achieving this goal, with both practical and fabrication related issues taken into considerations. Finally, we compare the potentials of hexagonal lattice photonic crystals for designing single-mode waveguides with those of triangular and square lattice structures.

2. Simulations

The main structure we use in the analysis of this paper is the photonic crystal waveguide formed by introducing a line defect in a perfect two-dimensional hexagonal-lattice photonic crystal. The unit cell of the 2D photonic crystal and one period of the PBG waveguide investigated in this paper are shown in Figs. 1 and 2 respectively. To analyze the PBG structures as well as the waveguides, we use two-dimensional finite difference time domain (FDTD) technique [13], and an order-N spectral method [14]. To obtain the photonic crystal band structures, we use a 2D unit cell of the photonic crystal with Bloch boundary conditions at all boundaries, which is shown in Fig. 1.

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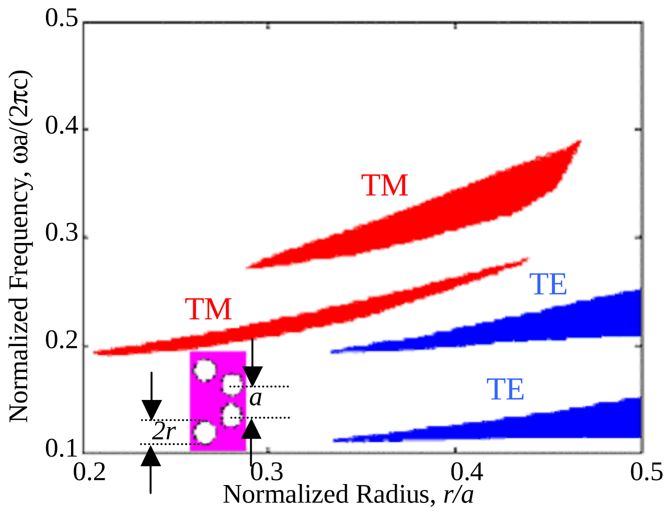

Fig. 1. Maps of photonic bandgap for TE (electric field perpendicular to the computation plane) and TM polarizations in a two-dimensional hexagonal-lattice structure of air cylinders in GaAs ($\varepsilon=12.96$) as functions of the ratio r/a.

As shown in Fig. 2, we use Bloch boundary conditions on the left and right sides to reduce the infinite PBG waveguides into a single unit cell, and use perfectly matched layers (PML) [15] on the top and bottom to simulate the open space surrounding the guiding structures. In the calculations of this paper, the speed of light in vacuum (c) is normalized to 1, and all spatial dimensions are in the units of calculation cells. The dielectric material is assumed to be GaAs (relative permittivity $\varepsilon=12.96$) throughout the paper.

3. Design of single mode PBG waveguides

PBG waveguides with single-mode propagation in the photonic bandgap can be used to route optical signals and are essential for any photonic crystal circuit with dense integration of functionalities such as demultiplexing, guiding, and filtering. Figure 1 shows the gap map (i.e., the frequency extent of the PBG for different values of the radius of the air column) for the first two bandgaps of the 2D hexagonal-lattice photonic crystal that we investigate in this paper. The TE (or TM) polarization in Fig. 1 represents the electromagnetic modes with electric (or magnetic) field normal to the computational domain. To avoid the overlap of the air columns (which complicate the fabrication of the photonic crystal), we limit the radii of the air holes (r) to $r < 0.5a$, where a is the lattice constant as shown in Fig. 1. In order to maximize the guiding bandwidth, we choose the parameters of the hexagonal photonic crystals that lead to the largest bandgap, which is the second TM bandgap with $r=0.38a$. As can be seen from Fig. 1, the second bandgap covers the normalized frequency (ω) range of $0.30<\omega a/(2\pi c)< 0.33$.

Conventional dielectric-core PBG waveguides in square and triangular lattices, formed by removing one row of air holes generally result in more than one guided mode in the PBG. The multi-mode nature of the conventional PBG waveguides is due to the large thickness of the middle dielectric slab, a direct result of removing one row of air holes [7-8]. The same situation holds for conventional waveguides in hexagonal lattice photonic crystals. Therefore, the simplest way to form single mode PBG waveguides, which is also the first approach we pursue, is to reduce the thickness of the middle slab. Figure 2 shows how this idea can be used to design a single-mode PBG waveguide in a hexagonal-lattice photonic crystal.

