Modeling of photonic band gap in two dimensional photonic crystals made by sol gel process

A. Kahlouche[1,*], A. Hocini[1,2], A. Mezache[1] , D. Khedrouche[1] ,M. Bouchemat[2], F.Royer[3] and J.J.Rousseau[3]

[1] *Département d'Electronique, Faculté de Technologie Université de M'sila, BP.166, Route Ichebilia, M'sila 28000 Algeria.*

[2] *Laboratore Micro système et Instrumentation, Université Mentouri Constantine, Algeria.*

[3] *Laboratoire Telecom Claude Chappé (LT2C)A 3523, Université Jean Monnet, 25, rue du Dr Rémy ANNINO 42000 St Etienne Cedex 2, France*

[*] *kahlouche_ahmed@yahoo.fr*

Abstract: Photonic band gap of two dimensional photonic crystals fabricated by SiO_2/ZrO_2 or SiO_2/TiO_2 with sol-gel process in which the refractive index varied in the range of 1.51 to 1.57 has been investigated in the present paper. The structure studied consists of circular air holes of radius r embedded in matrix, while a is the constant of triangular lattice.
Finite difference time domain method (FDTD) with perfectly matched layers (PML) was used to calculate the transmission spectrum by FullWAVE software. The results of simulation clearly demonstrate the existence of photonic band gap of which the position and the width are strongly affected by refractive index. In the other hand, the effects of geometric parameters (air hole radius r and lattice period a) on the photonic band gap have been investigated in this work.

Key words: 2D photonic crystals, low contrast, FDTD, photonic band gap, sol-gel process.

Introduction

Photonic crystals (PhCs) are artificial materials in which the dielectric constant ε (the refractive index n=) has a periodicity in one, two or three dimensions. They are called one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) photonic crystals respectively. Since the introduction of the concept of photonic crystals by E.Yablonovich [1] and S.John [2], they have attracted much interest due to their potential for controlling the propagation of light for its photonic band gap (PBG) and/or light diffraction properties [3-4].
In recent years, 2D (PhCs) composed of air holes drilled in a dielectric slab and structured in a triangular lattice are most commonly used due to the difficulty in the fabrication of other types of photonic crystals (3D). In the other hand, 2D photonic crystals have a great ability for integration [3]. Consequently, they have been widely studied and analyzed as the building blocks to realize functional devices for optical networking [3], waveguides [5-6], photonic crystal fibers [7], photonic cavities [8-9], and optoelectronics applications. Generally, in the optical and near-IR regions of the spectrum it is important to start with computational and modeling of design and properties before the fabrication processes because photonic crystals are expensive. In the first part of this work, we have demonstrated the existence of photonic band gap in 2D photonic crystals fabricated with SiO_2/ZrO_2 or SiO_2/TiO_2 made by sol-gel process [10], this later is characterized with low refractive index which varied in the range of 1.51 to 1.57 at λ=1.55µm [11]. In the second part, we have investigated the effects of the contrast and the geometrical parameters (lattice period and air hole radius) on the photonic band gap variations.
Fullwave is a simulation engine which calculates the electromagnetic field as a function of time and space in a given index structure in response to a given electromagnetic excitation. Fullwave is ideal for studying the propagation of light in a wide variety of photonic structures. In this work, the simulation engine is based on the well-known finite difference time domain method (FDTD) with perfectly matched layers (PML) in order to calculate the transmission spectrum [12].

I. Structure

The 2D photonic crystal to be studied and analyzed in the present paper consists of 33x33 array of circular air holes of radius r=0.27µm which are structured in triangular lattice of period a=0.75µm. However, the triangular lattice is very suitable to studying photonic band gap properties. The triangular lattice allows the opening of 2D photonic band gap, presents a good compromise namely for high felling factors and it's

lowly sensitive to the incidence angle compared to the square lattice [13-14].

The studied structure is showed in Figure 1, where the air holes (n=1) are embedded in a SiO_2/ZrO_2 or SiO_2/TiO_2 dielectric. The later is characterized by the background index varying in the range of 1.51 to 1.57.

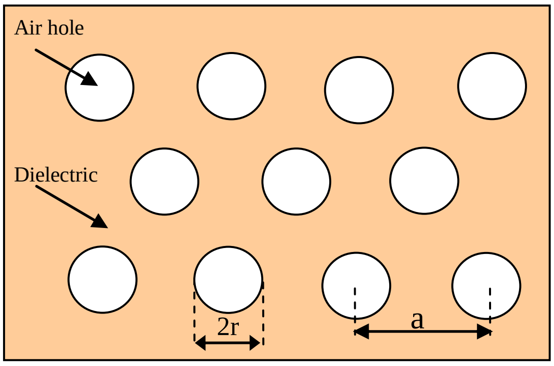

Fig.1.Connected structure of 2D photonic crystal made with air holes in dielectric.

