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Generation of Multiple Resonance Wavelengths from One Dimensional Photonic Crystal Wire for Nanoscopic Wavelength Division Multiplexing System

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ABSTRACT

Wavelength division multiplexing (WDM) is a core technology for high-bandwidth data transport system. As one of the major components in WDM system, a smaller footprint of multiplexer with two or more wavelengths is needed and photonic crystal (PhC) is a good candidate to make this approach feasible. PhC offers nanometer scale devices that can be fabricated via the existing matured silicon technology. We have modelled and simulated the design with FDTD solutions and show that multiple number of wavelengths can be generated via one-dimensional (1D) multiple cavity PhC wire. In this report, we show that with the introduction of three cavities in between embedded PhC holes, three fundamental resonance wavelengths at 1645.60, 1670.76 and 1698.68 nm were excited respectively. The number of resonance wavelengths were excited additively with the number of cavities. We observed asymmetrical free spectral ranges (FSR)s at 25.16 and 27.92 nm respectively for the generated wavelengths. The wavelengths can be tailored to any wavelength ranges; limited to silicon's light absorption and index. However, a complex mathematical algorithm is needed to control the FSR. The results in this study will contribute to the device development for future WDM equipment miniaturization.

Keywords: Cavity, Free Spectral Range, Nanometer, Photonic Crystal, Wavelength Division Multiplexing.

1. INTRODUCTION

Optical technology such as wavelength division multiplexing (WDM) has been adapted for transporting high bandwidth of data thanks to the advent of fiber optic [1]. The capital expenditure has suddenly increases due to the high demand of data that requires more space to be occupied due to the bulky size optical components. A smaller footprint devices with higher performance are needed to address this issue. WDM device miniaturization can be realized thanks to the matured silicon nano-fabrication technique [2, 3].

A clear transparency window at wavelengths from 1200 nm upwards [4] for silicon is helpful for all silicon platform devices. Silicon photonic wire with 2:1 width/height ratio gives strong optical confinement for TE-mode light propagation [5] re-simulated as shown in figure 1. The compactness of silicon photonic wire make it a possible solution for the future miniature components for optical interconnects that can replace electrical interconnects to overcome Moore's law limitations [6].

The discovery of photonic crystal (PhC) has bring the light manipulation technology to another level where the embedded nano-holes in silicon wire has helped in accurate light manipulation [7, 8].

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Photonic band-gaps over defined wavelength ranges can be induced by the introduction of photonic crystals (PhCs) in a periodic structures and, with the introduction of cavities formed by mirror sections (nano-holes section), resonance wavelengths can be excited within the forbidden region [9-11]. By utilizing, one dimensional (1D) PhC wire concepts, simple and compact structures with strong optical confinement can be fabricated and used as components in the realization of photonic integrated circuits (PICs). Previous studies on single-cavity photonic crystal structures have shown a quality-factor (Q-factor) values of several hundred thousand [12, 13]. Previous work has shown that having double cavity in the structure shows a splitting in resonance wavelengths in accordance with the number of cavities [14]. On the basis of these studies, we used FDTD solutions computer simulation for modelling and simulation the light generation behaviour with multiple cavity 1D PhC.

