

Fabrication of Photonic Crystal Line Defect Waveguides by Use of Optical Lithography and Focused Ion Beam

Hemant Sankar Dutta^{1,2*}, Amit Kumar Goyal^{1,2}, Sumitra Singh², Mandeep Kaur³, Sudhir Husale³ and Suchandan Pal^{1,2}

¹Academy of Scientific and Innovative Research (AcSIR), CSIR- Central Electronics Engineering Research Institute (CSIR-CEERI) Campus, Pilani-333031, India

²Opto-electronic Devices Group, CSIR-CEERI, Pilani-333031, Rajasthan, India

³CSIR-National Physics Laboratory, Dr. K. S. Krishnan Marg, New Delhi-110012, India

*Corresponding author: hemantdutta97@gmail.com

Abstract: A fabrication strategy for realizing photonic crystal structures with long interfacing waveguide has been reported. The technique utilizes a combination of optical lithography and focused ion beam milling to fabricate the device.

OCIS codes: (130.0130) Integrated optics; (130.5296) Photonic crystal waveguides

1. Introduction

Photonic crystals (PhCs) are structures with periodic dielectric functions that prohibit the propagation of electromagnetic waves for a particular band of frequencies indicated by the photonic band gap. The property of photonic band gap has been exploited by many researchers to realize various compact photonic devices like filters [1], lasers [2], sensors [3] and resonators [4]. PhCs can be realized in two-dimensions by etching holes periodically in a high index material. Breaking the periodicity of a PhC structure can be used to confine and to slow down the propagation of light. Line defects in a PhC structure has been used for slowing down light and exaggerating various optical phenomena.

Realizing submicron-scale PhC structures with long interfacing waveguides is challenging due to the issue of resolution. Focused Ion Beam (FIB) is a very promising tool for fulfilling such requirements. The advantage of using FIB is the removal of proximity effects because the substrate is etched directly without using any mask. FIB milling also allows real-time imaging of the substrate during the entire process of etching. This promotes accurate positioning of the ion beam and thus permit precise integration with a previously defined pattern in the substrate. However, realizing photonic components using FIB is still challenging. Fabricating perfect vertical walls is difficult because of the re-deposition of etched material. Furthermore, bombardment of ions lead to implantation and thus modifies the crystalline nature of the substrate. Implantation causes absorption of light and hence deteriorates the desired device performance. However, device performance can be improved by post-etch annealing [5].

This paper concentrates on fabrication of line-defect PhC waveguide (PhCW) based devices along with interfacing waveguides having a full device length of approximately 1 cm on a silicon-on-insulator (SOI) substrate by combining optical lithography with FIB processing. The outer layout comprising of interfacing waveguides is realized by lithography technique followed by reactive ion etching and the sub-micron PhC structure in a pre-defined area is patterned by using FIB milling. The technique is faster and cost-effective as compared to e-beam lithography process in defining large device area with PhC structures.

2. Structure Design

The device considered here comprises of a ring-type line defect in a PhC structure. The PhC structure is considered by placing holes with radius (R) of 240 nm hexagonally with a lattice constant (a) of 600 nm in 250 nm silicon device layer of a SOI substrate. The device has been designed for refractive index sensing applications where the filling factor of the line defect is vital. The sensitivity parameter of a PhCW highly depends on the amount of change in the effective refractive index in the waveguide region. It has been shown previously that ring-type line defect PhCW shows a higher sensing potential as compared to hole-type line defect PhCW for the same defect filling factor [6]. The ring-type PhCW has a relatively higher transmission strength as compared to hole-type line defect waveguide with comparable sensitivity for the same defect filling factor due to its narrower forbidden band gap range. Therefore, the PhCW in this paper has been realized by replacing a single row of holes with ring-type structures in the Γ -K direction of the PhC lattice. The rings have an outer radius (R_{out}) of 240 nm and an inner radius (R_{in}) of 140 nm, which create a trench width of 100 nm. The ring parameters create a defect filling factor of $\sim 40\%$, which corresponds to a sensitivity adequate for monitoring minute changes in the refractive index of analytes [7].

