One-dimensional photonic crystal waveguide based on the SOI platform for transverse magnetic polarization-maintaining devices

Nikolay Lvovich Kazanskiy[1,2], Muhammad Ali Butt,[*1,3]

[1]*Department of Technical Cybernetics, Samara National Research University, 34 Moskovkoye Shosse, Samara 443086, Russia*
[2]*Institute of RAS-Branch of the FSRC "Crystallography and Photonics" RAS, 151 Molodogvardeiskaya, Samara 443001, Russia*
[3]*Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland*

Abstract—In this letter, a TM-polarization C-band pass of one-dimensional photonic crystal strip waveguide (1D-PCSW) is presented. The waveguide structure is based on a silicon-on-insulator platform which is easy to realize using standard CMOS technology. A numerical study is conducted via the 3D-finite element method (FEM). The transmittance and polarization extinction ratio (*PER*) is enhanced by optimizing the geometric parameters of the device. As a result, a TM polarized light can travel in the waveguide with ~2 dB loss for all the C-band telecommunication wavelength window whereas the TE polarized light suffers a high transmission loss of >30 dB. As a result, a *PER* of ~28.5 dB can be obtained for the whole C-band wavelengths range. The total length of the proposed device is around 8.4 µm long including a 1 µm silicon strip waveguide segment on both ends. Based on our study presented in this paper, several photonic devices can be realized where strict polarization filtering is required.

Several integrated photonics devices that work on transverse-magnetic (TM) polarized light has an efficient performance [1]. Besides, TM polarized light is practical for sensing applications, as its evanescent field penetrates deeper to the top and bottom cladding compared to that of the transverse electric (TE) polarized light. Furthermore, devices used for polarization multiplexing require TM polarized light to facilitate most of the channel capacity [2]. That is why we can say that TM polarization pass devices are essential for designing proficient Photonic Integrated Circuits (PICs). Currently, most of the PICs are designed based on a silicon-on-insulator (SOI) platform to take advantage of high index contrast of silicon (~n=3.48 at 1550 nm) to silicon dioxide (~n=1.44 at 1550 nm), high structural birefringence, significant optical nonlinearities, and, its well-matured CMOS fabrication technologies [3-5].

Recently, several high performance SOI-based TM polarization filters have been proposed. For instance: a 10 µm long silicon strip waveguide has been optimized to produce a TM polarization filter with a polarization extinction ratio (*PER*) of 26 dB [6]. A TM pass

polarization filter (length=26 µm) has been proposed, capable of providing 20 dB *PER* [7]. The TM polarization pass device based on a Hybrid plasmonic waveguide provides a *PER* of 20 dB in ~7.5 µm length waveguide [8]. A 27 dB *PER* of TM to the TE polarized light has been achieved in a propagation length of 9 µm by using a sub-wavelength grating-based structure [9]. Moreover, a multilayer TM polarizer based on aluminium-doped zinc oxide has been proposed, which gives a *PER* of 22 dB [10]. However, these are undeniably high performance polarizers require multi photolithography steps to form different layers, which makes the manufacturing of these devices a bit complicated.

One-dimensional Photonic crystals (1-D PCs) are the straightforward structures in a photonic crystal family, Intriguingly, these crystals still hold numerous stimulating characteristics such as modifiable dispersion and birefringence, analogous to homogeneous materials. The uncomplicated structure of the 1-D PC is easily integrated with the existing photonic devices without varying the fabrication process in comparison with 2-D or 3-D PCs. Accordingly, several high-performance silicon-based devices have been studied and demonstrated by making use of those exciting properties of 1-D PCs such as modulators [11], sensors [12], filters [13] and polarizer [14,15], among others. In this letter, we proposed a compact design of a one-dimensional Photonic crystal strip waveguide (PCSW) capable of transmitting TM polarized light and rejecting the TE polarization. The waveguide design is based on a silicon-on-insulator (SOI) platform as shown in Fig. 1. The height and width of the silicon waveguide core are represented as *H* and *W,* which is fixed at 300 nm and 45 0 nm, respectively. A periodic array of rectangular cavity (void) is placed in the centre of the strip waveguide. A strip waveguide segment of 1 µm is maintained on both ends of the device. The height of the rectangular cavity is equal to the height of the

