Waveguides, Bends and Y-junctions with Improved Transmission and Bandwidth in Hexagon-Type SOI Photonic Crystal Slabs

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ABSTRACT

This paper presents novel ways of implementing waveguide components in photonic crystal slabs based on silicon-on-insulator (SOI). The integration platform we consider consists of hexagonal holes arranged in a triangular lattice ('hexagon-type' photonic crystal). The waveguides are made of one missing row of holes (W1) with triangular air inclusions symmetrically added on each side of the waveguide.

Size and position of these inclusions are tuning parameters for the band diagram and can be used for minimizing the distributed Bragg reflection (DBR) effect. The waveguides show single-mode behavior with reasonably high group velocity and large transmission window, inside the gap between H-like modes^{**}. These waveguides, closely resembling conventional ridge waveguides, can be combined to form efficient bends and Y-junctions. The bends and Y-junctions include intermediate short waveguide sections at half the bend angle playing the role of corner 'mirrors'. Qualitative design rules were obtained from 2D calculations based on effective index approximation.

Keywords: photonic crystal, line defect waveguide, effective index, bend, Y-junction

1. INTRODUCTION

An intense research on photonic crystals (PhC) has been going on during the last decade. In particular, photonic crystal slabs (PCS) have received a considerable interest because they have the potential to serve as an integration platform for densely packed photonic circuits.

Up till now, theoretical and experimental studies on PCS have almost exclusively concentrated on a triangular lattice of circular holes. The 'defect-free' air bridge slab has a large robust gap in H-like modes between the first two bands¹. Hexagonal holes provide the same large gap as their circular counterpart and also add some flexibility in design. An extra degree of freedom is the rotation angle of the hexagons with respect to their symmetry axis (see Figure 1). This can be used as tuning means for adjusting the configuration of the lattice (i. e. size and orientation of veins and islands). By increasing the filling factor one can obtain absolute gaps in guided modes², situated at higher frequencies in the band diagram. The absence of guided modes in a frequency region has potential applications in light extraction enhancement from a point-like cavity, through increasing the in-plane quality factor.

In a previous paper³ we have shown that the guided modes in a line defect can be tuned by combining hexagonal holes with triangular air inclusions (see Figure 3). These inclusions can be used to reduce the waveguide width (hence the effective index of the waveguide) independently of the lattice constant and without lattice distortion, and also to minimize the effect of boundary corrugations. Hexagonal holes, in combination with triangular air inclusions can make linear defect waveguides (bandgap-guided in the slab plane) that closely resemble ridge waveguides. The resulting waveguide shows single-mode behavior, with high group velocity and relatively large transmission window.

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^{**} The convention adopted in this paper for mode classification: in 2D, modes which have the E(H) field oriented along the infinite axis are called 'E-modes' and 'H-modes', respectively; in a 3D symmetric slab, modes either even or odd with respect to the mid-plane are called 'H-like' or 'E-like'; in a 3D slab with weak asymmetry modes are classified as 'quasi H-like' or 'quasi E-like'; the even-odd terminology is used in this paper to denote the modes' symmetry with respect to the central axis of the line defect waveguide

Figure 1 Hexagon-type PhC configuration – rotated hexagons arranged in a triangular lattice (for $\theta=0$, the vertices of neighboring hexagons are pointing towards each other, the rotation is taken counter-clockwise); geometrical parameters are indicated: lattice constant (a), radius (r), rotation angle (θ), vein thickness (x_{hex})

In this paper we consider further developments of these line defect waveguides, namely combining them to form bends and Y-junctions. The bends and Y-junctions include intermediate short waveguide sections at half the bend angle playing the role of corner ‘mirrors’. For hexagons with $\theta=30^\circ$ rotation angle, the inner edge of these waveguide sections is straight, and this opens the possibility to make them resemble ridge waveguides, too (see Figure 5 and Figure 6). Then, one can achieve good mode matching among input and output branches and intermediate sections.

