American Journal of Applied Sciences 7 (1): 77-80, 2010
ISSN 1546-9239

Design and Optimization of a 1.55 µm Waveguide Based on Silicon Planar Photonic Crystals

[1]R. Bchir, [1]A. Bardaoui, [2]M. Machhout, [1]R. Chtourou and [1]H. Ezzaouia
[1]Laboratory of Photovoltaic, Semiconductors and Nanostructures, Energy Center (CRTEn), Route Tourisitique Soliman, BP 95 Hammam-Lif 2050, Tunisia
[2]Laboratory of Electronic and Microelectronic, Faculty of Sciences of Monastir, Tunisia

Abstract: Background: Silicon based Planar Photonic Crystals (PPC) are used for the design of a 1.55 µm waveguide. Line defects are then formed in the PPC structures, by removing rows of holes, to obtain a Planar Photonic Crystal Waveguide (PPCW). **Objective:** First, we varied the thickness of the Silicon slab and the pore radius in order to obtain optimum design parameters leading to a large and complete bandgap. Next, we present a study of the guided modes in the PPCW for different widths of the waveguide by removing 1, 2 and 3 rows (W1, W2 and W3) of holes from the crystal. **Methodology:** Band structure calculations were performed using a block-iterative frequency-domain code to find the design parameters of both triangular and square photonic crystal slab lattices of air holes. The frequency domain method for Maxwell's equations in a plane-wave basis was used to calculate the dispersion relations for the guided modes for several widths of the waveguides. **Results:** The structure with the larger width has a much more complicated dispersion diagram. The most important difference between the three structures (W1, W2 and W3) is that in the case of the wider waveguide, several modes exist at all bandgap frequencies. **Conclusion:** The structures with a single line defect (W1), there are no leaky modes in the frequency range in which modes become guided. This result indicates that this structure is most preferable.

Key words: Planar Photonic Crystal (PPC), band structure, Planar Photonic Crystal Waveguide (PPCW), guided modes

INTRODUCTION

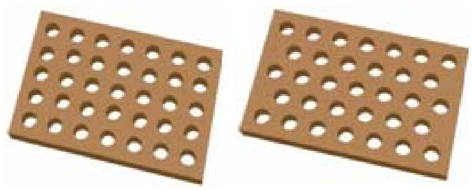
In most previously published study, Two Dimensional (2-D) silicon based photonic crystals have been extensively studied, both theoretically and experimentally (Jamois *et al*., 2002). In these structures, the dielectric constant is periodic in one plane (usually defined as the xy plane) and extends infinitely in the third direction (z direction). For light propagating in the plane of periodicity of the 2D PC, the polarizations decouple: either the electric field is aligned along the pores (E-polarization or Transverse Magnetic (TM)), or the magnetic field is in the direction of the pores (H-polarization, Transverse Electric (TE)) (Johnson *et al*., 1999). Now, we will carry that idea one step further, by studying structures with two-dimensional periodicity but a finite thickness. Such hybrid structures are known as photonic crystal slabs or planar photonic crystals (Kuchinsky *et al*., 2000).

This study is presented as follows: We will study two basic topologies: Square and triangular lattices of air holes in a dielectric medium. We will show that such structures can have a Photonic Bandgap (PBG) and we will vary the thickness of the Silicon slab and the pore radius to obtain the largest possible bandgap. Next we will consider a linear defect in the form of a missing row of holes in the slab and we will show that there are localized modes associated with the defect; these modes are localized both in the plane and out of plane.

MATERIALS AND METHODS

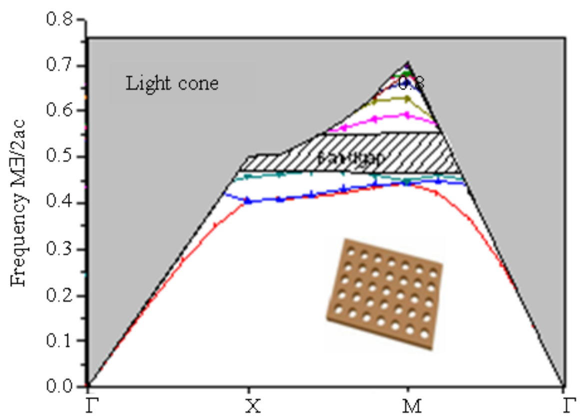
Planar Photonic Crystal (PPC): We start with a theoretical analysis of the band structure for both square and triangular lattices photonic crystal slabs (Fig. 1) in order to find the design parameters, such as the interhole spacing (a), the hole radius (r) and the slab thickness (h). The structure that we analyze combines two dimensional periodicity confinement (in the xy directions) and index guiding in the vertical (z) direction.