In this study, the triangular lattice was created using the array layout XZ utility. The different results of transmission spectrum obtained show that 2D photonic crystal characterized with low contrast present a photonic band gap only for TM polarization (transverse magnetic) and no band for TE polarization (transverse electric).

II. Effect of refractive index

In this section, we will discuss the conditions of opening a photonic band gap in 2D photonic crystals described in previous section and the variations of its position and size as a function of refractive index.

The simulations are based on the well known finite-difference time-domain (FDTD) technique. Firstly, before any simulation we are fixed geometrical parameters (a=0.75µm and r=0.27µm). After that, we calculated photonic band gap width for each value of refractive index. All results demonstrate clearly the existence of TM band gap.

Figure 2 shows the effect of refractive index on the width of the photonic band gap characterized with feeling factor r/a=0.36. Furthermore, from results we can conclude that the width of photonic band gap is strongly influenced by refractive index. The width $\Delta\lambda$ (µm) was increased from $\Delta\lambda$=0.0609µm, for low index (n=1.51), to $\Delta\lambda$=0.0942µm, for high index (n=1.57). Either the largest band gap, the high refractive index it is. Which agree with other studies concerning other materials [15-16].

In the second part, the finite difference time domain method FDTD is used to simulate the transmission spectrum for different values of refractive index.

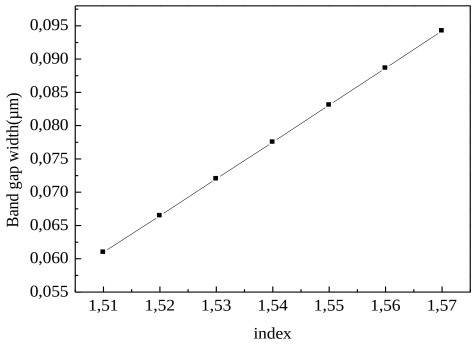

Fig.2.Variation of the TM photonic band gap with refractive index for r/a=0.36.

Figure 3 reports the simulations for three values of refractive index: n=1.51, n=1.54 and n=1.57. The results show that the largest band gap was found around telecommunications wavelength 1.55µm, it extends from λ_{min}=1.510µm to λ_{max}=1.604µm. In the other hand, we have found that more refractive index increases the band gaps shifts towards the higher wavelengths, and the midium wavelength $\lambda_0=(\lambda_{min}+\lambda_{max})/2$ varied from λ_0=1.521µm to λ_0=1.557µm.

Finally, we can conclude that the increasing of refractive index from 1.51 to 1.57 induced more increasing in the width. Consequently, the refractive index was fixed at 1.57 for different transmission spectrum simulations in the following sections.

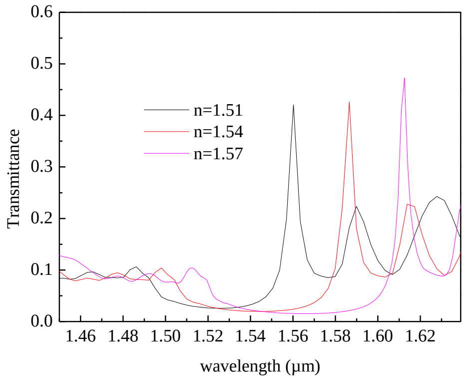

Fig.3.Transmittance versus wavelength for different value of index of 2D photonic crystal for r/a=0.36.

III. Effect of lattice period

In the following section, we consider the structure described in figure 1 which is formed by 33x33 triangular array, the air hole radius was fixed at r=0.27µm and the background index used in all simulations is n=1.57. Then we simulate the transmission spectrum for different lattice periods.

Figure 4 reports the variations of the photonic band gap width as a function of the lattice period a.