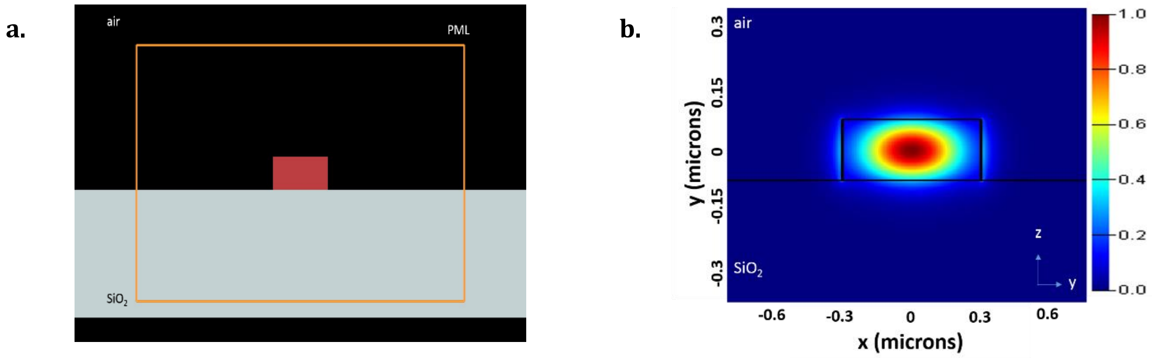

Figure 1. (a) Silicon wire cross-section dimensions of 600 nm (w) x 260 nm (h) on insulator with air clad on top of device. Perfectly matched layer (PML) boundaries was positioned at least half of an operating wavelength away from the structure. (b) Strong TE mode optical confinement shows negligible optical loss for the wire dimension chosen.

2. METHODS

The PhC devices were simulated by using silicon-on-insulator (SOI) model in which the refractive index of silicon was assumed to be 3.46 at the wavelengths of interest. The photonic wire structures, 600 nm (width) x 260 nm (height), supported by silica buffer layer having an assumed refractive index of 1.45, with air (refractive index of 1) surrounding the wire was used for the design. The PhC mirror sections had a lattice constant of ***a*** = 370 nm. The radius of the holes, ***r***, was designed to be 90 nm. A multiple number of a basic single cell unit as shown in figure 2 was simulated to show the forbidden region or the band-gap before proceeding with the device design [15]. The basic structure (the single cell unit) was repeatedly arranged to form PhC and three cavities, each with an inside cavity length of 400 nm cavity were embedded, as shown in figure 3a.

In order to obtain accurate simulation results that closely represent the fabricated device, a 3D version of the FDTD software was selected instead of a 2D version. However, this choice resulted in a significantly time consuming simulation. But the accuracy obtained is necessary in order to proceed with a proper comparison with the future work fabricated structure.

The simulation boundary was specified as a perfectly matched layer (PML). The PML was chosen so as to absorb all the radiation emitted from the structure without any reflection back into the simulation area [16]. To perform this, the PML simulation boundaries was positioned at least half of an operating wavelength away from any part of the structure being modelled - thereby avoiding reflection of the evanescent field from the PML, which would cause a shadow effect that influences the simulation results (figure 1).

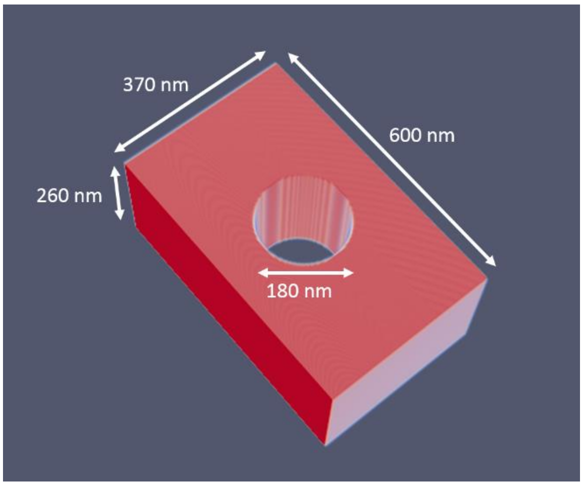

Figure 2. Single cell unit with a hole radius of 90 nm, slab dimension ***a***, 370 nm, width, 600 nm and height, 260 nm respectively.