3. Experimental Results

The fabrication process can be broadly divided into two parts- outer layout or host structure fabrication and PhC structure realization inside the host structure. The host structure, which includes the interfacing waveguides, is defined using optical lithography in a SOI substrate with 250 nm silicon device layer and 2 μ m buried oxide layer. The pattern transfer is carried out by coating the substrate with positive photoresist and UV exposing it in presence of the mask carrying the required pattern. The lithography is followed by reactive ion etching (RIE) process to transfer the pattern from the resist to the silicon device layer of the SOI substrate. The etching is done by using a plasma of CF₄ and O₂ in flow rate of 35 sccm and 2 sccm respectively. The RF power and the etching time has been optimized to obtain 250 nm depth of interfacing waveguides; this is obtained with a 100W RF power for a etch time of 3.5 min. The optical micrographic image of the achieved outer layout host structure (after lithography followed by etching) is shown in Fig. 1(a). Fig. 1(b) demonstrates the schematic layout of the ring-type line defect PhCW to be realized by using FIB milling technique.

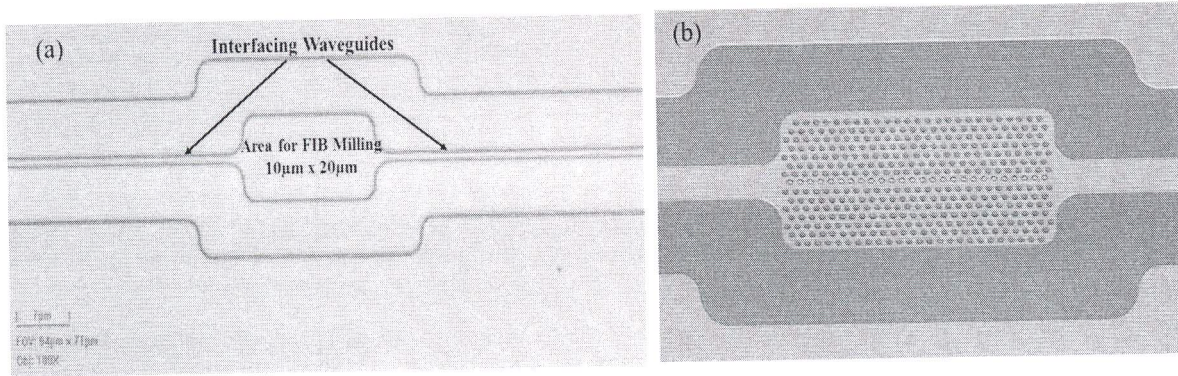


Fig. 1. (a) Optical micrograph image of the fabricated outer layout host structure and (b) schematic of the device to be fabricated.

Fabrication of PhC structure in the predefined host layout structure has been made using ZEISS FIB-SEM system. The system contains both electron beam as well as ion beam in the same vacuum chamber. Hence, structuring and inspection can be done simultaneously. The machine utilizes a Ga⁺ ion beam. The magnification of the system limits the writing area. The realization has been performed in ~6000 \times magnification, thus enabling a writing field of approximately 20 μ m \times 20 μ m, which is sufficient in this case. The acceleration voltage and the etch current are optimized to be 30keV and 50pA respectively for realizing the PhC structure. A high etch current is required for achieving deeper etch profiles along with a lower total milling time. However, lower etch current (50pA) reduces the charging and re-deposition effect, but increases the total milling time and hence will be more prone to drift distortion. Lower etch current also reduces the 1/e beam spot size; henceforth results in higher resolution. The SEM images of the fabricated PhCW structures are shown in Fig. 2. The imaging shows the measured PhCW have slight deviations from the designed parameters as mentioned in Table 1. Therefore, the technique demonstrated in this study to fabricate the PhCW structure along with interfacing waveguides has a high potential for realizing large-scale PhC devices suitable for various communication and sensing applications.