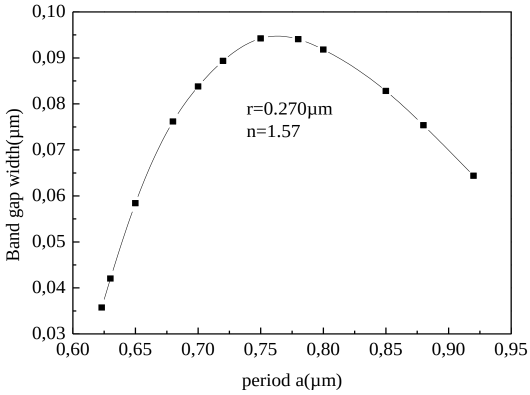

Fig.4. Band gap width as a function of lattice period of 2D photonic crystal for n=1.57 and r=0.27µm.

From results we can observe that the band gap was opened from a=0.623µm and disappears from a=0.92µm, between the two values of period the size of photonic band gap was varying like as a Gaussian function with lattice period a. In the other hand, the bandwidth is maximum for a=0.75µm ($\Delta\lambda$=0.0942µm) and the photonic band gap extends from λ_{min}=1.510µm to λ_{max}=1.604µm (Figure 3 for n=1.57).

Figure 5, shows the results of transmission spectrum simulated by finite difference time domain method (FDTD) in Fullwave of TM mode for three values of period: a=0.7µm, a=0.75µm and a=0.8µm.
The results demonstrate clearly that more the lattice period increases, the photonic band gap shifts towards the higher wavelengths, and the medium wavelength $\lambda_0=(\lambda_{min}+\lambda_{max})/2$ increases from λ_0=0.078µm for a=0.7µm to λ_0=0.0918µm for a=0.8µm.

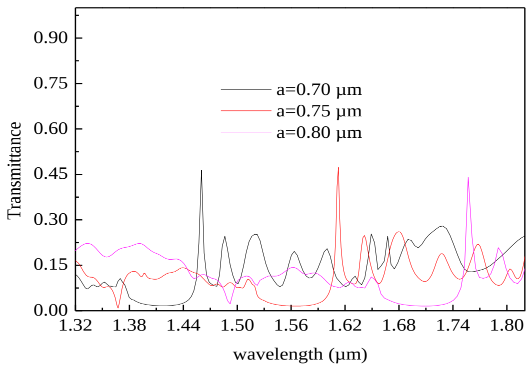

Fig.5.Transmittance versus wavelength for different value of lattice period of 2D photonic crystal for n=1.57 and r=0.27µm.

IV. Effect of air hole radius

In order to study and analyze the effect of air hole radius on the variations of photonic band gaps of 2D photonic crystals characterized with low contrast and structured in triangular lattice, we consider the structure shown in figure 1 which is characterized with a lattice constant a=0.75µm and a refractive index n=1.57. After that, a series of simulations of spectrum transmission for different values of radius from r=0.223µm to r=0.325µm were carried, then we calculate the band gap width for each radius. The results show that photonic band gap exists only for TM polarization (transverse magnetic), the band gap width is maximum for r=0.27µm (r/a=0.36).
In figure 6, we have reported the variations of the bandwidth as a function of air hole radius for a lattice period a=0.75µm and a refractive index equal 1.57.

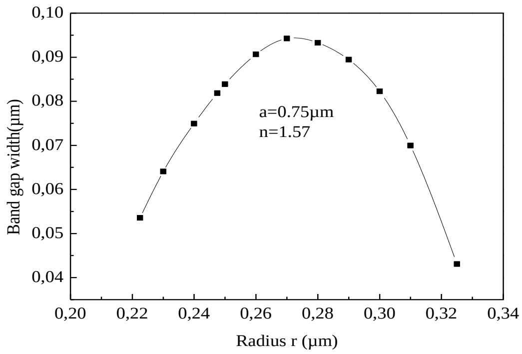

Fig.6. Band gap width as a function of air hole radius of 2D photonic crystal for n=1.57 and a=0.75µm.

The simulation of the transmission spectrum by finite difference time domain method (FDTD) of TM mode (transverse magnetic) for three values of radius r=0.23µm, r=0.27µm and r=0.32µm were reported in figure 7. They occur that more radius increase the photonic band gaps shift towards the lower wavelengths where the medium wavelength λ_0 varied from λ_0=1,645µm for r=0.23µm to λ_0=1,436µm for r=0.32µm.

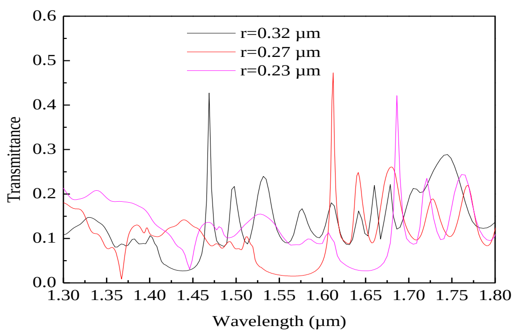

Fig.7.Transmittance versus wavelength for different value of air hole radius of 2D photonic crystal for n=1.57 and a=0.75µm.