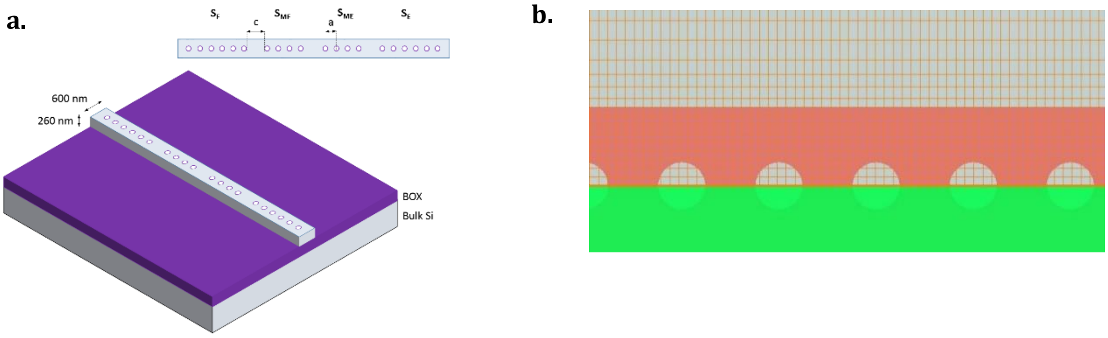

Figure 3. (a) Schematic structure of the basic PhC wire device fabricated on SOI with silicon wire cross-section dimensions of 260 nm (h) x 600 nm (w). Inset, a top view of multiple cavity structure with the hole section arrangement to be noted as: front section S_F, middle-front section S_{MF}, middle-end section S_{ME} and end section S_E respectively with lattice constant, ***a*** = 370 nm; symmetrical cavity, ***c*** = 400 nm; mirror radius, ***r*** = 90 nm. (b) Graded mesh were adopted for simulation accuracy.

In most simulation packages, the size of the mesh is important for accurate results to be obtained. A graded mesh approach was used for simulation accuracy as in figure 3b for the Lumerical software that we used.

In the simulation, the source used was the 'mode source' - and the mode selected was the TE mode, with a wavelength range from 1200 to 1800 nm - and light was injected at the left side of the device, with propagation towards positive x-direction. A frequency-domain monitor was used to record the results. In FDTD simulation, a large number of points is needed to ensure that the whole wavelength response is captured and displayed, but obeying this condition results in a slow simulation process.

3. RESULTS AND DISCUSSION

Single cell unit has been arranged to form PhC embedded in the silicon wire to observe the band-gap or light forbidden region as shown in figure 4. From the simulation results, the band-gap shows a blocked region from 1470 to 1750 nm. This step is important to ensure that no other light will be allowed to pass through the wire accept from the designated wavelengths. PhC hole arrangement was designed to have S_F-6 holes, S_{MF}-4 holes, S_{ME}-4 holes and S_E-6 holes – using similar hole radii and separated by equal cavity spacer lengths of 400 nm. Figure 5 shows the simulated response of the basic 6-4-4-6 device structure, with three distinct resonances. Three resonance wavelengths were produced - at 1645.60, 1670.76 and 1698.68 nm respectively, with different resonance peak quality-factor values. Asymmetric free spectral ranges (FSR)s, with values of 25.16 and 27.92 nm respectively, were observed. The splitting of a single cavity resonance wavelength into three distinct resonance wavelengths are due to the number of cavities (three) specified in the structure [17, 18].

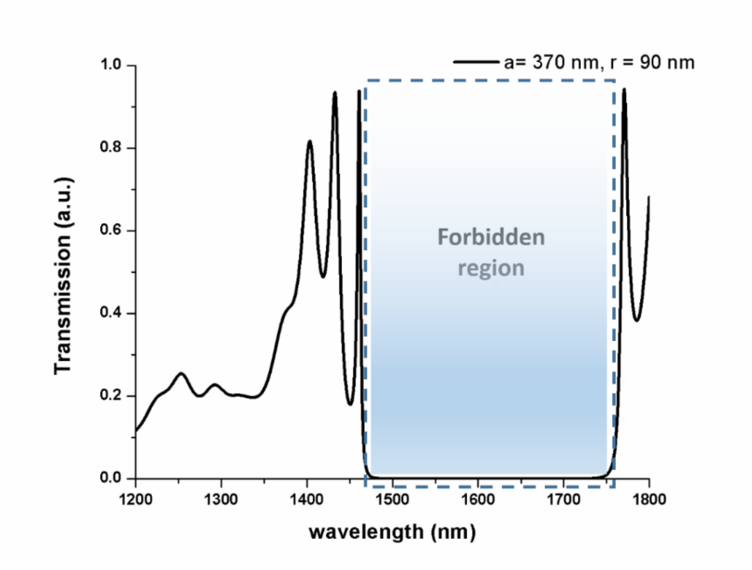

Figure 4. Forbidden region from 1470 to 1750 nm were observed for a single cell unit simulated.