* E-mail: ali_ciit_engineer@yahoo.com

waveguide core. While the length and width of the cavity are denoted as l and W_1, respectively. The gap between the two voids is denoted as d while the period (Λ) is $l+d$.
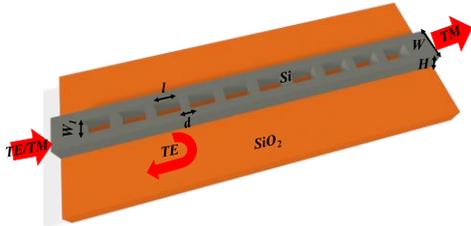

Fig. 1. Schematic representation of a proposed TM polarization pass 1D-photonic crystal strip waveguide based on the SOI platform.

The device design is simulated using COMSOL Multiphysics 5.5 based 3D finite element method (FEM). The electromagnetic (EM) wave frequency domain (*emw*) is chosen as a physics interface. The waveguide model sub-domains are divided into triangular mesh elements with $\lambda/20$ mesh grid size for the entire design. The meshing depends on the solution accuracy and the computational power of the system. For wave propagation systems, it is enviable to model a domain with open boundaries of the computational domain as it allows the electromagnetic wave to pass through without any reflection. The open geometry is set by assigning scattering boundary conditions (SBC) at the outer edges of the simulation window.
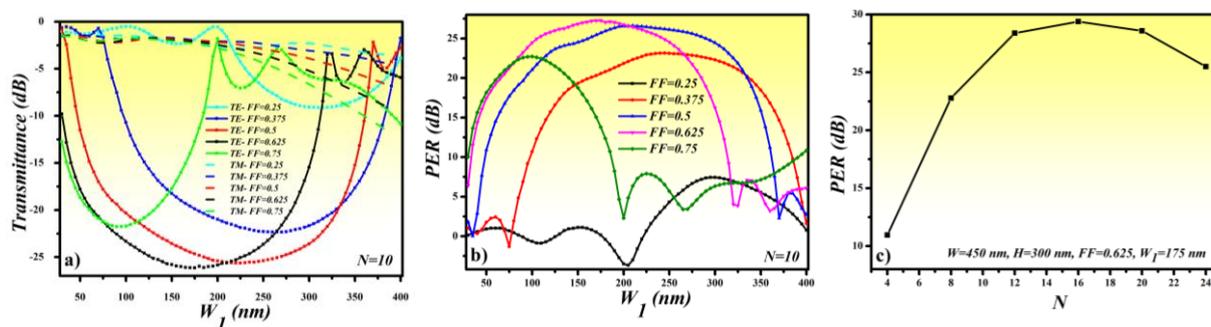
Here, we have optimized the PCSW structure by considering the geometric parameters of the PC. In the first step, the transmittance of the TE and TM mode at 1550 nm is calculated by varying the fill factor ($FF=l/\Lambda$) and W_1 of the PC. The number of period (N) of the PC is initially maintained at 10. The transmittance is calculated using the following expression:

Transmittance $(dB)=10\text{x}\log(P_{out}/P_{in})$, where P_{out} and P_{in} are the power at the output and input, respectively. For the optimization of 1D-PCSW, the W_1 and FF are considered in the range of 30 nm to 400 nm and 0.25 to 0.75, respectively. For 30 nm $< W_1 <$ 175 nm, TM polarized light has a transmission loss of $<$ 1.9 dB for the FF of 0.25-0.75 and W_1 in the range of 30 nm to 175 nm, whereas there is a bandgap for TE polarized light which shifts with varying FF. The maximum transmission loss of 26.14 dB is obtained at $W_1=175$ nm and $FF=0.625$ as shown in Fig. 2a. In Figure 2b, the polarization extinction ratio (PER) is calculated for the transmittance of TE and TM polarized light obtained in Fig.2a. PER is the ratio of the output power of TM polarized light to the optical power of TE polarized light and is calculated using the following expression: $PER\ (dB)=10\text{x}\log(P_{TM}/P_{TE})$, where P_{TM} and P_{TE} are the optical power at TM and TE polarization, respectively.