V. Conclusion

Photonic band gap of two dimensional photonic crystals made with SiO_2 / ZrO_2 or SiO_2 / TiO_2 and characterized by low refractive index which change in the range of 1.51 to 1.57 have been investigated and reported in the present paper. The different results of simulation obtained by FDTD method in Fullwave software are clearly demonstrated the existence of the photonic band gap of triangular lattice structure which formed by air holes embedded in matrix. Firstly, the results show that the refractive index has a great effect on photonic band gap width. Furthermore, the results show that the geometric parameters (air hole radius “r” and lattice period “a”) have a great influence on the position and the width of photonic band gap. In the other hand, the PBG exist only for radius r varied in the range of 0.223µm to 0.325µm and for period a change in range of 0.623µm to 0.92µm. Thus we reveal that a maximum absolute band gap for this structure is achieved for n=1.57,a=0.75µm and r=0.27µm.

Acknowledgment

The authors wish to thank l'Agence Nationale pour le Développement de la Recherche Universitaire (ANDRU).

References

[1] E.Yablonovitch, «Inhibited spontaneous emission in solid-state physics and electronics» Phys. Rev. Lett. **58,** 2059-2062,(1987).

[2] S.John, «Strong localization of photons in certain disordered dielectric superlattices», Phys. Rev. **58,** 2486-2489,(1987).

[3] J-M. Lourtioz et al., «Photonic Crystals», Ed. Springer, 2005.

[4] E. Yablonovitch, «Photonic band-gap structures », J. Opt. Soc. Am. B., vol. 10, No 2, February 1993.

[5] M. Loncar, D. Nedeljkovi, T. Doll, J. Vuckovic, A. Scherer, and T. P. Pearsall, «Waveguiding in planar photonic crystals», Appl. Phys. Lett. 77(13), 1937–1939 (2000).

[6] S. G. Johnson, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and L. A. Kolodziejski, «Guided modes in photonic crystal slabs», Phys. Rev. B 60, 5751–5758 (1999).

[7] J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, «All-silica single-mode optical fiber with photonic crystal cladding», Opt. Lett. 21, 1547–1549 (1996).

[8] J.D. Joannopoulos, R.D. Meade, J.N. Winn, «Photonic Crystals: Molding the Flow of Light», Princeton University Press, Princeton, NJ, USA, 1995.

[9] O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O’Brien, P. D. Dapkus, and I. Kim, «Two dimensional photonic band-gap defect mode laser». Science 284, 1819–1821 (1999).

[10] B rinker CJ, Scherer GW. «Sol–gel science: the physics and chemistry of sol–gel processing». London: Academic Press; 1990.

[11] Hadi Amata, François Royer, Fadi Choueikani, Damien Jamon, Jean-Emmanuel Broquin, Jean Claude Plenet, Jean Jaques Rousseau , «Magnetic nanoparticles doped silica layer reported on ion-exchanged glass waveguide: towards integrated magneto-optical devices», Proceedings of SPIE Photonic Europe - Silicon Photonic and Photonic Integrated Circuits vol 7719.

[12] RSoft Design Group, FullWAVE v3.0.1, Inc. 200 Executive Blvd. Ossining, NY 10562.

[13] Weimin Kuang, Zhilin Hou, Youyan Liu and Hai Li, «The bandgap of a photonic crystal with triangular dielectric rods in a honeycomb lattice », J. Opt. A: Pure Appl. Opt. 7 (2005) 525–528

[14] Beghoul M.R., Boudrioua A., Kremer R.,Fontana M., «2D Photonic Band Gap Strucures in LiNbO3: Optimal Design», Microelectronic Engeneering, soumis 2006.

[15] Y. Kalra and R. K. Sinha, «Modelling and design of complete photonic band gaps in two-dimensional photonic crystals», Pramana- J. Phys., Vol. 70, No. 1, January 2008.

[16] K. Inoue, M. Wada, K. Sakoda, M. Hayashi, T. Fukushima, and A. Yamanaka, «Near-infrared photonic band gap of two-dimensional triangular air-rod lattices as revealed by transmittance measurement», Phys. Rev. B 53, 1010–1013 (1996).