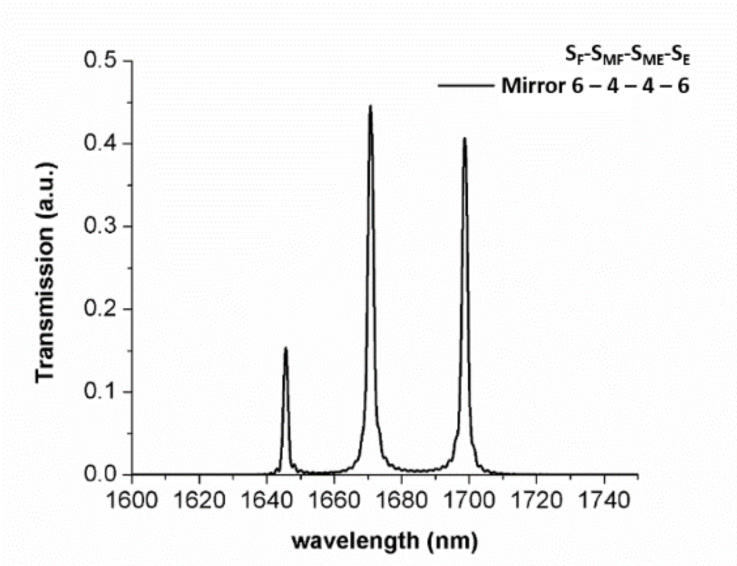

Figure 5. Three distinct resonance wavelengths at 1645.60, 1670.76 and 1698.68 nm with asymmetrical FSRs values of 25.16 and 27.92 nm respectively for the device design S_F-S_{MF}-S_{ME}-S_E, 6-4-4-6 holes, obtained from 3D-FDTD solution simulation software.

The multiple cavity PhC wire has been designed to produce distinct resonance wavelengths in the U-band region, as shown in figure 5. The percentage of transmission values has been observed to be less than 50 percent for all the resonance wavelengths. This is due to the abrupt changes in the light transition from guiding medium, silicon to hole, air. This can be improved by introducing tapering hole size [19] which smoothly guide the light transition from the guiding medium towards the end of the wire. Note that with simulation, negligible discrepancies in term of resonance wavelength value are to be expected due to the true refractive index value of the material used for the waveguide, the mesh size will also affect the simulation results and due to the computer memory limitation in simulating the devices a feasible mesh setting need to be configured to give a good simulation pattern without sacrificing the results quality.