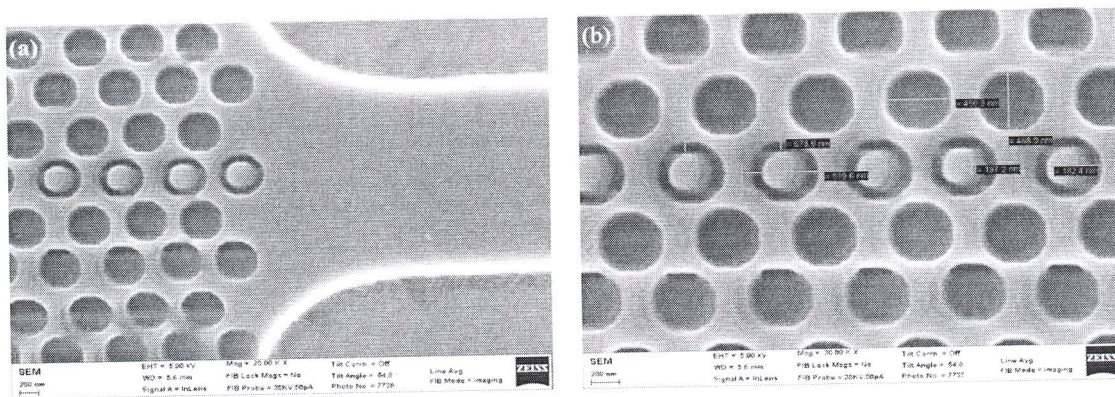


Fig. 2. SEM images of fabricated PhCW structure with ring as a line defect.

Table 1. Parameters of PhCW structure: designed values vs. measured values

Parameters	Designed Values	Measured Values (Average)
Hole diameters ($2R$)	480 nm	450 nm
Lattice constant (a)	600 nm	673 nm
Outer ring diameter ($2R_{out}$)	480 nm	540 nm
Inner ring diameter ($2R_{in}$)	280 nm	197 nm

4. Conclusion

A fabrication strategy to realize PhC structures with long interfacing waveguide has been reported. The fabrication technology incorporates optical lithography for realizing host layout structure followed by RIE. The realized layout is then used as a platform for defining PhC structures by FIB milling. The PhC structure fabricated comprises of a ring-type line defect PhCW which can be used in field of refractive index based sensing applications. The obtained parameters are very close to the targeted design. The proposed fabrication technique provides an effective alternative for fabricating relatively long-length photonic devices with nanostructures.

5. Acknowledgement

Authors are thankful to the director, CSIR-CEERI, Pilani for his encouragement in this work. Authors thank to all members of Optoelectronic Devices Group, CSIR-CEERI and R. K. Kotnala CSIR-NPL for their help and cooperation. Authors would like to acknowledge CSIR for sponsoring the PSC-0102 network project. Authors (AKG and HSD) would like to acknowledge CSIR for their support through SRF fellowship. Authors also acknowledge Arvind Singh and A. K. Gupta for helping in RIE and mask fabrication.

6. References

- [1] S. Guo and S. Albin, "Numerical techniques for excitation and analysis of defect modes in photonic crystals," *Opt. Express* **11**, 9, 1080–1089 (2003)
- [2] A. M. Kasten, M. P. Tan, J. D. Sulkin, P. O. Leisher, and K. D. Choquette, "Photonic crystal vertical cavity lasers with wavelength-independent single-mode behavior," *IEEE Photonic Technol. Lett.* **20**, 23, 2010-2012 (2008)
- [3] A. K. Goyal, S. Pal, "Design and simulation of high-sensitive gas sensor using a ring-shaped photonic crystal waveguide," *Phys. Scr.* **90**, 025503 (2015)
- [4] H. Altug, J. Vuckovic, "Two-dimensional coupled photonic crystal resonator arrays," *Appl. Phys. Lett.* **84**, 2, 161-163 (2004)
- [5] L. J. Sargent, A. B. Massara, M. Gioannini, J. C. L. Yong, P. J. Heard, and J. M. Rorison, "Investigation of polarization-pinning mechanism in deep-line-etched vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.* **76**, 4, 400-402 (2000)
- [6] H. S. Dutta, A. K. Goyal and S. Pal, "Sensitivity enhancement in photonic crystal waveguide platform for refractive index sensing applications," *J. Nanophotonics* **8**, 083088 (2014)
- [7] H. S. Dutta, S. Pal, "Sensitivity analysis for photonic crystal waveguide based refractive index sensing using plane wave expansion simulations," in *Proc. of Workshop of Recent Advances in Photonics* (IISc Bangalore, India, 2015) P-10