2. DESIGN GUIDELINES

2.1. Line defect waveguides

In telecom applications the line defect waveguides in PhCs should act as ‘light pipes’ for efficient and directional transmission of signals. Therefore, their desired characteristics would be: broad bandwidth, flat top response, single-mode, large group velocity and low-losses. These are traits of usual ridge waveguides which are not all fulfilled in usual W1 waveguides made by omitting a row of holes in an otherwise periodic PCS.

Omitting a row of holes in a high-index material (e.g. silicon) is a strong perturbation. Therefore, W1 waveguides have several guided modes in the gap, so that there is no truly single-mode range available⁴. The dispersion curves of these modes are flat at the edge of the line-defect Brillouin zone. This means that the guided modes span a narrow frequency range and have a low group velocity. The physical explanation of these characteristics lies in the fact that in a W1 waveguide the lateral walls of the dielectric channel are periodically corrugated by the neighboring rows of air holes. Therefore, a W1 waveguide looks like a 1D photonic crystal and distributed Bragg reflection (DBR) takes place. Partial back-reflections from individual corrugations interfere constructively for certain frequencies, gradually converting the forward propagating wave into a backward propagating one⁵. The energy cannot flow along the waveguide, a phenomenon known as *mode gaps* or *mini stopbands*. This also explains the low group velocity, especially at the edge of the line-defect Brillouin zone. In a W1 waveguide that is symmetric with respect to its middle axis the guided modes can be classified as odd and even with respect to it. The corrugation being symmetrical, it can couple only the modes with the same parity propagating in both directions along the waveguide. Dispersion curves of the modes with opposite parity can cross, regardless of mode order, while the ones of modes of same parity and different order repel each other, producing *anticrossings*. These anticrossings give rise to mode gaps⁵.

Several ways of tuning the band diagram in order to obtain single-mode low-loss propagation have been proposed: (1) reducing the waveguide width by displacing blocks of holes with respect to the original lattice⁶; (2) reducing the hole-size and shifting with half-period the holes along the waveguide axis⁷; (3) increasing the hole-size⁸ and changing the hole-shape into elliptical⁹ along the waveguide axis; (4) increasing the hole-size for the two rows adjacent to the W1 waveguide⁴; (5) changing the corrugation symmetry by offsetting two blocks of a perfect lattice in the longitudinal and/or transversal direction of the waveguide^{4,10}, or omitting an even number of lines¹⁵; (6) reducing the refractive index of a W1 waveguide⁸ (e.g. by etching pores into it); (7) inserting air trenches on each side of a W1 waveguide¹¹.

Changing the waveguide width destroys the periodicity of the original lattice and makes it more difficult to introduce bends and junctions. From this point of view, approaches (1) and (5) are not convenient. Increasing the hole-size can lead to higher losses if the mode profile has a significant overlap with the holes.

Only approaches (5) and (7) have solved the DBR problem in line defect waveguides. Lau and Fan¹¹ applied structural tuning without lattice distortion. The structure is a normal ridge waveguide embedded in a photonic crystal with trenches that cut through the adjacent rows of holes. The trench width is a design parameter which helps eliminating the surface states from the region of interest. The DBR effect is eliminated in this case, but this structure would have in practice a low mechanical stability and rigidity without a solid bottom cladding.

Adibi and co-workers¹² have shown that the most important role in the behavior of a line defect waveguide is played by the adjacent rows of PhC boundaries that modulate the waveguide width. In the case of circular holes, the waveguide edges will always be curved, whereas in the case of hexagonal holes, the edges can be straight. The guided modes in a line defect can be tuned in a hybrid design by combining hexagonal holes with triangular air inclusions (see Figure 3– left panel). These inclusions can be used to reduce the waveguide width (i.e. the effective index of the waveguide) independently of the lattice constant and without lattice distortion and also minimize the effect of boundary corrugations. The resulting line defect waveguide (gap-guided in the slab plane) resembles closely a ridge waveguide and shows single-mode behavior, with high group velocity and relatively large transmission window. The triangular inclusions perturb only slightly the waveguide properties, by producing surface states at the interface between PhC and waveguide. In principle, angle θ can be used for designing a waveguide that does not have a central axis of symmetry. But, when the symmetry is preserved, the modes can be classified as ‘even’ or ‘odd’ with respect to the central axis, and these classes have theoretically zero cross-coupling. Then, the fundamental mode of an input ridge waveguide can preferentially excite the lowest order mode of the line defect waveguide.