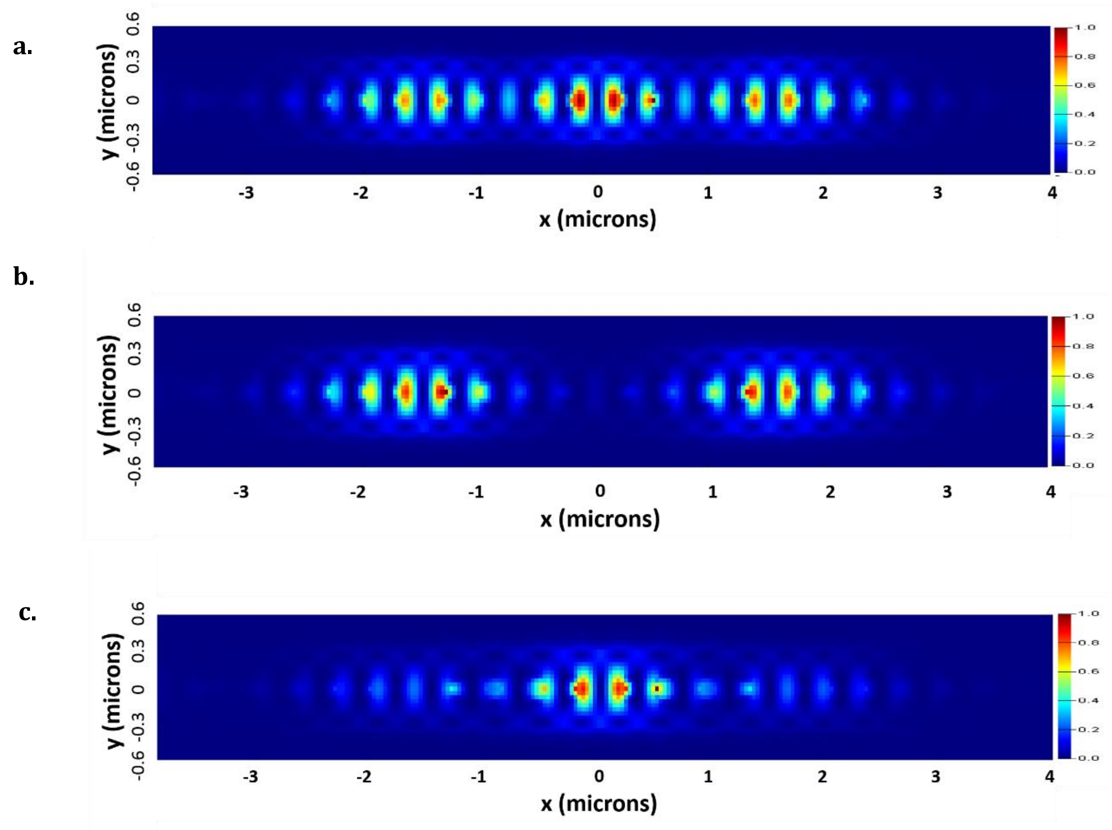

Figure 6. Light intensity profiles of the structure for three different resonance wavelengths: (a) the 1645.60 nm resonance wavelength from all cavities in the structure, (b) the 1670.76 nm resonance wavelength from the two outer cavities - and (c) the 1698.68 nm resonance wavelength from the middle cavity.

From the simulation results as in figure 6, it can be deduced that the first resonance wavelength was confined in the three cavities where all of the light energy coming through will be reflected by the mirrors in between the cavities. The second resonance wavelength shows that the two cavities at the side were responsible for such resonance wavelength and finally the third resonance wavelength was confined in the middle cavity where only at this wavelength, the energy will abide by the refractive index changes governed by both side combined PhC and cavities. Jugessur *et. al* [20] have studied the effect of introducing two cavities to the 1D PhC wire to have several phase shift regions inside the cavity, where the length of the grating sections (PhC) defined the transmission characteristics. The phenomenon of having multiple resonance wavelengths related to the number of cavities has also been observed by Foubert *et. al* [21], with the observed peak splitting being controlled by the coupling strength between one single cavity waveguide and another single cavity waveguide being positioned close together - through variation of the separation distance. This phenomenon can limit the device size due to the number of waveguides needed to produce multiple resonance wavelengths resulting in bigger dimension of device in comparison with proposed study.

4. CONCLUSION

The resonances of the designed structure can be tuned to specific desired wavelengths - whether these are a single or multiple wavelength resonances limited to the material's index, using the required control of the number, detailed specification and size of the cavities. A large resonance, Q-factor, together with usefully high transmission values, can be obtained by introducing and controlling the dimensions of tapered sections at the edges of the PhC mirror sections and thereby enable the light to propagate smoothly through the photonic wire. We have been able to demonstrate agreeable number of wavelength excitations from our simulation results. By adding progressively more cavities into PhC embedded single photonic wire structures (based on previous study and our design), we have shown that multiple number of resonance wavelengths can be introduced that make this ultra-small device suitable for the next generation WDM and other applications.

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