Planar photonic crystal.

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Abstract. We present results of guiding light in a single-line-defect planar photonic crystal (PPC) waveguide with 90° and 60° bends. The wave guiding is obtained by total internal reflection perpendicular to the plane of propagation and by the photonic band gap for the 2D photonic crystal in the plane. The results for photonic waveguiding are shown and demonstrated at 1.5 μm wavelength.

INTRODUCTION

Waveguiding in planar photonic crystals (PPC) may enable a new class of integrated optical components for optical telecommunications. First attempts at planar waveguides in PPCs without a defect were shown by Baba[1] and with a defect by Tokushima [2]. In this second case, factors such as the large waveguide thickness, the choice of the pitch, diameter of holes and the wavelength at 1.55μm, cause the guiding to occur in the silica slab and not in the photonic crystal waveguide. Our research is focussed on finding the right parameters for the silicon slab thickness, the lattice constant, the diameter of holes to guide light in a photonic crystal waveguide at 1.5 μm. We use the MIT program "mpb" which solves the Maxwell equations in the frequency domain.

This investigation is divided into two parts:

- The first is the study for the determinations of the thickness of the silicon slab with holes for triangular and rectangular lattices in order to optimize the photonic band gap. Johnson et al[3] have done this study for the radius of holes equal 0.45*a and find that the thickness of slab must be equal to 0.5*a in order to have a maximum gap size (for modes with even symmetry), where "a" is the lattice constant".

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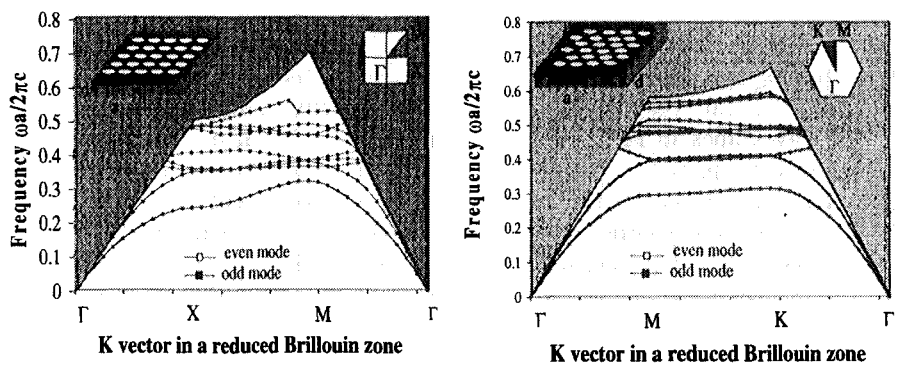
- The second part is devoted to the study of waveguiding by introducing a line defect in the PPC. We calculate the dispersion curves in the photonic band gap to determine which guided modes exist. We will present the confinement of the electromagnetic field in the line defect of the PPC for these guided modes. We will describe the fabrication of the planar circuit on SOI (Silicon on insulator), the experimental setup and the results for guiding light in the line defect with 90° and 60°degree bends in the PPC.

MODELING

Planar photonic crystals

Determining the appropriate design parameters of photonic crystal components is the first critical step. We have studied the band structure for several thicknesses of the silicon slab (index n=3.5) with holes in triangular and square lattice symmetry. The maximum opening of the band gap is obtained for the ratio (radius/lattice constant) r/a=0.45. In the present study we have chosen to investigate the band structure for r/a=0.4 taking into account the practical limitations of nanolithography. Modeling results for triangular and rectangular lattice are shown figure 1: The optimal thickness d, given in terms of the pitch, of the PPC and for the ratio r/a=0.4 is d/a= 0.55. This ratio is the same for triangular and square lattices.



