Robust Low-loss Topological Photonic Crystal Waveguides

Masudur Rahim, Heijun Jeong, Yahui Xiao, and Tingyi Gu
Electrical and Computer Engineering, University of Delaware, Newark, DE 19711 USA
Author e-mail address: tingyigu@udel.edu

Abstract: We observe ultra-low propagation and coupling loss (<2dB) in topological photonic crystal waveguide with integrated metalens coupling.

1. Introduction

Elimination of backscattering losses is one of the key aspects of developing optical devices towards system applications, such as data communication, sensing, signal processing and quantum photonics [1]. Topological photonic crystals (TPhC) exhibit potential of less sensitivity to fabrication variations/surface roughness, towards low loss integrated components [2-3]. Especially, the topological photonic crystal waveguide exhibit robustness against sharp bending the fabrication variations. Those merits can potentially contribute to large-scale low loss nanophotonic circuits topologies with ultra-compact dimensions. The topological waveguides lead to low propagation loss. The insertion loss caused by the mode/effective index mismatch between channel waveguide and photonic crystal waveguides can be addressed by using the metalens coupler. Integration of the on-chip broadband dielectric metalens system instead of low-loss conventional channel waveguides allows the exclusion of challenges with postprocessing yield [4], insertion loss [5] and the requirement for high precision engineering of the waveguide high-transmission band with that of PhC or TPhC waveguide. Reducing the insertion loss at component level can pave the way for developing robust optical devices with unprecedented characteristics.

In this work, we have experimentally compared the light propagation of TPhC and conventional photonic crystal (PhC) waveguides to quantify the robust light transportation ability of TPhC waveguides. Structural variation has been introduced by designing a heterogeneous waveguide framework where a segment of periodic photonic crystal with a higher radius offset has been sandwiched between two segments of zero-offset structures. Inclusion of such a region introduces a band offset in the light propagation pathway, intuitively causing it to undergo partial reflection at the interface of the two regions. Segments having the same lattice constant and multiple of unit cell have been added to both TPhC and PhC waveguide structures, having a length of 24.3 µm, while the region with radius offset covers a length of 8.1 µm in the sandwiched region. From the experimental results, it has been observed that TPhC waveguide structures are able to facilitate the low-loss transmission of light in both homogeneous and heterogeneous structures, with losses reaching as low as <2dB, while the PhC waveguide heterojunction structure experiences higher losses >9dB; thus validating that TPhC structures enable the elimination of backscattering losses and are immune to structural variations.

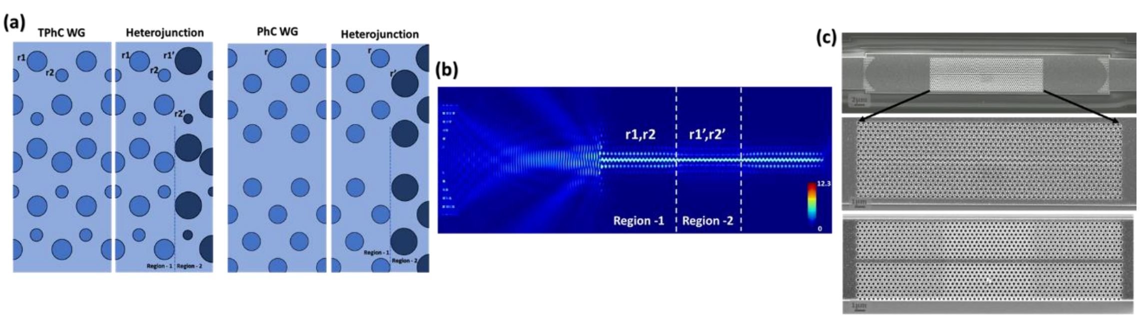

Fig. 1. (a) Schematic view of the TPhC and PhC structures. (b) In-plane mode profile of light coupling between broadband dielectric metalens with the TPhC heterostructure. (c) SEM images of the fabricated TPhC structure with integrated metalens (top), TPhC heterojunction structure (middle) and PhC heterojunction structure (bottom).

2. Device structure and fabrication

Both the TPhC and PhC structures consist of a honeycomb lattice of circular holes with a lattice constant a = 405 nm etched into a silicon slab. For the TPhC heterostructure, radius pairs of 108 nm (r1) and 38 nm (r2) respectively, have been used for the first region (region – 1) and 113 nm (r1') and 33 nm (r2') for the second (region - 2); whereas the PhC structure consists of 100nm (r) and 110nm (r') holes in the first and second junctions, respectively. Four different device structures have been considered, where the TPhC structure consists of a homogeneous waveguide having a radius equal to r1 and r2, covering a length of 24.3 µm and a heterogeneous structure where the overall length is the same as that of homogeneous; however, we have introduced a different radius pair of r1' and r2' in the region - 2, having a length of 8.1 µm. Similarly, a pair of homogeneous and heterogeneous waveguide sections of PhC having the same lengths have been used. The schematic of both TPhC and PhC homogeneous and heterogeneous pairs has been illustrated in Fig. 1(a). To accommodate low insertion loss of incident beam at the interface [6], a metalens having a focusing length of 13 µm has been integrated into the TPhC and PhC waveguide. The metalens enables strong coupling at the waveguide interface, as depicted in Fig. 1(b) and the inset of Fig. 2, showing the electric field propagation along the guided interface of TPhC and PhC. Apodised grating couplers have been used in the input and output segments to couple light into the waveguide.