Corresponding Author: R. Bchir, Laboratory of Photovoltaic, Semiconductors and Nanostructures, Research and Technology Center of Energy (CRTEn), Route touristique Soliman, BP 95 Hammam-Lif 2050, Tunisia

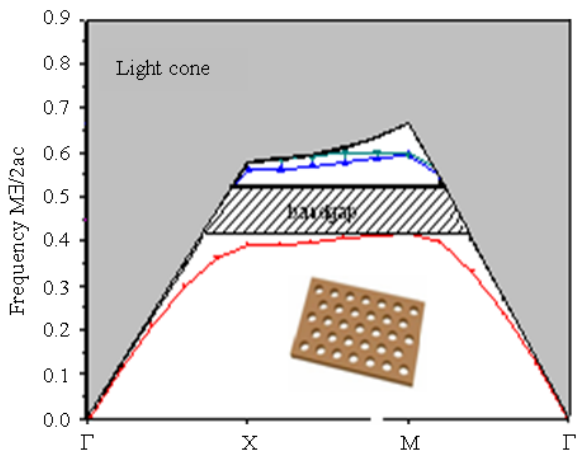


(a) (b)

Fig. 1: Examples of photonic crystal slabs. (a) A square lattice of air holes in dielectric (b) a triangular lattice of air holes in dielectric



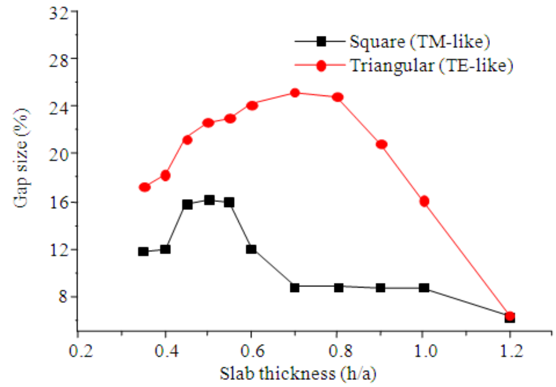
(a)



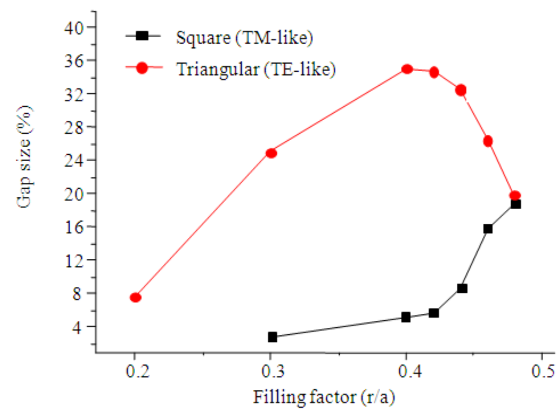
(b)

Fig. 2: Band diagrams for photonic crystal slabs (a) TM-like (odd) modes for a square lattice (b) TE-like (even) modes for a triangular lattice

The symmetry of the lattice (triangular and square) plays a crucial role to determine properties of the PPCs. Due to the periodicity of the lattice, frequency bandgaps for guided modes are opened and light of certain frequencies cannot propagate in the PPCs.



(a)



(b)

Fig. 3: Gap size versus (a) slab thickness (b) filling factor for both a square lattice and a triangular lattice

In Fig. 2, we present the projected band diagrams for both structures: square and triangular lattices of air holes in dielectric with a slab thickness h = 0.5a and a pore radius r = 0.46a. The extended modes propagating in air form a light cone for $\omega \geq c\,|\,k_{||} = (k_x, k_y)|$. Below the light cone, the higher dielectric constant of the slab has pulled down discrete guided bands. Eigenstates in these bands decay exponentially in the vertical direction (away from the slab).

We can classify the modes as TE-like and TM-like. The square slabs favor a TM-like gap and the triangular slabs favor a TE-like gap. For this reason only TM-like (odd) and the TE-like (even) modes are shown for a square and triangular lattices respectively (Fig. 2). We can explain this behavior by the fact that in the case of a square lattice, the TE-like modes are forced to penetrate the low-ε regions since the field lines had to be continuous. This problem disappeared for the triangular lattice, since the fields could follow the high-ε paths from site to site (Joannopoulos *et al*., 2008).