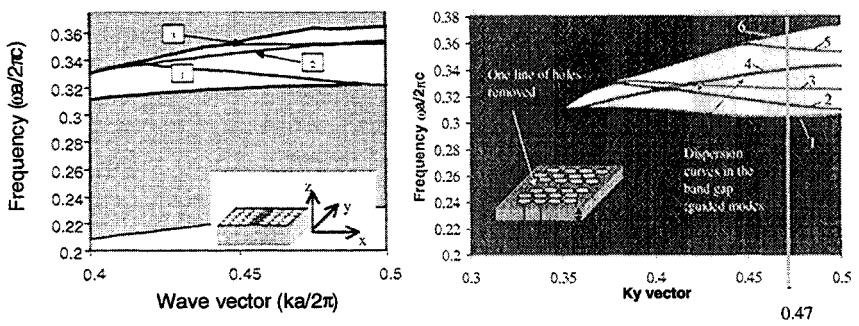
a) b)

FIGURE 1:
a) Band diagram for a square lattice of holes in a thin silicon slab (d/a = 0.55 r/a = 0.4).
b) Band diagram for a triangular lattice of holes in a thin silicon slab (d/a = 0.55 r/a = 0.4)

The optimum parameters for the silicon slab with holes in order to maximize the band gap of the PPC are d/a=0.55 r/a=0.4 using an index for Si of n=3.5.
Next, we introduce a line defect in the periodic structure to find the guided modes.

Properties of a line defect in PPCs

In the second part of the present work we studied line defects in the PPC slab in silicon. We remove one line of holes in the square and triangular lattice pattern of the PPC and obtain the results shown in figure 2 a) and 2 b). We choose to work in the first photonic band gap region (even mode) for the frequency $\omega a/2\pi c$ = 0.33. For λ = 1.5 μm, in which case we determine the design parameters to obtain waveguiding to be a=0.5 μm, d= 0.275 μm and r = 0.2 μm for n=3.5. For the curves in the figure 2a) the curve n°1 is a refractive-like mode of propagation, 2 and 3 are diffractive-like modes[4] with a group velocity close to zero. For the triangular lattice (figure 2 b) all modes except the one in the middle of the band gap (green curve n°3) are refractive-like modes of propagation.



a) b)

FIGURE 2:
a) Dispersion curve in the photonic band gap for line defect waveguide in the square lattice.
b) Dispersion curve in the photonic band gap for line defect waveguide in the triangular lattice.

The MIT code "mpb" allows to calculate the mode field distribution in the line defect waveguide of the PPC, figure 3 shows the cross section used for the calculation.

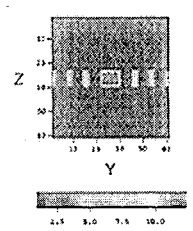


FIGURE 3: Dielectric function (cross section in the Y-Z plane). In the center of the picture we see the wave guiding line defect with the photonic crystal structure on either side.

The distribution of the mode field for $k_y = 0.47$ for each of the modes in figure 2 b) is shown in figure 4.

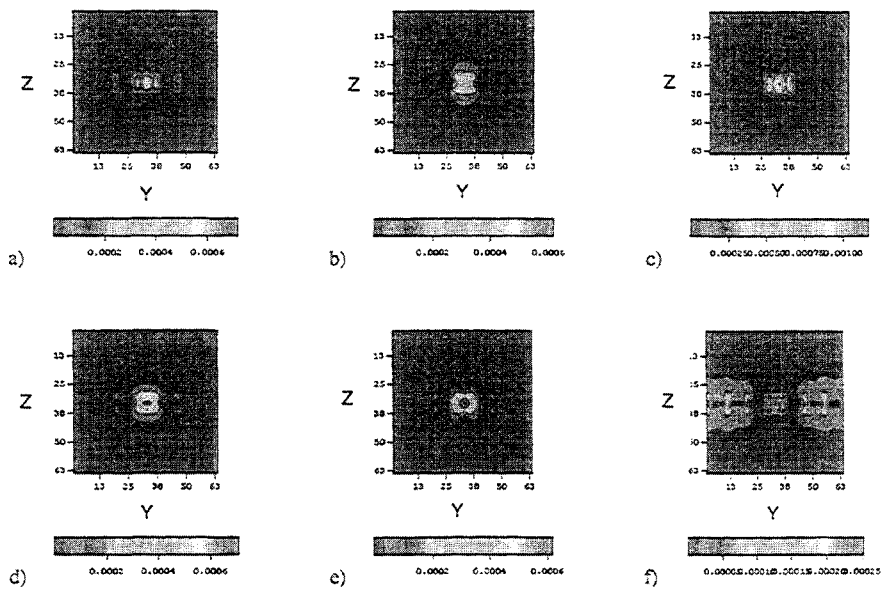


FIGURE 4: Power distribution of the electromagnetic field calculated for the vector $k_y = 0.47$ for the dispersion curves figure 2 b):

