Model of 1D Photonic Crystal Silicon Waveguides by Varying the Lattice Constant in Their Geometry Stucture via FDTD Method, in the Field of Communication Photonics for Telco Purpose

Jamilah Husna[1], Azmi Rizki Lubis[1], Yusniati[1], Ahmad Rifqi Md. Zain[2] and Mohd Ambri Mohamed[2]
[1]*Faculty of Engineering, Universitas Islam Sumatera Utara, Medan, Indonesia*
[2]*Institute of Microengineering and Nanoelectronics (IMEN), Level 4, Research Complex, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia*

Keywords: 1D Photonic Crystal, Waveguide, (FDTD), Wavelength Divisionmultiplexing (WDM), Siliconon Insulator (SOI).

Abstract: The theoretical investigation of tuning a geometry structure of one dimensional (1D) photonic crystal waveguides based on silicon on insulator (SOI) which has been conducted in UKM lab using Crystalwave software (FDTD method) is the object of the research. The lattice distance has been varied from 110 nm up to 165 nm, meanwhile the hole diameter iskept constant at 70 nm. The results show that the main physical effects of the structure of numerical model could be applied towards the total Q factor and the transmission performances and the ultrahigh Q factors reached to 3840 and the transmission obtained up to 65%.

1 INTRODUCTION

Photonics have existed as a new research field for more than ten years. It was founded in the late 1960s, with the purpose of using light to perform functions that traditionally fall into the domain of electronics. Since few years ago, one of the major topics of interest in photonic research is the study and development of micro- and nano-structures for fast signal processing in the telecom window. In addition, due to their unique ability for manipulating photon transmission, we assumed that the photonic crystal (PhCs) will play a significant role in future photonic and optical applications.

The first successful inventions of photonics such as laser diode and optical fibers for long-haul data transmission gave rise to the telecommunication revolution in the end of the 20 century, which, in return, became a strong driving force for further photonic research. With the exception of the past decade, photonics focused mainly at telecom applications. Combining or replacing the electronic circuits by integrated nanophotonic devices should lead to a dramatic increase in the capacity of transmitted data (ultra-high band- width with Wavelength Division Multiplexing) and considerable reduction of the power consumption. Wavelength division multiplexing (WDM) is a technology used for multiplexing signals in optical fibre. The main advantage of the WDM technique in telecommunication is that it allows the capacity of the network to be increased without the need to change the backbone of the fibr network.

This is made possible through implementing WDM and deploying optical amplifier throughout the optical network. The WDM optical spectrum is divided into several distinct wavelengths that do not overlap, and each wavelength corresponds to a single communication channel, thus providing several WDM channels in the same fiber and greatly utilising the fibers huge bandwidth. With such large bandwidth potential, research on WDM devices has increased with the aim of employing WDM-based optical backbones for the Internet. The conventional WDM systems were dual-channel 1.31/1.55 μm systems including both the minimum dispersion window and minimum attenuation window.

The WDM consists mainly of two types: Coarse WDM (CWDM) and Dense WDM (DWDM). In communication systems, WDM devices show the ability to improve coherence without losing the quality of transmission, tightly compact (micrometre scale) and practical to fabricate on integrated optical circuits. This is where photonic crystals have much

Husna, J., Rizki Lubis, A., Yusniati, ., Rifqi Md. Zain, A. and Ambri Mohamed, M.
Model of 1d Photonic Crystal Silicon Waveguides by Varying the Lattice Constant in Their Geometry Stucture via Fdtd Method, in the Field of Communication Photonics for Telco Purpose.
DOI: 10.5220/0008882200460051
In *Proceedings of the 7th International Conference on Multidisciplinary Research (ICMR 2018)* - , pages 46-51
ISBN: 978-989-758-437-4

potential, as PhC-based WDM for different wavelength selective-filterin techniques have been recently realised. Such devices include filter adjacent to waveguides, using coupling techniques (Zimmermann et al., 2004) or cavities (Pustai et al., 2002) for the purpose of achieving PhC-based wavelength multiplexing and demultiplexing.

Photonic crystals (PCs) are artificial structures with a periodic dielectric constant in one, two or three dimensions. They are characterized by photonic band structures owing to the multiple Bragg scatterings (Qin et al., 2003). In 1987 the concept of photonic crystals (PCs) was first proposed by Yablonovitch and John(Yablonovitch, 1987). They found that by using periodic arrangement of dielectric mate-rials which possible for us to control the propagation of the electro-magnetic waves. If this periodic arrangement is on the order of the wavelength of light, then for some range of wavelengtht, it is called Photonic Band Gap, where in this gap light cannot reach the crystal. The propagation of light waves is strongly influenced by the band structures and forbidden in the photonic band gaps (PBG) (Shiveshwari and Mahto, 2006). The propagation of a light wave can be manipulated by PBG. Therefore, many optics effects may be realized in PCs. By introducing defects into the PBG structure, for example, resonance modes or defective modes (Noda et al., 2000).