The on-chip device structures (circular holes of TPhC and PhC, metalens, grating coupler and waveguide) have been defined by patterning on a positive resist (CSAR 6200.09) using a Raith EBPG5200ES electron beam lithography system with a 100 kV acceleration voltage. Arrays of TPhC and PhC devices have been fabricated on an SOI substrate from SOITEC having 250 nm device layer and an oxide isolation layer of 3 µm. Etching for the device structures have been performed using a single-step F-ICP dry etching process, followed by the deposition of a top cladding layer of 900 nm amorphous SiO_2 using the PECVD process to serve as a passivation layer. SEM images of the fabricated TPhC structure along with the integrated metalens and the conventional PhC structure are shown in Fig 1(c).

3. Optical characterization

To characterize the low insertion losses in TPhC and compare that with PhC, we measured the broadband transmission spectra. A continuous-wave semiconductor laser (AQ4321A) tunable from 1480nm to 1580nm with a polarization controller is used to inject light into the input grating coupler for each device with the aid of a single-mode fiber. The signal emitted from the output grating coupler is connected to a photodetector (Newport optical power meter 1830-C), where the loss at every iteration of the wavelength sweep is recorded. From Fig. 2, we observe that the transmission spectra for TPhC heterojunction shows much lower losses (<2 dB) as compared to the higher losses of PhC heterojunction at >9dB. Additionally, while comparing the TPhC heterogeneous structure with its homogeneous waveguide, the loss only varies by <1dB whereas a variation of >2dB is observed in the case of PhC structures. The total lengths of all the waveguides shown in Fig. 2 are same of 24.3 µm.

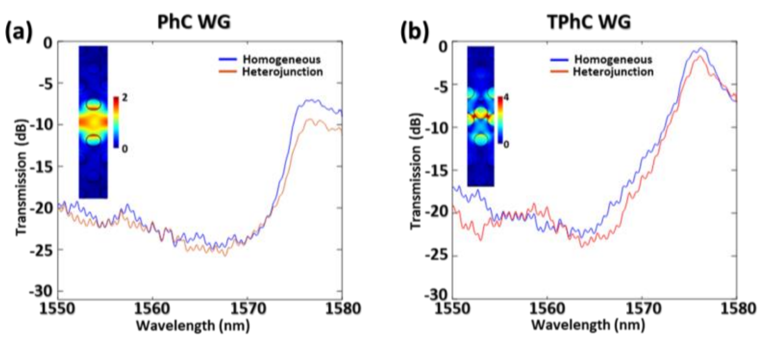

Fig. 2. Experimental transmission spectra comparing WG without (blue) and with heterogeneous (red) for (a) PhC and (b) TPhC waveguides. Inset: correspondent mode profiles.

4. Conclusion

This work experimentally demonstrates that TPhC waveguides are immune to structural variations and offer robust transport of light with very low loss as compared to conventional PhC waveguides. The high transmission and immunity to imperfections can allow such a waveguiding scheme to be employed in developing optical devices with superior functionality.

References

[1] J. Wang and Y. Long, "On-chip silicon photonic signaling and processing: a review," Sci. Bull. **63**(19), 1267–1310 (2018).
[2] Shalaev, M. I., Walasik, W., Tsukernik, A., Xu, Y., & Litchinitser, N. M. (2019). Robust topologically protected transport in photonic crystals at telecommunication wavelengths. Nature nanotechnology, 14(1), 31-34.
[3] Lin, C. Y., Wang, A. X., Lai, W. C., Covey, J. L., Chakravarty, S., & Chen, R. T. (2012). Coupling loss minimization of slow light slotted photonic crystal waveguides using mode matching with continuous group index perturbation. Optics letters, 37(2), 232-234.
[4] Hafezi, M., Mittal, S., Fan, J., Migdall, A. and Taylor, J.M., 2013. Imaging topological edge states in silicon photonics. *Nature Photonics*, *7*(12), pp.1001-1005.
[5] Vlasov, Y. A., O'boyle, M., Hamann, H. F., & McNab, S. J. (2005). Active control of slow light on a chip with photonic crystal waveguides. nature, 438(7064), 65-69.
[6] Xiao, Y., Wang, Z., Wang, F., Lee, H., Kananen, T., & Gu, T. (2021). Engineering the light coupling between metalens and photonic crystal resonators for robust on-chip microsystems. Journal of Optical Microsystems, 1(2), 024001-024001.