Figure 2(a) shows one unit cell of a PBG waveguide made by placing a dielectric slab of thickness d between two PBG mirrors, each consisting of a two-dimensional hexagonal lattice of air columns in GaAs. The period of the hexagonal lattice and the radius of each air column

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are *a* and *r=0.38a*, respectively. In the simulations of this section, we choose *a=29* calculation cells. Figure 2(e) shows the dispersion diagrams for the two dominant TM modes (magnetic field normal to the computation plane) of the PBG waveguides with different values of slab thickness d. Typical magnetic field patterns of the four modes in Fig. 2(e) are shown in Figs. 2(a), (b) (c), and (d). The field patterns of Figs. 2(a) and (c) have odd symmetry with respect to the center of the PBG waveguide, while those of Figs. 2(b) an (d) have even symmetry. The slab thickness of the conventional PBG waveguide (made by removing one row of air holes) is *d=0.66a*. For this thickness, two modes (one with even symmetry and one with odd symmetry and represented in Fig. 2(e) as dashed lines) are guided in the PBG. By reducing the slab thickness d both modes are shifted to higher frequencies and for *d>0.52a*, the odd mode is pushed up and separated from the even mode, as shown in Fig. 2(e). Therefore, we can obtain single-mode guiding in the PBG by reducing the slab thickness to *d=0.52a*.

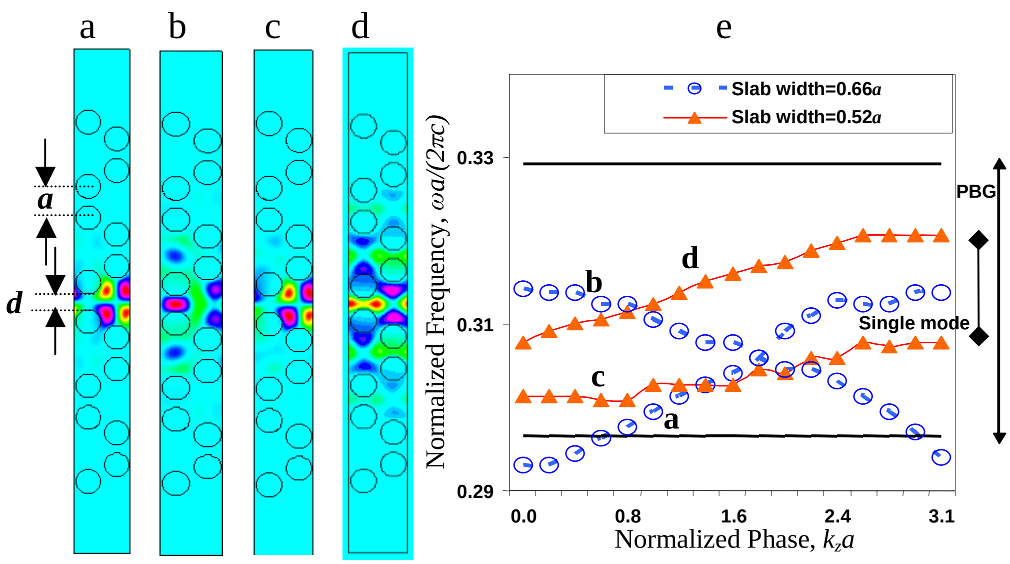

Fig. 2. (a)-(d) One period of the waveguide structure and magnetic field pattern in a PBG waveguide made by putting a dielectric slab of thickness *d* between two hexagonal lattice PBG mirrors. The radii of air holes in all cases are *r=0.38a*, with *a* being the distance between the centers of nearest neighbor air holes. The thickness of the middle slab in (a) and (b) is *d=0.66a*, and that in (c) and (d) is *d=0.52a*. The dispersion diagrams for the two dominant guided TM modes of these PBG waveguides calculated by the FDTD technique are shown in (e). The dielectric material is GaAs with relative permittivity *ε=12.96*. The distance between the centers of the nearest neighbor holes and the radius of each hole in the photonic crystal are *a=29* calculation cells and *r=0.38a*, respectively. The frequency ranges of bandgap (PBG) and single-mode guiding for *d*=0.52*a* are shown in the figure.

As discussed previously, a major disadvantage of reducing the slab thickness of the PBG waveguides is that it breaks the discrete translational symmetry of the photonic crystal and complicates the design of waveguide bends, especially when cascading multiple bends. To avoid this difficulty, we investigate the second approach, where the air hole centers remain on the same photonic crystal lattice and the reduction of the slab thickness is achieved via increasing the radii of the air holes adjacent to the middle slab [8] as shown in Fig. 3. The PBG waveguide in Fig. 3(a) is formed by removing the first and third rows adjacent to the slab and enlarging the radius of the second row to $r=0.73a$ on both sides (above and below) of the middle slab. The field patterns and the dispersion diagrams of the TM modes are shown in Fig. 3. Figure 3(d) demonstrates single mode guiding in this PBG waveguide.