For the last few years, Photonic crystals (PCs) structures have attracted, and have been the research subjects of growing interests. It is well-known, that the structure is designed to control the propagation of electromagnetic waves in the same way as the periodic potential in semiconductor crystals (Soukoulis, 2006). The dimensional photonic gems have been referred to for quite a few years as Bragg reflects. Impedance of the Bragg disseminating is considered as a reason for the Bragg hole or band hole. The periodicity makes the band holes rely upon a few parameters, as the dielectric differentiate between the utilized materials, and the filling component of the rudimentary cell. Valuable property is owned by one gem photonic structure (1D-PC), which is utilized as an unfortunate optical waveguide, reflective mirror, optical switch, optical barrier, and dielectric optical channel.

2 MATERIAL AND METHOD

Silicon on insulator (SOI) was chosen as the main material to use in this work. A few materials have been connected with a specific end goal to acquire one photonic precious stones (1D, for example,Si/SiO2,SiO2/TiO2,Na3AlF6/ZnSe,Na3Al F6/Ge(Srivastava and Ojha, 2007). Among the many existing material frameworks, silicon on cover (SOI) is considered as the best possibility to create coordinated nano-photonic gadgets as it permits the solid reconciliation of optical and electronic gadgets, that is by staying away from the utilization of half and half bundling procedures. Silicon PhC structure-based devices have been used in a wide range of applications, including light flow control applications such as waveguides, photonic band gap structures, and resonators. In this case, all the requirements can be satisfied by varying one-dimensional photonic crystal (PhC) structures with narrow\ waveguides in high refractive index contrast materials, such as silicon-on insulator (SOI) as reported byLee. (2014).

We then created the defect on one-dimensional (1D) Photonic crystals waveguide geometry structure. Furthermore, the brief report regarding the problem of determining the quality (Q) factor of localized cavity modes are presented. Each cavity is formed by introducing a central region with no holes and tapering the lattice constant and hole size near the cavity region (McCutcheon and Loncar, 2008). The observed influence of the presented defect on the geometry 1DPhotonic crystal cavity structure waveguide has been conducted. The simulation results such as the overall characteristics are investigated.There are the resonance peak wavelengths, transmission and the Q-performances affected by the tuning geometry structure in lattice segment particularly. For further step, we hope the results from this model devices are considered as potential building blocks in Silicon-On-Insulator (SOI) planar photonic integrated circuits operating, in particular at optical wavelengths for advanced telecom applications.

As reported that by tuning the geometry/dimension of the 1-D PhC structures, the transmission properties can be affected, and by replacing the homogeneous cavity construction with double cavities of the normal 1-D PhC, a multi-wavelengh-transmission optical filter can be realized. In fact those resonances can be controlled through the variation of parameters, such as hole dimension, lattice and cavity lengths (Md Zain et al., 2010). Some years ago, Srinivasan et al report that if the cavity has the proper size to support a mode in the band gap, then light cannot escape, resulting in the pinning of the mode to the defect (Quan et al., 2010), and this gave the effect that a resonant cavity is formed. This structure allows nearly an independent tuning of each resonant frequency by tuning the parameters (e.g. width, lattice constant, cavity length) each beam and has natural channels for coupling through each beam to an access waveguide at each wavelength (Lourtioz et al., 2008), and this pattern model inspired our model design in our work.

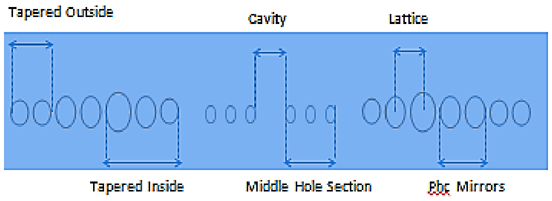

Figure 1: Schematic Design of Hole Pattern of One Dimensional (1D) Photonic Crystal Cavities Waveguide.