To obtain the optimal thickness and optimal radius, we have varied the silicon slab thickness and the pore radius. We define the gap-midgap ratio (gap size) as $\Delta\omega/\omega_0$ with $\Delta\omega$ as the gap width and ω_0 as the frequency at the middle of the gap. Figure 3a shows the gap sizes of the square and triangular slabs structure as a function of the slab thickness with a pore radius r = 0.46a. In both cases the results of the optimization thickness in the even/odd guided modes are h = 0.7a and h = 0.5a respectively. If the slab is too thick, then higher-order modes can be created with little energy cost by adding horizontal nodal planes. If the slab is too thin, then the slab will provide only a weak perturbation on the background dielectric constant (Joannopoulos *et al*., 2008).

On the other hand, Fig. 3b shows a graph of the band gap size as a function of the pore radius for the square and the triangular structures.

The existence of an optimal thickness for each slab can be easily seen. For the triangular lattice slab the optimal pore radius is r = 0.41a and for the square structure the optimal pore radius is r = 0.48.

RESULTS AND DISCUSSION

Waveguide design: A waveguide is generally intended to transport waves of a particular frequency from place to place along one direction. By introducing a linear defect into the periodic structure, we can create a waveguide mode that propagates along the defect. Photons having energy within the gap can now propagate only along this line defect. The localization of the waveguide mode relies on both the band gap within the plane of periodicity and also on index guiding in the vertical direction and this will restrict the kinds of modes that we can guide (Loncar *et al*., 2001). If we want our operating wavelength $\lambda = 2\pi c/\omega = 1.55$ µm to lie at the middle of the gap we need $\omega a/2\pi c = f0 = a/\lambda$ $a = f0*\lambda$. Once we've found the optimal design parameters h/a and r/a corresponding to a maximum bandgap for each structure and given a, we can calculate the radius (r) and the thickness (h).

In this part, we have used the results summarized in the Table 1 as design parameters of the waveguide.

We present a study of the guided modes in the PPCW for different widths of the waveguide by removing 1, 2 and 3 rows of holes from the crystal. The waveguide width values are mentioned in Table 2. It is then convenient to present the projected band diagram for the different line defect widths (Fig. 4) in the ΓX direction for the square lattice and ΓJ direction for the triangular lattice.

