Photonic Crystal/Photonic Wire Multiple-micro-cavity Structure

Mohd Nuriman Nawi[1], Dilla Duryha Berhanuddin[1], Ahmad Rifqi Md Zain[1,2], Richard M. De La Rue[3]
[1] Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia (UKM), 43600, Bangi, Selangor, Malaysia
[2] John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, 02138, United States
[3] Optoelectronics Research Group, School of Engineering, Rankine Building, Oakfield Avenue, University of Glasgow, Glasgow G12 8LT, UK
e-mail: rifqi@ukm.edu.my

ABSTRACT

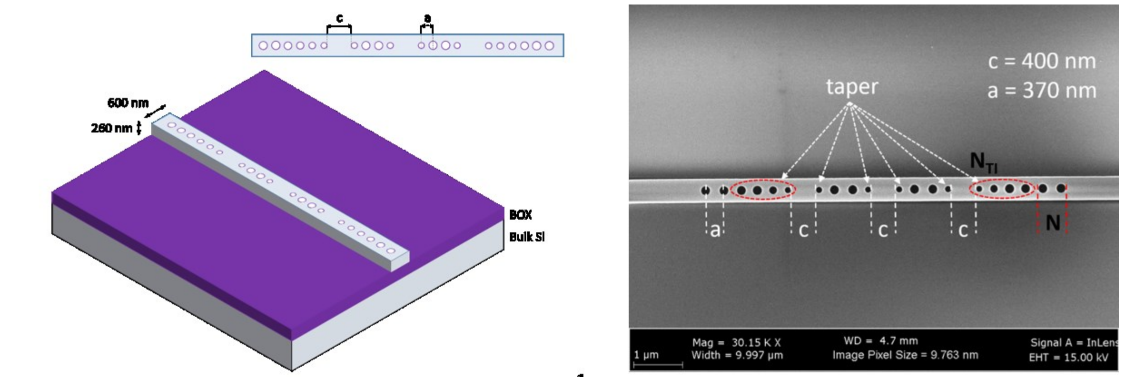
We present a study of triple-cavity 1-dimensional (1D) photonic crystal structures embedded in silicon photonic wire (PhC/PhW). Three cavity resonance wavelengths were observed. Structures with a greater number of resonance wavelengths would result from increasing the number of coupled cavities. The structure was designed to operate at fibre telecommunication wavelengths where all the resonance wavelengths fall in the C and L band regions. Factors that define the performance of the device - such as wavelength selectivity, resonance quality factor and transmission magnitude can be controlled by precise definition and simulation of the photonic crystal micro-cavity. The accuracy of the prediction of the resonance wavelengths was evaluated in both simulation and experiment, with good agreement between them. This approach is promising for exploitation in photonic integrated circuits (PICs) for wavelength division multiplexing (WDM) applications, providing a possible solution for smaller footprint devices.

Keywords: multiple-resonance, multiple-cavity, micro-cavity, 1D photonic crystal, wavelength division multiplexing, photonic integrated circuit.

1. INTRODUCTION

The limitations of compact electronic devices form a serious bottleneck [1]. To overcome such problems, PICs have been foreseen as one of the possible solutions [2]. With current advances in fabrication technology, nanostructured devices can be realised with dimensional precision down to the nanometer scale [3]. Device structures that exploit photonic crystal principles can be used to guide and restrict the propagation of light [4]. Various device structures based on PhC principles have been investigated [5-7] . The present work focuses on 1D PhC/PhWs because of their compactness and the importance of small scale component integration. WDM technology is mature and is now widely used in the transfer of large bandwidth data between different locations. The progressively increasing demand for high data transmission rates implies continuing pressure on available space in fibre-optical networks. This issue can be addressed using PICs in which PhCs play a key role in the realisation of densely integrated photonics circuit components [1].

The 1D PhC/PhW micro-cavity concept has been well researched and can provide high quality factor resonances that are suitable for filtering in very small scale structures [8]. The wavelength selectivity can be precisely controlled by properly specifying and realising the required structure parameters [5, 8-9]. Silicon on insulator (SOI) with a silicon thickness close to 260 nm, a buried oxide thickness of 2 µm and substrate thickness of 700 µm has been chosen as the platform for the realisation of PIC due to its CMOS compatibility and ease of integration. Previous work has reported two-cavity stuctures, in which the single-cavity resonance wavelength was split into two [9]. The present work inherits the same SOI platform, with similar PhC/PhW micro-cavity structures, but uses an additional cavity, as shown schematically in Fig. 1(a).



a. b.

