Line-Defect Waveguides in Hexagon-Hole type Photonic Crystal Slabs: Design and Fabrication using Focused Ion Beam Technology

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Photonic-crystal slabs (PCS) patterned with a 2D triangular-lattice having hexagonal holes rotated with respect to their symmetry axis can provide a larger bandgap than similar slabs with circular holes. A step forward towards integrated optical devices is introducing line 'defects' in PCS, the goal being the achievement of single-mode waveguiding over a frequency range as large as possible, inside the gap. We present the design for defect waveguides with reduced width and a novel fabrication technique, which is an integration of optical lithography with focused ion beam (FIB) high-resolution etching. This technique allows a good alignment between a line 'defect' and conventional ridge waveguides.

Introduction

In a recent paper [1] we demonstrated that photonic crystal slabs (PCS) with carefully oriented hexagonal holes in a triangular lattice (further referred to as 'hexagon-type') show large *absolute* gaps in guided modes. A natural continuation of this work is to introduce line defects in PCS, the goal being the achievement of single-mode waveguiding over a frequency range as large as possible, inside the gap. The present paper is divided into two main parts: first we present the design for defect waveguides with reduced width; then we present the fabrication technique, which is an integration of optical lithography with focused ion beam (FIB) high resolution etching.

Design

Linear waveguides created by removing one row of holes in PCS (W1) are inherently multimode if the slab has a high refractive index. One way towards achieving single-mode guiding, which has been described in [1] would be reducing the width of the waveguide, by bringing the lateral photonic crystal arrays close to one another. This provides a way of tuning the band diagram, with the goal of obtaining a sufficiently large transmission window, covered by a single guided mode. We performed calculations using a numerical method based on minimization of the Rayleigh quotient in a plane wave basis [2]. The subject of our study was a line-defect waveguide along Γ-K direction in a PCS consisting in a 2D hexagon-type lattice of air holes in a silicon-on-insulator (SOI) material system, see FIG. 1. Side-length of the hexagons is $r = 0.45\,a$ (a is the lattice constant) and the rotation angle of the hexagons with respect to their symmetry axis is $\alpha = 9^\circ$. As shown in [1], these give a large absolute gap in 2D. The line-defect has a width $w = 1.41\,a$. The computational domain, on which Bloch boundary conditions are applied, is also indicated in FIG. 1.

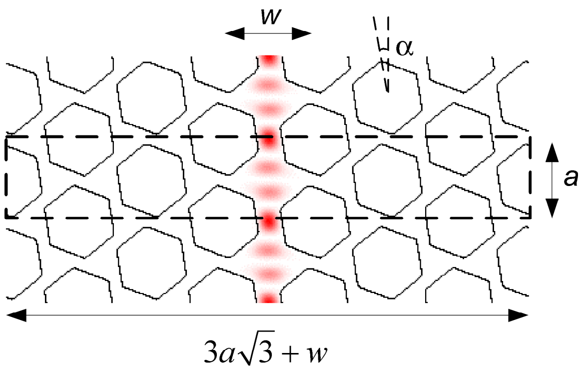

FIG. 1. Intensity distribution ($|H_y|^2$) of well-confined guided TE defect mode (normalized frequency 0.466 at $k_z = 0.5$) in hexagonal-type PCS. The supercell used for calculation is shown by the dashed contour.

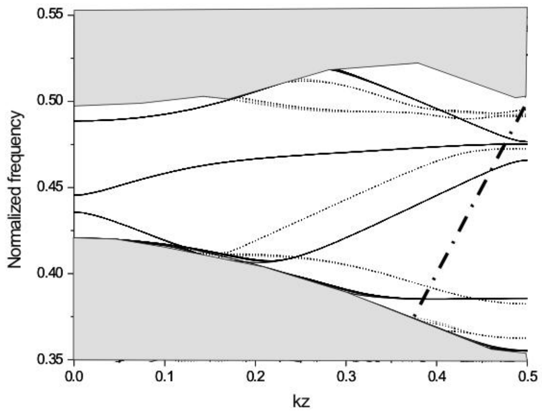

FIG. 2. Zoom-in of the projected band diagram (see text for structure details); grey areas are modes allowed in the bulk PCS and the white area is the photonic bandgap; TE and TM gap-guided modes are represented by continuous and dotted lines, respectively; the thick dash-dotted line is the light line of the air claddings.

Qualitative design rules can be obtained from a 2D calculation [3] in which the band diagram is projected along the direction of the 'defect' waveguide. This is combined with the light-line of a cladding that restricts the ω-k range available for guided modes in the actual 3D case.

From the band calculations, shown in FIG. 2, several dispersion curves can be identified that are isolated from the continuum and are located in the bandgap, below the light line. Of particular interest is the TE mode that covers the normalized frequency range (0.46...0.466), has a quite high group velocity, and does not have any crossings with other modes. The last point is important in order to avoid mode mixing.

In actual experiments one is using finite-sized samples. Their behavior cannot be readily expressed in terms of Bloch modes and an important role is played by evanescent modes and reflections from the boundaries.