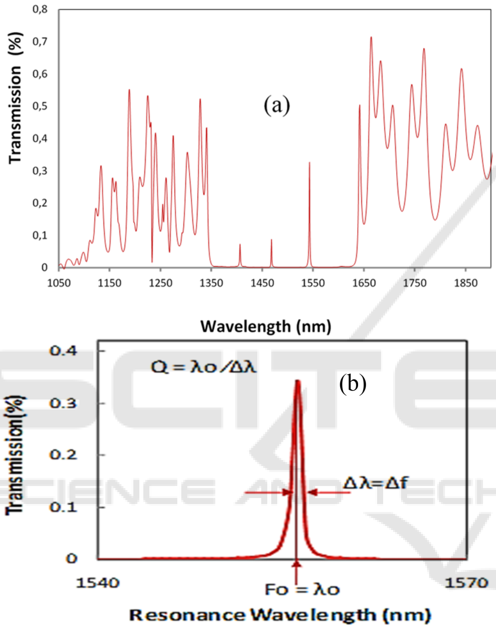

Figure 2: Sketch of 3D FDTD simulation transmission spectra of the compound photonic crystal cavity waveguide with multiple resonance results (a), and (b) calculation for Q factor by Lorentzian fitting.

The three-dimensional (3D) FDTD method has been used to simulate the designs. We employed the Crystalwave (Omnisim) software, the available software in lab, and to overcome some problem memory leading to large 3D simulations for which we employed the supercomputer infrastructure at National University of Malaysia (UKM). Numerical simulations play an important role for the design and modelling of guided wave optoelectronic devices. 1D periodic computational techniques and modelling are useful and sufficiently well-established (Joannopoulos et al., 1995). The FDTD method is a quite general method for the simulation of electromagnetic devices for all range of frequencies from the microwave to the optical regime. The power of the method lies in its simple formulation in which no restrictive assumptions are made in order to preserve its applicability to a wide range of problems, considering a 3D space with no electric or magnetic current sources, but with materials that present electric and magnetic conductivity. The last decade has witnessed dramatic progress and interest in micro- and nanofabrication techniques of complex photonic devices (Yee, 1966). FDTD method is famous due to its large flexibility and extendibility. Many types of calculations can be performed through fairly robust algorithms. The design process consists of engineering three elements: (a) the taper, (b) the photonic crystal mirror (Phc), and (c) the cavity length and (d). Middle hole section. The progress in micro and nanofabrication techniques of complex photonic devices have been observed. An accurate quantitative theoretical modelling of these devices has to be based on advanced computational techniques that can solve the relevant linear, nonlinear or coupled partial differential equations since over last decade (Obayya, 2011).

The proposed waveguide PhC structure that we presented in this work, consists of a 1D hole array in a silicon-on-insulator (SOI) photonic wire waveguide, and the geometry of the proposed waveguide is as illustrated in Fig. 1. The references are (Lan and begs) based on the tight requirement of a WDM system operating to the ITU standard. A coupled cavity structure was investigated as an ideal candidate to form a band-pass optical filter based on 1-D PhCs. Based on this, we created the design of geometry/dimensional structure of one dimensional (1D) photonic crystal waveguide by placing the three cavity in that structure, with the purpose to obtain the multiple peak resonances, good transmissions and higher Q factor. Numerical simulations play an important role for the design and modeling of guided wave optoelectronic devices. 1D periodic computational techniques and modeling are useful and sufficiently well-established (Anon, 1995). The design process consists of engineering three elements: (a) the taper, (b) the photonic crystal mirror (Phc), and (c) the cavity length and (d). Middle hole section. The details of the description of the basic design can be seen in Fig. 1, where the taper is located on the external cavity side of the mirror and the row of seven holes with diameters of 110, 110, 135, 135, 165, 135, 110 nm respectively, and is separated by increasing distances. Here, between the external cavities there are several additional tapers as shown in Fig. 1, the name is the middle hole section taper, and we keep the those hole diameters at 70 nm. In this work, we focus on varying the lattice constant by varying the lattice distance from 320nm - 355nm.Here, the structure is restructured as follows: silica (n=1.445) with a thickness of 1100 nm; silicon (n=3.48) with a thickness of 600 nm; and the last layer is air (n=1) with a thickness of 1000 nm. For the adjusting refracting index parameters value for SOI device structures we keep them constant.

The resonance wavelength, the Q-factor and the transmission/reflectance performance have been computed using the Finite Difference Time Domain (FDTD) approach. The Q-factor results was obtained from Lorentzian fitting and the description of this calculation as illustrated in Fig.2.

3 RESULTS AND DISCUSSION

In this study, we try to explore the possibility of employing more cavities waveguide design supporting two or more resonances (especially with both mode design the telecom window). In the other case, by design, a longer or a shorter of lattice wide, and/or coupled photonic cavities geometry structure waveguide and this increases the Q factor and transmission values. The change in *Q* depends strongly on the waveguide properties such as the width band gap. The other fact shows that the Q factor value was also affected by other parameters such as defect and etch. First, we investigated the influence of the presented defect geometry structure by varying the lattice constant size and placing three cavities between the mirror/taper. We define that by applying 325 nm lattice size in geometry waveguide design which we achieved from the highest Q- factor. The Q-factor was calculated using $\lambda p/\Delta\lambda$, where $\Delta\lambda$ is the band width of the resonance peak. The spectrum shows a resonance for the wavelength 1525 nm with a Q-factor of approximately 3840.