- a) corresponds to curve #1, i.e. the lower border of the band gap in figure 2 b).
- picture b) corresponds to the second dispersion curve #2
- The field in the picture c) corresponds to the third curve in the figure 2 b) etc…

The field is well confined when the dispersion curve is far from the edge of the band gap. This is the case for the fields in b), c), and d). For the curve figure 2 b) close to the band edge the field is partially confined in the slab of PPC. In that case we have leaky modes of propagation.

Fabrication

The process of fabrication is shown figure 5. A silicon-on-insulator substrate is used to build the PPC. Oxidization of the silicon layer and etching in hydrofluoric acid are used to obtain the desired thickness of silicon. E-beam lithography is done using a PPMA layer deposited on the silicon layer. Reactive Ion Etching (RIE) transfers the mask pattern to the silicon. The sacrificial silica layer is removed by etching in hydrofluoric acid.

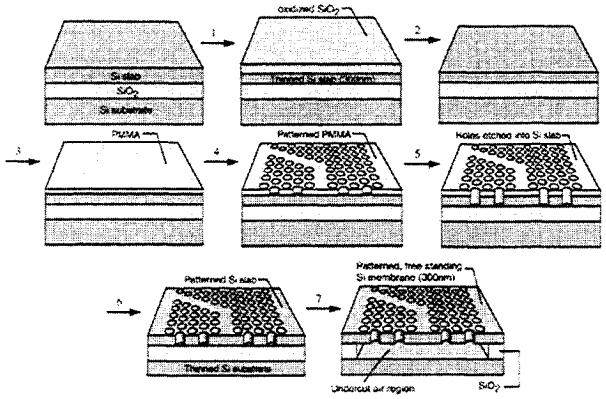


FIGURE 5: Fabrication process for Planar Photonic Crystals.

Experimental setup

The experimental setup used to characterize waveguiding in the line defect in the PPC at 1.5 μm is shown figure 6. Light is coupled into the planar component by means of a single mode fiber, the visualization of the scattered field from the top of the sample is obtained with an IR camera through a microscope.

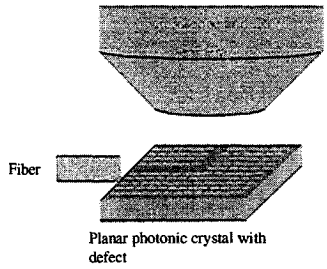
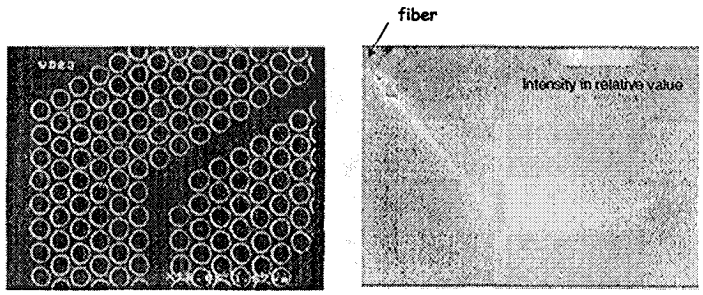


FIGURE 6: Experimental setup

Results

60° turn

Using the setup above, we examined the light scattered in 60°-turn as shown in figure 7. We see that light is guided in the straight line defect of the PPC, and that enhanced scattering occurs in the bend itself as the structure represents a cavity.



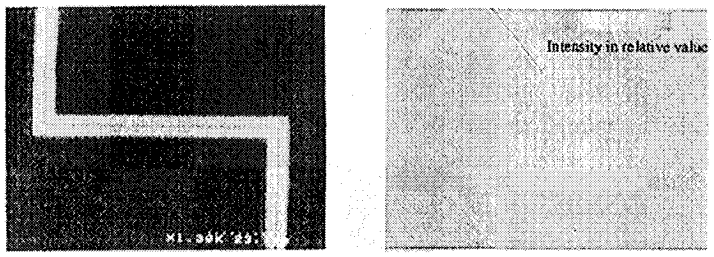
Top view

Total length of guide
300μm

Figure 7: Top view of 60° bend on the left side and guided light by leaky mode on the right side.