Fig. 1(a). Schematic structure of 1D PhC/PhW on SOI platform with photonic wire waveguide dimensions of 600 nm width and 260 nm height. The lattice constant, a = 370 nm; cavity internal spacer distance, c = 400 nm; mirror hole radius, r = 90 nm for N number of mirror holes and hole size taper for optimization were chosen to work at telecommunication wavelength, C+L-band. Fig. 1(b). The SEM image of the fabricated device structure shows the high-quality device fabrication obtainable with currently available nanofabrication technology.

2. DEVICE STRUCTURE DESIGN AND SIMULATION RESULTS

PhC/PhW micro-cavity devices in an SOI platform with the schematic structure shown in Fig. 1(a) were designed and specified for fabrication. The photonic wire dimensions were selected to be 600 nm (width) x 260 nm (height) to guide TE-mode light. This ridge structure was supported by a silica buffer cladding with air surrounding the top and sides of the wire. As shown in Fig. 1(b), the exterior six hole mirror/taper structure had a first section that comprised two identical holes, each with a radius of 90 nm and a lattice constant, ***a*** of 370 nm, forming the Bragg mirror and a second section with four holes that form a taper in the N_{TI} region, with hole radii of 90, 92, 80 and 65 nm respectively. The distances between these taper holes were 350, 325, 315 and 300 nm respectively. The interior PhC/PhW structures comprised four holes with radii of 65, 90, 90 and 65 nm, spaced at distances of 310, 370 and 310 nm respectively. Two more PhC micro-cavities followed periodically - as mirror images of the first two structures. The interior cavity distance between each section, *c*, was designed to be 400 nm, in all cases. The inner tapers were introduced to guide the light smoothly, with reduced scattering and increased light transmission [9].

3D-FDTD analysis was used for simulation of the designed structure before fabrication. The silicon, silica and air indices were taken as 3.46, 1.45 and 1 respectively. The full multi-micro-cavity structure was designed to produce distinct resonance wavelengths in the C and L band fibre-network spectral regions, as shown in Fig. 2. The simulated resonance wavelengths were at 1534.87, 1554.63 and 1594.86 nm. The Q-factor values obtained for the three resonance wavelengths were 1136.09, 922.37 and 904.91 respectively. The wavelength spacing or free spectral range (FSR) obtained in simulation between the first resonance wavelength to the second resonance wavelength was 19.76 nm while the FSR from the second to the third resonance wavelength was 35.53 nm. The unequal FSR obtained was due to the resonance wavelengths being governed by the combination of the individual cavities in the PhC structure and the summation cavity of the overall PhC structure.

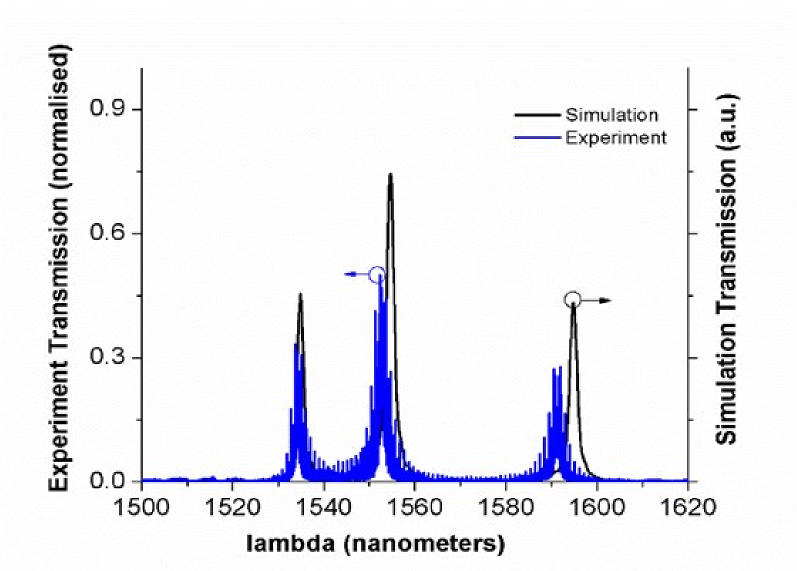


Fig. 2. Comparison between simulation and experiment results. The simulated resonance wavelengths were 1534.87, 1554.63 and 1594.86 nm while the experiment resonance wavelengths were 1534.34, 1552.77 and 1591.19 nm respectively.