2.2. Bends and Y-junctions

Line defect waveguides can be combined to form bends and branches. Connecting two or three line defect waveguides at an angle (e.g 60° in a triangular lattice) makes a bend or a Y-junction, respectively. The main role of the PhC is to prohibit the in-plane bend losses, and allow curvature radii as small as the wavelength. The translational symmetry of straight waveguide is broken when introducing a bend or a Y-junction; then, even and odd modes can couple to each other. The following phenomena that occur at a normal bend are detrimental to the transmission: (a) strong back-reflections; (b) increased out-of-plane losses; (c) relatively poor matching between the guided modes of the straight sections (because the bend is usually multimode). On the other hand, the transmission along a bend can be higher than in a line defect waveguide, in the minstop bands of the latter.

Several designs of bends and Y-junctions have been proposed, targeting minimization of back-reflections and improvement of mode-matching: (1) place small holes in the center of constituent W1 waveguides¹³ or at the connection point of a Y-junction¹⁴; (2) displace holes from the inner to the outer corner of the bend¹⁵; (3) introduce an intermediate short section at half of the bend angle^{15,16}; (4) reduce the corner angle in a polycrystalline PhC made by dislocating lattice blocks¹⁷; (5) deform the lattice in and around the bend¹⁸; (6) modify the lattice topology by connecting several holes at the corner¹⁹

Resonant elements incorporated in the waveguide (e.g. displaced holes that act as resonators) can give an increased transmission for certain wavelengths but, most of the time, do not provide a large bandwidth. Lattice deformation can be effective, but then the concept of PhC is somewhat obscured. In a naïve ray picture, an intermediate short section at half of the bend angle acts as a corner mirror that directs an incident ray from the input to the output branch of a bend. This intuitive argument proved to be effective^{15,16}, therefore we apply it in our designs, aiming also at keeping the resemblance with ridge waveguides. When using $\theta=30^\circ$, the inner edge of a short intermediate waveguide section at 30° appears naturally, without the need to change any hole. Some modifications of the PhC structure are needed to obtain the proper outer edge of the intermediate waveguide section. For a bend, half of the hexagonal corner hole is filled and the hole-shape is changed into a trapezium (Figure 5-right panel). For a Y-junction, an extra equilateral triangle is introduced at the connection point (Figure 6-right panel).

3. SIMULATION

3.1. Effective index approximation and computational method

Rigorous modeling of PCS structures requires 3D calculations that are very demanding in terms of time and memory requirements. Effective index approximation of PCS has been used for relieving these requirements by reducing the full 3D calculations to simpler, though approximate 2D calculations. The PCS is essentially a slab system perforated with a lattice of holes. In the effective index method, the PCS is replaced by a 2D system with the background dielectric medium having the effective refractive index of the fundamental guided mode of the slab system. In high-index contrast systems (like SOI) effective index approximation is valid for a narrow frequency range²⁰ in which the guided mode dispersion is small enough. In ref. 3 we have applied the effective index approximation for qualitative

design of 3D photonic crystal structures (slabs and line defect waveguides). The bands of the real 3D structure are shifted upwards in frequency with respect to the 2D bands calculated by effective index approximation. But the shape of the lowest order bands is roughly preserved, allowing conclusions regarding the mode classification of modes in 3D. Qualitative design rules can be obtained from a 2D calculation combined with the light-line of a cladding that restricts the ω - k range available for guided modes in the actual 3D case.

We choose a slab system (Figure 2) in which the bottom cladding is a quasi-2D SiO₂ slab (i.e. the air holes penetrating both Si and SiO₂ layers of a SOI wafer). Etching the air holes into the bottom cladding has beneficial effects: it decreases the asymmetry and increases the frequency range below the light cone, available for truly guided modes. Moreover, the structure is mechanically stable and the etch depth can be moderate, due to high-index contrast. To avoid complications due to possible coupling to higher order modes, we choose a slab system that supports only a single mode, for both polarizations.