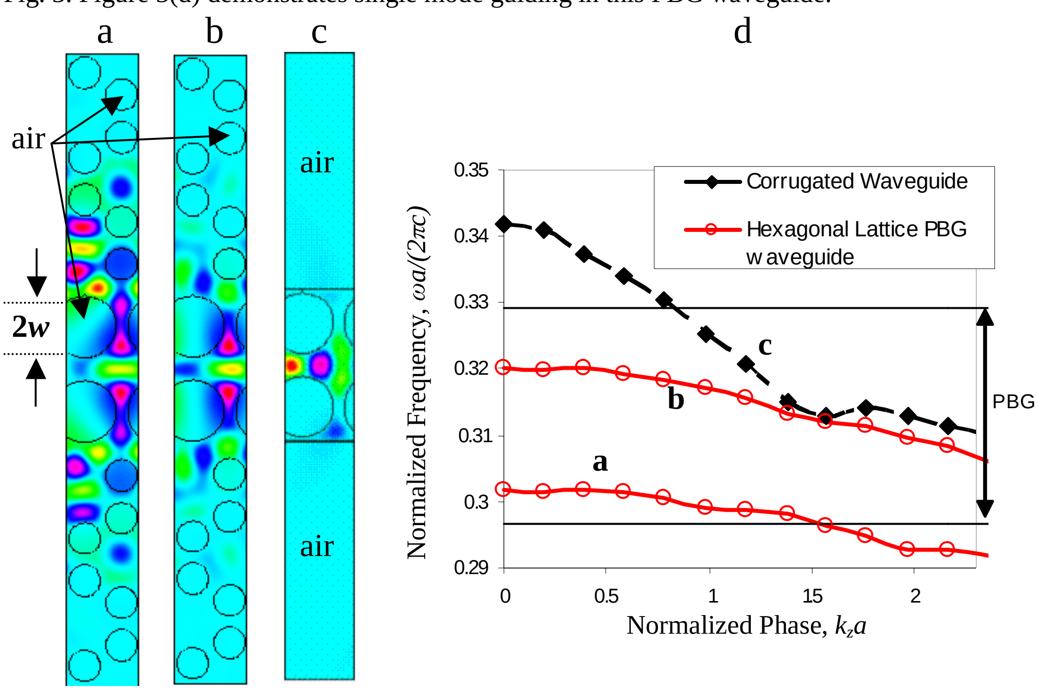

Fig. 3. (a) One unit cell of the waveguide structure and the magnetic field patterns for different TM modes of: (a), (b) a specially designed waveguide as discussed in the text, and (c) the equivalent corrugated waveguide made by considering only two rows of the photonic crystal adjacent to the middle slab with air above these two rows. (d) Dispersion diagrams of the dominant guided modes corresponding to hexagonal lattice waveguide and corrugated waveguide shown in (a), (b), and (c). The dielectric material in all waveguides is GaAs (ε_s=12.96). The cladding region of the corrugated waveguides is air (ε=1). The period of the hexagonal lattice and the radius of each air column in the PBG waveguide are $a=29$ calculation cells and $r=0.38a$, respectively.

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An interesting feature of the PBG waveguide in Fig. 3 is the substantial amount of electromagnetic field outside the middle slab. We believe this is due to the creation of multiple line defects in the PBG structure that are coupled to each other. As described earlier, the PBG waveguide in Fig. 3(a) is made by removing three rows of air holes and increasing the radii of all air holes in two other rows. The enlargement of the air holes in Fig. 3(a) simultaneously creates three defect channels: one between the two middle (large) holes, one between the large holes and the adjacent (normal) holes above the middle slab, and one between the large holes and the adjacent holes below the middle slab. These line defects forms three PBG waveguides that are strongly coupled together due to their close proximity. As a result, the overall modes of the structure are extended over these three waveguides. Further increasing the radii of the air holes next to the middle slab can shift the second mode upward and increase the single-mode guiding bandwidth. However, fabrication of the structure with too large of a hole diameter may be difficult, due to the small spacing between adjacent holes. From the discussion above, it is clear that the main drawback of the hexagonal lattice photonic crystals for designing single-mode waveguides is the relative positions of the air holes, where removing one row of holes cause an asymmetric and highly corrugated structure. In order to make a less corrugated structure, either hole periodicity below or above the waveguide slab must be broken (method 1, Fig. 2) or an extensive line defect over several rows of air holes (method 2, Fig. 3) must be introduced.

In Fig. 3(b), the guided mode of the PBG waveguide is mainly confined within the middle slab, which suggests that for these modes the PBG waveguide can be approximated by an equivalent corrugated waveguide that only retains the two rows of air holes adjacent to the middle slab [10], as shown in Fig. 3(c). The dispersion of the guided mode in this corrugated waveguide, as shown in Fig. 3(d), is similar to that of the corresponding PBG waveguide mode in a portion of the bandgap. The differences between the dispersion diagrams of the two waveguide are caused by the multi-line defect nature of the PBG waveguide that makes it different from the corrugated waveguide. It is also interesting to note that the lower mode of the PBG waveguide (Fig. 3(a)) does not correspond to the corrugated waveguide mode. This can be explained by the observation that the waveguide mode in Fig. 3(a) is a result of coupling between three defect channels in the guiding structure, which makes it essentially different from the corrugated waveguide mode.