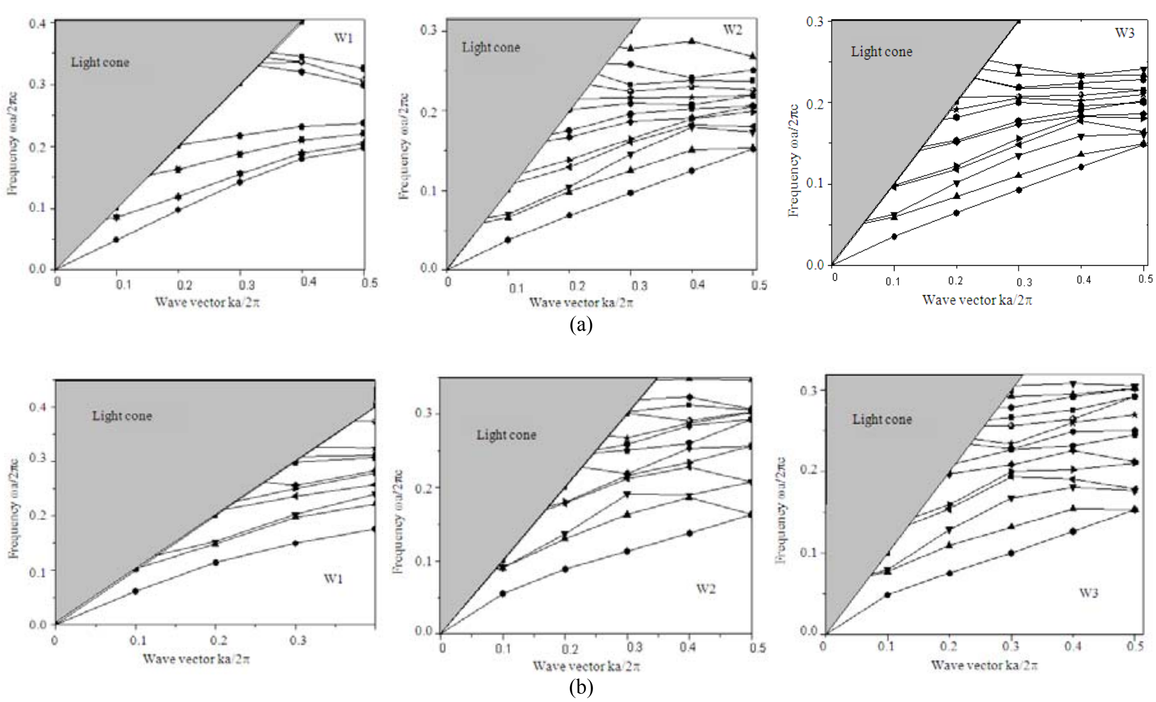


Fig. 4: Projected band diagram for different waveguide widths (a) square lattice; (b) triangular lattice

Table1: Optimized design parameters of a photonic crystal lattice of air holes for a photonic bandgap centered around 1.55 μm

Lattice type	Bandgap width	Midgap frequency f_0	$a = f_0*\lambda$ (nm)	Design parameters r (nm)	h (nm)
Triangular	0.110	0.45	698	r = 0.41a = 286	h = 0.7a = 488
Square	0.082	0.51	790	r = 0.48a = 379	h = 0.5a = 395

Table 2: The waveguide widths for square and triangular lattices

Lattice type	W1 (nm)	W2 (nm)	W3 (nm)
Triangular	637	1241	1845
Square	824	1522	222

This waveguide is a hybrid one : In the out of plane dimension (z direction), guided modes can be confined due to the total internal reflection, while in the plane of the photonic crystal (x,y), light can be confined by means of both the total internal reflection and diffraction by the photonic crystal structure.

In the Fig. 4, the straight solid line represents the light line. The modes above the light line, in the light-gray region, will leak energy into the air (leaky modes).

It is clear that the structure with the larger width has a much more complicated dispersion diagram. The most important difference between the three structures (W1, W2 and W3) is that in the case of the wider waveguide, several modes exist at all bandgap frequencies. On the other hand, in the structures with a single line defect (W1), there are no leaky modes in the frequency range in which modes become guided. It is important to notice the appearance of an anti-crossing (two bands that are expected to intersect will instead couple to one another and then repel) that yields to mini stop bands open for $ka/2\pi = 0.5$ (Joannopoulos *et al*., 2008; Loncar *et al*., 2001).

We also remark that all photonic bandgap guided modes (below the light line and inside the bandgap) has an almost flat dispersion relation. Therefore these modes will have small group velocities and will be able to guide light only in a very narrow frequency range (Loncar *et al*., 2001).

CONCLUSION

Silicon based Planar Photonic Crystals (PPC) are used for the design of a 1.55 μm waveguide. Two different silicon Planar Photonic crystal geometries have been analyzed. The triangular lattice favors a TE-like mode and the square lattice favors a TM-like mode. Line defects are formed in the PPC structures, by removing rows of holes, to obtain a Planar Photonic Crystal Waveguide (PPCW). We have shown that a line defect supports both diffractive and refractive modes in its band gap. The frequency domain method for Maxwell's equations in a planewave basis was used to calculate the dispersion relations for the guided modes for several widths of the waveguides.

ACKNOWLEDGMENT

The researchers are very grateful to the MIT Abinitio group for allowing the use of their computation package.

REFERENCES

Jamois, C., R.B. Wehrspohn, J. Schilling, F. Müller, R. Hillebrand and W. Hergert, 2002. Silicon-based photonic crystal slabs: Two concepts. IEEE J. Quantum Elect., 38: 805-810.

Johnson, S.G., S. Fan, P.R. Villeneuve and J.D. Joannopoulos, 1999. Guided modes in photonic crystal slabs. Phys. Rev. B., 60: 5751-5758.

Kuchinsky, S., D.C. Allan, N.F. Borrelli and J.C. Cotteverte, 2000. 3D localization in a channel waveguide in a photonic crystal with 2D periodicity. Opt. Commun., 175: 147-152.

Joannopoulos, J.D., S.G. Johnson, J.N. Winn and R.D. Meade, 2008. Photonic Crystals Molding the Flow of Light. 2nd Edn., Princeton University Press, ISBN-10: 0691124566 pp: 304.

Loncar, M., J. Vuckovic and A. Scherer, 2001. Methods for controlling positions of guided modes of photonic-crystal waveguides. J. Opt. Soc. Am. B., 18: 1362-1368.