Figure 2 Illustration of effective index approximation

For an asymmetric slab system consisting in a core with refractive index n and height h , sandwiched between two claddings with refractive indices n_1 and n_2 ($n_1 < n_2$), the single-mode condition for free space wavelength λ_0 is²¹:

$$h_{\max} = \frac{\lambda_0}{2\pi} \cdot \frac{1}{\sqrt{n^2 - n_2^2}} \cdot \left[\pi + \tan^{-1} \left(\sqrt{\frac{n_2^2 - n_1^2}{n^2 - n_2^2}} \right) \right] \quad (1)$$

Our design parameters are: $\lambda_0 = 1.55 \mu\text{m}$, $n = 3.45$ (Si), $n_1 = 1$ (air) and $n_2 = 1.45$ (SiO₂). Then the maximum thickness for single-mode, according to equation (1) is $h_{\max} = 273 \text{ nm}$. We choose a core thickness $h = 260 \text{ nm}$. The effective indices of H and E guided modes will be: $n_{\text{eff}}^H = 2.924$ and $n_{\text{eff}}^E = 2.24$. There is no 2D gap in E modes for $n_{\text{eff}}^E = 2.24$, therefore we focus only on the H modes.

The projected band diagrams of line defect waveguides have been calculated using the MIT Photonic Bands program²². We used a supercell (see Figure 3 –left panel) containing 8 rows of holes and the line defect in the middle with the length of a (the periodicity along Γ -K). Bloch boundary conditions were applied at the sides of the supercell.

The behavior of finite-sized samples used in actual experiments cannot be readily expressed in terms of Bloch modes and an important role is played by evanescent modes and reflections from the boundaries. Therefore, we calculated the spectral transmittance through 2D finite-element (FEM) simulations using FEMLAB²². FEM has the advantage of outputting the stationary field profiles, so that one can quantify the field energy localization and power flow directionality. Although the material dispersion is neglected here (assumption valid for Si and SiO₂ at the working wavelengths), this can be easily accounted for in FEM dispersion, which is a frequency-domain method. The computational domain is finite, with transparent (‘low reflecting’) boundary conditions. At the waveguide input a constant amplitude field is applied. Power outflow is monitored at the other end of the waveguide. Transmittance is given by the ratio between the power outflow at the output boundary and power inflow at the input boundary (it is influenced by the coupling of the input field with the waveguide modes). Normalized frequency ($u = a/\lambda$) is scanned in the gap range, with a small step.

3.2. Results

We apply the considerations from section 2 and consider a waveguide along Γ -K direction with central symmetry axis and lattice orientation $\theta = 30^\circ$; the lattice is undistorted and air inclusions are isosceles triangles with 120° apex angle and equal sides $1.1a$ (see Figure 3-left panel).

The band diagram of the original perfect periodic lattice was projected along Γ -K direction, revealing continua of states that extend in the bulk photonic crystal (grey regions in Figure 3 – right panel) and the projected gap opened

between them. The isolated dispersion curves that appear in the projected gap correspond to states localized in the line defect. The light line (straight solid line) corresponds to an effective index of the bottom cladding $n_{\text{eff}}^{\text{SiO}_2} = 1.238$.

We focus our attention on the even mode in Figure 3-right panel. This is in fact the fold-back of the index-guided mode at the edge of the line defect Brillouin zone. This mode undergoes an anticrossing with another even mode from the lower edge of the gap (around $k=0.36$). As consequence, the spectral region below the light line of the even mode is very limited ($u=0.284\dots0.29$) and the group velocity is small. However, the even mode covers a broad range of frequencies above the light line. Even for modes situated above the light line the propagation losses might be low in practice. For $u=0.29\dots0.326$ there is a single mode region, covered by the even mode that has a high group velocity ($v_g=0.31c$).

An important parameter is the position of the triangles with respect to the waveguide's central axis (x_t). The influence of x_t on the band diagram has been assessed through a series of simulations. An example of computed band diagram, for $x_t = r\sqrt{3}/2$, is shown in Figure 3-right panel. When x_t increases, the following changes in the band diagram take place: (a) the odd mode shifts upwards; (b) the even mode shifts downwards; (c) the anticrossing decreases and shifts to lower k values.