4. Discussion

The results of Section 3 suggest that a hexagonal lattice of air holes in a dielectric material can be used for building integrated photonic circuits, and it is possible to design a single-mode PBG waveguide within the frequency band gap. However, there are several drawbacks in using the hexagonal lattice photonic crystals for integrated optics applications. First, single-mode propagation can be achieved only within part of the PBG, which may limit the frequency bandwidth of the integrated optics devices. Second, we demonstrate that designing single mode waveguide in hexagonal lattice structures relies on the following two approaches: (1) reducing the center slab thickness, which breaks the lattice symmetry and complicates the design of waveguide bends, and (2) creating an extensive line defect by modifying the radius of the air holes adjacent to the center slab material, which leads to a complicated field distribution and possibly coupling between different guiding channels.

Having discussed the benefits and drawbacks of the hexagonal lattice PBG structures, it is instructive to compare it with other photonic crystal lattices. We begin with the normalized width of the PBG, which is defined as the size of the bandgap divided by the gap center frequency. The maximum normalized gap widths of three different lattices of air holes in GaAs are compared in Table 1. The normalized gap width depends on the radius of the air holes (r), which cannot be made too large due to fabrication difficulties. In order to ensure enough separation between the neighbor air holes, we only consider the cases with $r<0.43a$, where a is the lattice constant. The maximum value of the normalized gap width is then calculated for different lattices. For each photonic crystal lattice, the bandgap for both TE and TM polarizations over the entire range of hole radius (r) has been calculated, and the maximum value of the gap width and its corresponding polarization has been reported in Table 1. The radius of air holes corresponding to the maximum normalized gap width is also shown in Table 1.

Table 1. Comparison of the maximum photonic bandgap size and the corresponding radius of the air holes in different photonic crystal lattices. The radius of the air holes and the distance between the centers of the nearest neighbor air holes are represented by r, and a, respectively.

Photonic crystal lattice	Triangular	Square	Hexagonal
Polarization for maximum bandgap	TM	TM	TM
Gap Ratio (size of PBG/center frequency)	~52%	~17%	~10%
Radius of air holes corresponding to largest gap ratio (r/a)	0.42	0.42	0.38

The results shown in Table 1 suggest that triangular lattice photonic crystals are the best candidates for applications in integrated photonic circuits, where the maximum PBG size is desired. Furthermore, the large PBG in triangular lattices is obtained at smaller hole radii compared to other types of lattices. This allows for more flexibility in designing PBG waveguides (and cavities). Recently, there have been reports [7] that it is possible to design PBG waveguides in square and triangular lattices with only one mode in the entire PBG. Combining these studies with the results in the previous section, we believe the best choice for designing single-mode dielectric-core planar waveguides for practical applications is a triangular lattice photonic crystal. We also emphasize that the two methods for designing single-mode PBG waveguides described in this paper can be applied to any photonic crystals structures (triangular lattice, square lattice, etc.).

Note that the results of this paper were calculated using 2D-FDTD technique. Thus, the accuracy of the results is determined by the well-known accuracy of the technique [16]. More accurate results can be obtained by 3D simulations and taking the finite thickness of the structure into account. While 3D simulation results in the modification of the PBG and the single-mode waveguide frequency range, the general conclusions of this paper, i.e., the superiority of triangular lattice for designing PBG waveguide and structural problems of the PBG waveguides in hexagonal lattice structures remains intact.

5. Conclusion

We presented here two systematic methods of designing dielectric-core single-mode PBG waveguides in two-dimensional hexagonal lattice photonic crystals. We showed that the properties of the guided modes in these waveguides can be modified by changing the geometry of only the air holes that are adjacent to the middle slab. Single mode guiding can be obtained in at least a portion of the photonic bandgap by changing the geometry of the photonic crystal in the guiding region. In an ideal structure, extra modes can be pushed out of the bandgap by either reducing the thickness of the middle slab or by increasing the radii of the air holes adjacent to the middle slab. The second method is preferable for applications that require waveguide bends as well since it does not modify the locations of the centers of the air holes (i.e., it conserves the periodicity of the centers of the air holes). Both of these methods have limitations in applying to hexagonal lattice structures due to the geometry of the air holes which result in highly corrugated waveguides. The existence of some unwanted modes due to the coupling of multiple line defects in hexagonal lattice structures is an example of such limitations.

We also compared different 2D photonic crystal lattices for designing single-mode waveguides. Our results show that triangular lattice photonic crystals are the best candidates, since they have the largest bandgap and a larger frequency range for single mode guiding.