3. FABRICATION AND EXPERIMENTAL RESULTS

The design was fabricated on an SOI wafer section by using electron-beam lithography (EBL) for patterning and inductively-coupled plasma reactive ion-etching (ICP-RIE) for structuring. Prior to the patterning process, hydrogen silsesquioxane (HSQ) with a thickness of 200 nm was used. The pattern was written using an Elionix ELS-F125 EBL tool. The pattern was developed with warm tetra-methylammonium hydroxide (TMAH) at 25% concentration in de-ionized water. The sample was etched using ICP-RIE with SF_6 and C_4F_8 gases, in order to remove the unwanted silicon region. Figure 1(b) shows a fabricated device.

The devices were measured using a tunable laser source range over the range 1480 nm to 1600 nm, with end-fire coupling of polarized light. The output of the device was detected using a germanium photodetector. The results obtained were normalised with respect to those of an unstructured photonic wire. The results obtained from measurements on the fabricated structure shown in Fig. 1(b) are in close agreement with the simulation results, as is shown in Fig. 2. The measured resonance wavelengths were 1534.34, 1552.77 and 1591.19 nm, respectively. Discrepancies between the simulation and measured results are probably caused by factors such as imperfect device fabrication – in particular small errors in the fabricated hole diameters [10]. The fine structure that is observable in the experimental results of Fig. 2 is primarily due to Fabry-Perot (FP) effects produced by the cleaved waveguide end-facets [9].

4. CONCLUSIONS

We have shown that properly designed multiple cavity structures result in predictable multiple resonances. This characteristic behaviour is suitable for application in WDM systems or other multiple wavelength filter applications that require photonic integration. The performance that we have demonstrated indicates that design based on available simulation tools can lead to viable fabricated devices for important applications.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Higher Education in Malaysia (MoHE) through LRGS/2015/UKM-UKM/NANOMITE/ 04/01 and LRGS (2015)/NGOD/UM/KPT.

REFERENCES

[1] B. J. Shastri *et al.*, "Neuromorphic Photonics, Principles of," in *Encyclopedia of Complexity and Systems Science*, R. A. Meyers, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 1-37.

[2] M. Smit, J. van der Tol, and M. Hill, "Moore's law in photonics," *Laser & Photonics Reviews,* vol. 6, no. 1, pp. 1-13, 2012.

[3] K. Li *et al.*, "High speed e-beam writing for large area photonic nanostructures—a choice of parameters," *Scientific reports,* vol. 6, p. 32945, 2016.

[4] J. D. Joannopoulos *et al.*, *Photonic crystals: molding the flow of light*. Princeton university press, 2011.

[5] N. Nawi *et al.*, "Enhancement and reproducibility of high quality factor, one-dimensional photonic crystal/photonic wire (1D PhC/PhW) microcavities," *Journal of the European Optical Society-Rapid Publications,* journal article vol. 14, no. 1, p. 6, February 20 2018.

[6] R. Rajasekar and S. Robinson, "Trapezoid 2D photonic crystal nanoring resonator-based channel drop filter for WDM systems," *Photonic Network Communications,* journal article vol. 36, no. 2, pp. 230-245, October 01 2018.

[7] Y.-H. Ye *et al.*, "Self-assembly of three-dimensional photonic-crystals with air-core line defects," *Journal of Materials Chemistry,* 10.1039/B207441A vol. 12, no. 12, pp. 3637-3639, 2002.

[8] A. R. Md Zain *et al.*, "Ultra high quality factor one dimensional photonic crystal/photonic wire micro-cavities in silicon-on-insulator (SOI)," *Optics Express,* vol. 16, no. 16, pp. 12084-12089, 2008/08/04 2008.

[9] A. R. Md Zain and R. M. De La Rue, "Control of coupling in 1D photonic crystal coupled-cavity nano-wire structures via hole diameter and position variation," *Journal of Optics,* vol. 17, no. 12, p. 125007, 2015/10/15 2015.

[10] R. M. De La Rue and C. Seassal, "Photonic crystal devices: some basics and selected topics," *Laser & Photonics Reviews,* vol. 6, no. 4, pp. 564-597, 2012.