Figure 3 Line defect waveguide: left - domain geometry and supercell (dashed line); right – band diagram guided (grey regions are bulk modes; light line is solid); $x_t = r\sqrt{3}/2$

Spectral transmittance through the line defect waveguide, bend and Y-junction was calculated by FEM for $u=0.28\dots0.42$ with 200 steps.

The transmittance through the line defect waveguide (Figure 4-left panel) has a broad band, with a small ripple. The maximum transmittance is about 85%, because the coupling between the input source and the mode guided in the line-defect waveguide was not optimized. The field distribution for an H mode at normalized frequency $u=0.315$ is shown in Figure 4-right panel. The field profile clearly resembles that of an index-guided mode. The transmittance through the line defect waveguide is considered as a reference for assessing the efficiency of bends and Y-junctions. We define the relative transmittance (T_r) as the ratio between the transmittance through the bend or Y-junction and the transmittance through the straight line-defect waveguide.

We consider a bend and a Y-junction with almost the same length as the line-defect waveguide (Figure 5, Figure 6-right panels). For the bend in Figure 5-right panel, $T_r > 89\%$ in the range $u=0.302\dots0.316$ (Figure 5-left panel). For the Y-junction in Figure 6-right panel, $T_r > 63\%$ in the range $u=0.302\dots0.32$ (Figure 6-left panel). Both the bend and the Y-junction are characterized by resonances of the corner cavities ($u=0.33$ for the bend, $u=0.373$ for the Y-junction). Then light is ‘trapped’ at the corner instead of being transmitted through and the transmittance is close to zero. The separation in even and odd modes is not possible anymore in a bend or Y-junction, and this leads to mode mixing. The mixing between two modes can be seen in the transmittance, in the form of rapidly oscillating spikes in the range $u=0.338\dots0.352$ (Figure 5, Figure 6-left panels).

Figure 4 Left: spectral transmittance through a line defect waveguide (see text for details); Right: the H field distribution at normalized frequency $u=0.315$

Figure 5 Left: spectral transmittance through a bend; Right: the H field distribution at normalized frequency $u=0.315$

Figure 6 Left: total spectral transmittance through a Y-junction (sum of the two branches); Right: the H field distribution at normalized frequency $u=0.315$

4. DISCUSSION AND CONCLUSIONS

We presented a design approach for line-defect waveguides in ‘hexagon-type’ PCS, based on a novel way of tuning ‘defect’ modes by means of triangular air inclusions. The size and positions of these inclusions modify the effective index of the waveguide independently of the lattice constant (in some cases without lattice distortion) and also minimize the effect of boundary corrugations. The waveguides are integrated in a hexagon-type PCS and they have the following characteristics: reduced DBR effect, single-mode, high group velocity and large transmission window. These waveguides, closely resembling conventional ridge waveguides, can be combined to form efficient bends and

Y-junctions. The bends and Y-junctions include intermediate short waveguide sections at half the bend angle playing the role of corner ‘mirrors’. For hexagons with $\theta=30^\circ$ rotation angle, the inner edge of these waveguide sections is straight, and this opens the possibility to make them resemble ridge waveguides, too. In this way, one can achieve good mode matching among input and output branches and intermediate sections. PhC's may be a good way for obtaining small high-Q resonators or sensing elements which should be coupled to the outside world through waveguides. For combining several of these basic devices, possibly in MZI-configurations, bends and Y-junctions are needed. In principle, these could be made almost as small using conventional high-index waveguides. An important reason for implementing them with PhC waveguides is the problem of matching conventional waveguides to PhC waveguides (probably a lot of those transitions result in larger overall loss and larger size than implementing the entire circuit in PhC).] In this case the coupling efficiency with in/out ridge waveguides has a more prominent role than radiation losses. One has also to consider the wavelength dependency of the transmission, due to DBR and Fabry-Perot effects (these depend on the length of line defect arms). The effective index method, allowing for efficient 2D calculations, gives qualitative results, which could be used for a first design. Fine-tuning through 3D calculations is necessary to account for out-of-plane losses.

It is worth noting that we have considered only H modes and it seems very hard to obtain polarization-independent functioning in these devices.

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