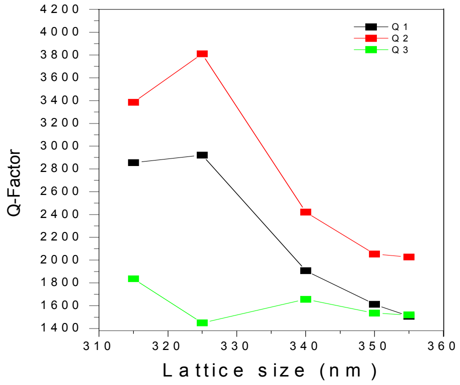

Figure 3: The graph of Q-factor toward lattice constant.

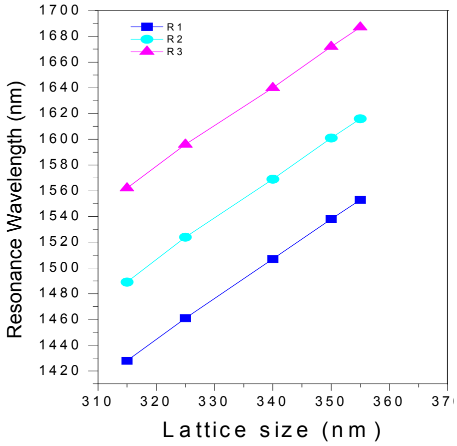

Figure 4: The graph of Multi Resonance wavelength peaks by varying lattice distance.

We assumed that the higher Q-factors achieved from simulation in this work probably was caused by the small of the lattice size. On the other hand, the simulation results show that changing the geometry parameters of waveguide has the effect on the enlargement of the band gap wavelength. This means that the lattice constant is an important factor in the performance of the band gap width beside other parameter. Based on simulation analyzed, we found that the band gap width becoming larger with the increase of the lattice size for all the five cases. As illustrated in fig.3. it shows that the structure exhibits various band gaps (or stop band) where the photonic states are not forbidden with the existence of three resonance peaks for each case/design. The multiple resonances peak for overall designs were found in range wavelength area from 1430 up to1690 nm. As can be seen in Fig. 4. it shows the linear resonance wavelength peaks resulted of a whole device with identical geometry parameters, for all case designs. In addition, Obayya reports that the shift of the resonance towards longer wavelength can be explained by a strong nonlinear effect due to the effect of the magnetic field applied to the structure.

The changing of lattice size modified in this study has significant effect on the optical response especially to control the transmittance of the device. Furthermore, the transmission spectra for a whole design has been computed and plotted with different wavelength cantered value for each design. As can be seen from the graft (Fig.5.) that the transmission results were varied with a little fluctuation, and obtained values via transmission spectrum method. The transmissions obtained were above 30 %, with the maximum value achieved at 75% when the lattice size was set at 350 nm. From our perspective, we assume that fluctuation of the transmission values are due to the numerical errors of the calculations. As reported in our previous paper that for further increase, the transmission coefficient peak can be expected by optimizing the size of the hole radius of middle hole sections, and with the realization of taper sections inside the resonant cavity (Husna et al., 2015). As the Q factor gets higher then the transmission (T) result will be smaller, and the trend of the transmission results obtained from our work are consistent with those previous reports. As overall, the presented results as illustrated in our calculated curves (Q- factor, transmission and resonance wavelength) coincide well and match with the simulation results in Fig. 2. On the other hand, the normalized transmission of the resonance varies at which we believe that the Q-factor and optical transmission is optimum for a certain cavity condition as reported by Zain et al., (2015). The other group researchers supporting our results mention that the structures may have application to WDM devices in the range IR to THz, depending on the geometry (Faneca et al., 2018).

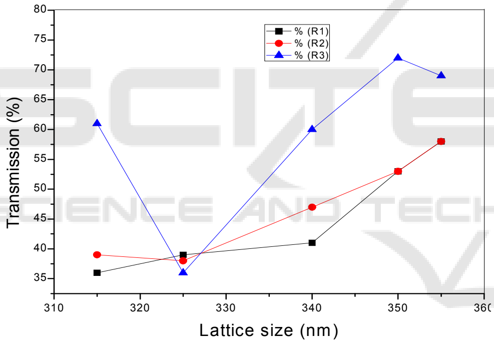

Figure 5: The graft of the normalized transmission spectrum of 1D photonic crystal cavities waveguide.