90° turn

We see the guided light in the waveguide with two 90°-bends. The scattered field decreases after each turn and stays constant along the straight waveguide. It is clear we have losses in the bend (right side of the Figure 8).



top view

top view of the scattered light

λ = 1500nm

Total length of the guide
~200 μm

Figure 8: Top view of two 90° bend (left) and scattered guided light by leaky mode (right)

Output field

An additional IR camera is placed at the output of the waveguide. We see that the scattered light is reduced when the coupling between the fiber and the waveguide optimizes the transmitted signal at B (see figure 9). In that case, light is guided in the confined mode of propagation. When we shift the fiber output far from the waveguide, the light propagates through the slab, and we see that the output spot of the field in B disappears.

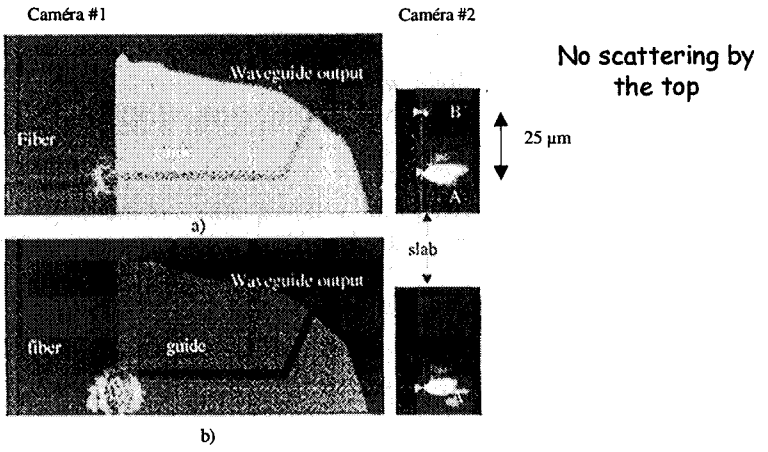


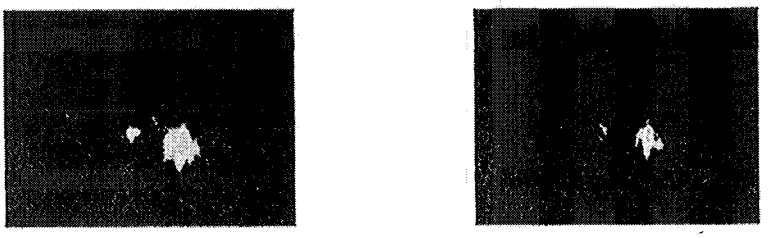
Figure 9:

a) Top view of the sample and the fiber with the first IR camera and side view of the output field with second IR camera . The output field appears in B when the coupling between the mode field of fiber and the mode of waveguide is optimized.

b) Top view of the sample and the fiber with the first IR camera and side view of the output field with second IR camera . The output field disappears in B when the coupling is frustrated.

Polarization

According to figures 1b and 2b only even (TE) modes can propagate in the photonic crystal. This is confirmed by measurements of the output intensity as a function of the polarization of the light launched into the waveguide (figures 10 a and b).



TE mode TM mode

a) b)

Figure 10:

a) signal A and B of the figure 9 with polarizer between the output signal and the camera 2 TE mode analyzed.

b) signal A and B of the figure 9 with polarizer between the output signal and the camera 2 TM mode analyzed.

Conclusions

We have demonstrated guided light wave propagation by a line defect in a planar photonic crystal having 90° and 60° degree sharp bends. Guiding of light has been observed in both leaky (figure 7 & 8) and well-confined modes (figure 9).

Theoretical results given by solving Maxwell's equations in the frequency domain show three guided confined modes introduced by removing one row of holes.

Fabrication of planar photonic crystals has been achieved using E-Beam lithography and Reactive Ion Etching.

Measurements of the variation of the output signal as function of the polarization and coupling demonstrate that low-loss guiding by a confined mode of TE-like symmetry can be achieved.

References:

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