Fig. 2. a) Transmittance versus W_{hole}, b) PER versus W_{hole}, c) PER versus N.

In telecommunication, PER is used to illustrate the degree of polarization in polarization-maintaining devices or fiber. The maximum PER of 27.27 dB is obtained at $W_1=175$ nm and $FF=0.625$ for $N=10$. Afterwards, the dependence of PER on N is calculated for the optimized parameters of the PCSW. From Fig. 2c, it can be seen that as N increases from 4 to 16, the PER gradually increases from 10.9 dB to 29.4 dB, which drops as N continues to increase. Therefore, we have to find the optimum values of W_1, FF and N to have a maximum PER.

The normalized E-field distribution for TE and TM mode at 1550 nm is shown in Figs. 3a and 3b, respectively. The optimized geometric parameters of the PCSW is also

shown in Fig 3. It is worth noting that TE polarized light suffers Bragg reflection at the designed waveguide parameters whereas TM mode travels without any loss. The E-field distribution of the TM mode at the cross-section of the waveguide is shown in Fig. 3c.

The transmittance of the proposed PCSW structure is directly related to l of the PC as the bandgap can shift depending on the Λ. In Fig. 4, the transmittance of TE and TM polarized light is calculated versus l while d is kept constant at 150 nm. Λ is varied in the range of 250 nm to 550 nm.
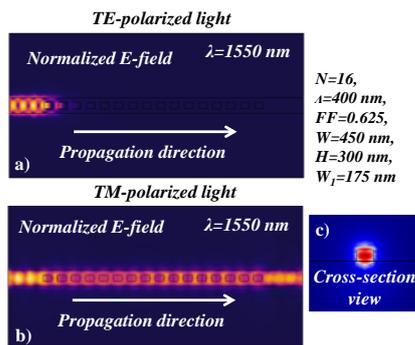
Fig. 3. Top view of a) normalized E-field distribution for TE-polarized light, b) normalized E-field distribution for TM polarized light, and c) cross-section view at TM polarized light.
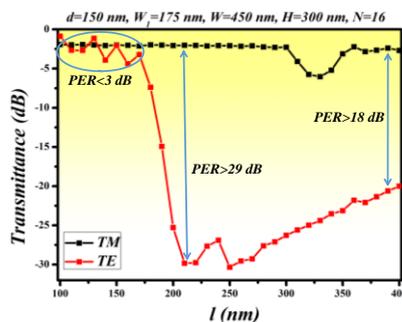

Fig. 4. Transmittance versus *l*, where *d* is fixed at 150 nm.

Here, we have used the optimized parameters obtained from Fig. 2, i.e. W=450 nm, H=300 nm, W_l=175 nm, d=150 nm and N=16. From Fig. 4, it can be seen that TM polarized light at 1550 nm has a constant transmittance of ~2 dB for l=100 nm to 300 nm. From l=300 nm to l=350 nm, there is a fall in power to 6 Db, which recovers as the l increases. However, for TE polarized light, the region where 200 nm < l < 300 nm is interesting as *PER* is greater than 25 dB.
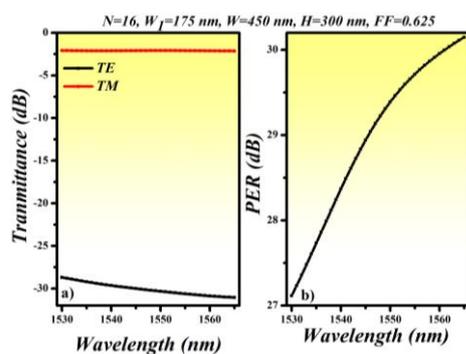

Fig. 5. a) Transmittance versus telecommunication C-band wavelength, b) PER versus telecommunication C-band wavelength.