4 CONCLUSION

For the conclusion, we successfully investigate the confine light process in a 1D PhC a silicon waveguide structure. We have confirmed that it is possible to modify the geometry of waveguide structure by varying the number of cavity, lattice, radius and the number of hole in the periodicity. The wavelength range in this area (1300 -1550 nm) window has become very vital in view of the availability of wavelength division multiplexing (WDM) transmission system and optical amplifiers (erbium-doped fiber amplifiers). We found that the model of 1D photonic crystal silicon waveguide designed in our research is in accordance with properties expected for different lattice design condition based on simulation results and it is acceptable to be utilized for Telco purpose. We optimized that these wavelengths could be used in a wavelength division Multiplexing (WDM) system.

REFERENCES

Anon., 1995. Photonic Crystals: Molding The Flow of Light.

Faneca, J., Perova, T.S., Tolmachev, V., Baldycheva, A., 2018 One-Dimensional Multi-Channel Photonic Crystal Resonators Based on Silicon-On-Insulator With High Quality Factor. Frontiers in Physics. 6(May), 1–9.

Husna, J., Mohamed, M.A., Sampe, J., Zain, A.R.M., 2015 Numerical simulation of one dimensional (1D) photonic crystal multiple cavities based on silicon on insulator (SOI). RSM 2015 - 2015 IEEE Regional Symposium on Micro and Nano Electronics, Proceedings.

Joannopoulos, J.D., Meade, R.D., Winn, J.N., 1995 Photonic Crystals: Molding the Flow of Light. Princeton University Press.

Lee, C.C., 2014. The Current Trends of Optics and Photonics. Springer Netherlands.

Lourtioz, J.-M., Benisty, H., Berger, V., Gerard, J.-M., Maystre, D., Tschelnokov, A., Pagnoux, M.D. 2008. Photonic Crystals.

McCutcheon, M.W., Loncar, M., 2008. Design of a silicon nitride photonic crystal nanocavity with a Quality factor of one million for coupling to a diamond nanocrystal. Optics Express. 16(23), 19136.

Md Zain, A.R., Johnson, N.P., Sorel, M., De La Rue, R.M., 2010. Design and fabrication of high quality-factor 1-D photonic crystal/photonic wire extended microcavities. IEEE Photonics Technology Letters. 22(9), 610–612.

Noda, S., Chutinan, A., Imada, M., 2000. Trapping and emission of photons by a single defect in a photonic bandgap structure. Nature. 407(6804), 608–610.

Obayya, S., 2011. Computational Photonics. Wiley.

Pustai, D.M., Sharkawy, A., Shi, S., Prather, D.W., 2002. Tunable photonic crystal microcavities. Applied Optics. 41(26), 5574.

Qin, Q., Lu, H., Zhu, S.N., Yuan, C.S., Zhu, Y.Y., Ming, N.B., 2003. Resonance transmission modes in dual-periodical dielectric multilayer films. Applied Physics Letters. 82(26), 4654–4656.

Quan, Q., Deotare, P.B., Loncar, M., 2010. Photonic crystal nanobeam cavity strongly coupled to the feeding waveguide. Applied Physics Letters. 96(20), 20–23.

Shiveshwari, L., Mahto, P., 2006 Photonic band gap effect in one-dimensional plasma dielectric photonic crystals. Solid State Communications. 138(3), 160–164.

Soukoulis, C.M., 2006. Photonic band gap materials: the ‘semiconductors’ of the future? Physica Scripta. T66, 146–150.

Srivastava, S.K., Ojha, S.P., 2007. Enhancement of omnidirectional reflection bands in one-dimensional photonic crystals with left-handed materials. Progress In Electromagnetics Research, PIER 68, 91–111.

Yablonovitch, E., 1987. Inhibited spontaneous emission in solid-state physics and electronics. Physical Review Letters. 58(20), 2059–2062.

Yee, K.S., 1966. Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media. IEEE Transactions on Antennas and Propagation. 14(3), 302–307.

Zain, A.R.M., Majlis, B.Y., De La Rue, R.M., 2015. Reproducibility and free spectral range (FSR) control of a high quality factor-1D photonic crystal (PhC) extended cavity. RSM 2015 - 2015 IEEE Regional Symposium on Micro and Nano Electronics, Proceedings, 1–3.

Zimmermann, J., Kamp, M., Forchel, A., März, R., 2004. Photonic crystal waveguide directional couplers as wavelength selective optical filters. Optics Communications. 230(4–6), 387–392.