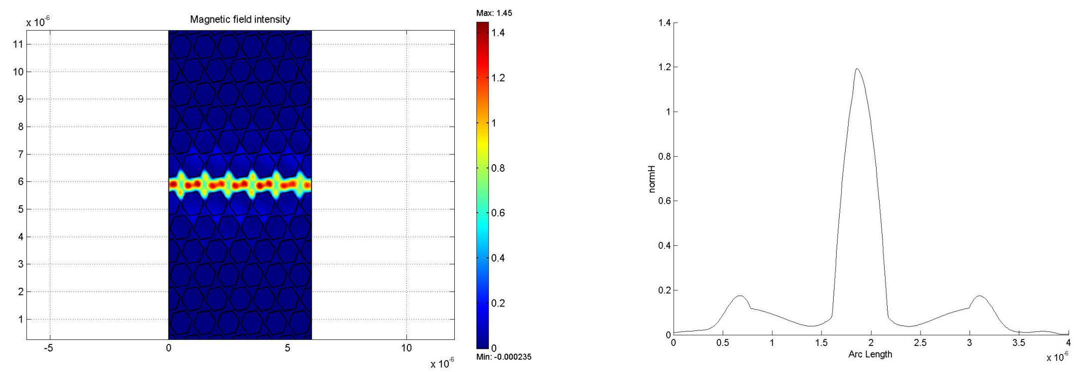

FIG. 3. Intensity distribution ($|Hy|^2$) of a guided TE defect mode with normalized frequency 0.466. Left panel: surface plot; Right panel: cross-sectional view.

Therefore, in order to check the results obtained using the supercell approach, we performed a 2D finite-element simulation using FEMLAB™ [5]. Results presented in FIG. 3 confirm the existence of a TE mode confined in the defect waveguide. The mode

profile in FIG. 3 does not coincide with that of the corresponding Bloch mode, because it is influenced by the finite length of the waveguide (although the in/out waveguide boundaries are specified as 'matched', a certain amount of reflection takes place there).
High-index contrast systems require full 3D calculations of the band structure and further optimization of structural parameters. We are currently performing these computationally intensive calculations.

Fabrication

Several fabrication techniques for photonic crystal devices have been proposed. Deep UV laser lithography [6] is parallel, fast and expensive (requires steppers). However, it cannot reproduce sharp corners (because of diffraction) and proximity effects need to be compensated at the mask design level. Laser interference lithography (LIL) [7] is fast, cheap and suitable for large area PCS. On the downside, it is difficult to introduce defects precisely aligned with other integrated optical components (e.g. ridge waveguides used for light in/out coupling). E-beam lithography [8] is the most popular method for fabricating PCS. It is very precise (typical resolution 5 nm) but it is serial, hence slow, and needs proximity correction. For large design areas, stitching errors may become noticeable. Usually it is necessary to transfer the pattern from resist to another material, more resistant to reactive ion etching (RIE). FIB has been applied for bulk micromachining of macroporous silicon in order to fabricate 3D Yablonovite-like photonic crystals [9]. Here we apply FIB for planar definition of patterns. FIB has a resolution close to E-beam, and does not need proximity correction if used on conducting surfaces. Moreover, it provides direct transfer of the pattern into an etch resistant mask (metal) and can be integrated with conventional optical lithography.
Practical photonic crystal-based photonic integrated circuits would contain both broad and fine features: waveguides (few millimeters long and microns wide) and fiber coupling sections on the one hand and photonic crystal arrays (with lattice constants around 500 nm) on the other hand.

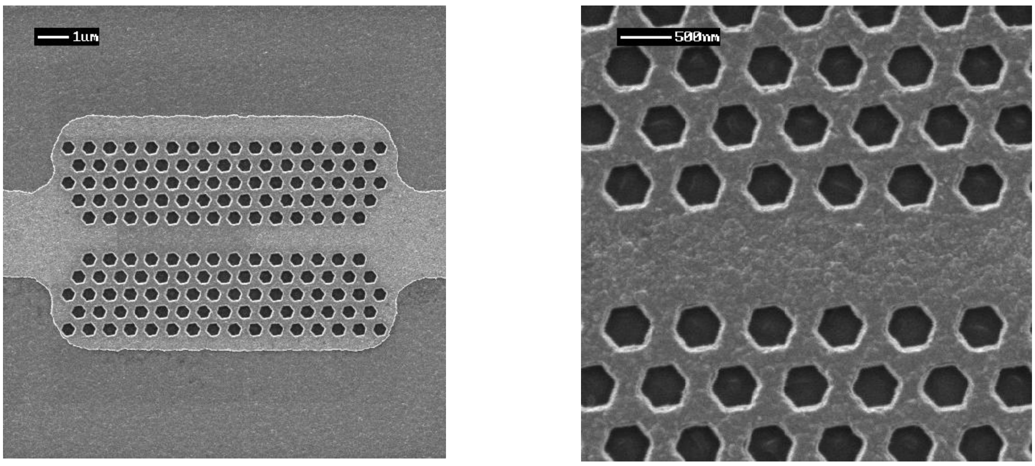

FIG. 4 Left panel: FIB-etched hexagonal-type photonic crystal pattern, aligned with waveguide pattern defined by conventional lithography in chromium. Right panel: detailed view.

Writing the broad features using E-beam is expensive and time-consuming, especially from the replication point of view. Broad features can be easily and fast transferred to the wafer level by using optical lithography. Photonic crystals for optical frequencies require nm resolution, which can be obtained with FIB. In our view, the combination of moderate resolution optical lithography and FIB etching provides an excellent tool for fast prototyping of PCS-based devices.

Figure 4 shows a structure where a conventional mask with about 1 μm resolution defines the dielectric waveguides and areas where PhC's will be defined in a metal layer. The arrays of sub-micron holes are etched into the metal with FIB, aligned (using FIB imaging) with the coarse metal pattern. The figure shows that FIB resolution is suitable for defining non-circular holes.

Conclusions

Hexagon-type PCS's provide a larger bandgap than the circular-type. FIB provides the necessary resolution for fabricating them and aligning the hole arrays with dielectric channel waveguides. Thus combining conventional lithography and FIB provides a suitable prototyping tool.

Acknowledgements

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