In the end, we have simulated the optimized device design for the C-band telecommunication wavelengths to calculate the transmittance of TE and TM polarized light and PER as shown in Figs. 5 (a, b). In infrared optical communications, a C-band is dedicated to the wavelength range of 1530÷1565 nm, which corresponds to the

amplification range of an erbium-doped fiber amplifier. It can be seen that TM polarized light has a constant transmittance of ~2 dB while it is in the range of 28 dB to 31 dB for TE polarized light for the whole C-band. Thus, it is concluded that our proposed device can work as a TM-polarized telecommunication C-band pass filter of length 8.4 µm, which offers a *PER* of ~28.5 dB.

In conclusion, the TM polarization C-band telecommunication wavelengths pass filter based on one-dimensional photonic crystal strip waveguide is numerically studied. The waveguide structure is optimized to obtain the maximum transmittance of TM polarized light using the finite element method. The length, width and number of periods of the photonic crystal play an important role in the transmittance of the light (TE or TM). The optimized length of the device is approximately 8.4 µm, which includes 6.4 µm PC segment and 1 µm of the strip waveguide segment on both ends of the device. The maximum transmittance of ~2dB of TM polarized light is obtained for the whole C-band telecommunication wavelengths for the following geometric parameters: W=450 nm, H=300 nm, W_l=175 nm, d=150 nm, l=250 nm, N=16. However, for TE polarized light, the transmittance is at ~ 28 dB to 30 dB, which leads to a high *PER* of 27.1 dB to 30.1 dB.

References

[1] B. Wang, S. Blaize, R.S-Montiel, Nanoscale **11**, 20685 (2019).
[2] D. Dai, J.E. Bowers, Nanophoton. **3**, 283 (2014).
[3] M.A. Butt, S.N. Khonina, N.L. Kazanskiy, Comp. Opt. **43**, 1079 (2019).
[4] M.A. Butt, S.N. Khonina, N.L. Kazanskiy, Laser Physics **28**, 116202 (2018).
[5] M.A. Butt, S.N. Khonina, N.L. Kazanskiy, Laser Physics **29**, 046207 (2019).
[6] Q. Wang, S.-T. Ho, IEEE Photonics J. **2**, 49 (2010).
[7] C.-H. Chen, L. Pang, C.-H. Tsai, U. Levy, Y. Fainman, Opt. Expr. **13**, 5347 (2005).
[8] S. Yuan, Y. Wang, Q. Huang, J. Xia, J. Yu, 11th International Conference on Group IV Photonics (GFP) (IEEE, 2014), pp. 183-184.
[9] X. Guan, P. Chen, S. Chen, P. Xu, Y. Shi, D. Dai, Opt. Lett. **39**, 4514 (2014).
[10] A.E.- S. Abd-Elkader, M.F.O. Hameed, N.F. Areed, H.E.-D. Mostafa, S.S. Obayya, J. Opt. Soc. Am. B. **36**, 652 (2019).
[11] J. Li *et al*., J. Lightwave Technol. **31**, 1601 (2013).
[12] N. Skivesen *et al*., Opt. Expr. **15**, 3169 (2007).
[13] S. Lin, J. Hu, L. Kimerling, K. Crozier, Opt. Lett. **34**, 3451 (2009).
[14] T. Liu, A.R. Zakharian, M. Fallahi, J.V. Moloney, M. Mansuripur, IEEE Photon. Technol. Lett. **17**, 1435 (2005).
[15] R.K. Sinha, Y. Kalra, Opt. Expr. **14**, 10790 (2006).