

Optical Mode Cross-Connect Using Multimode Interference Mmi Based On Silicon Material

Ho Duc Tam Linh*, Vo Duy Phuc, Nguyen Quang Viet, Nguyen Duc Hien, Nguyen Tan Hung

Abstract—An optical mode cross-connect (OMXC) between fundamental modes using a multimode interference coupler (MMI) with high performance has been proposed in this paper. These basic modes can be transmitted in turn or at the same time to any input and be able to select arbitrary outputs. The following inputs can only select the remaining outputs, so this process will not cause bottlenecks in the circuit. In order for the signals to be flexibly switched to the outputs without conflict, the phase shifters will be used to control their lightpaths. Through the BPM-3D beam propagation method, we have shown the flexible switching process between the input and output ports of the device with an insertion loss always smaller than 1.8 dB in the range of wide wavelength from 1.53 μm to 1.57 μm . Specifically, attenuation only reaches -0.5 dB at the central wavelength of 1.55 μm . In addition, the crosstalk is always in a very small range from -30 dB to -20 dB for the entire band considered above. With these advantages, it is a promising device for optical mode processing circuits in the MDM system.

Index Terms—Optical mode cross connect; BPM-3D; SOI; channel structure; MMI.

1. Introduction

IN recent years, with the rapid development of optical transmission, it has contributed to solve the electric transmission disadvantages, which are limited in bandwidth and slow transmission speed and difficult to develop further in the future. Currently, WDM wavelength division multiplexing technology dominates the optical transmission network, but this technology is also facing the exhaustion of the number of wavelengths. Therefore, MDM technology is being studied in combination with WDM technology to overcome the shortage of these wavelengths. A very important component of the WDM system is the optical cross connector (OXC), which is widely studied and applied [1]–[5]. However, optical mode cross-connectors (OMXC) for mode division multiplexing networks are rarely studied. Several 2-mode switches that act as optical mode cross-connectors are published. Specifically, based on an asymmetric directional coupler and optical thermal effect, a two-mode

selective switch with a total size of 16.5 mm is proposed [6]. Each mode is selected for any output by controlling the heater. The paper [7] is also a two-mode flexible switch using a multimode interference coupler, a Y-junction and a PN-doped junction-based phase shifter. Another proposal uses MEMs microelectromechanical systems to switch LP01 and LP11 modes at the desired output [8].

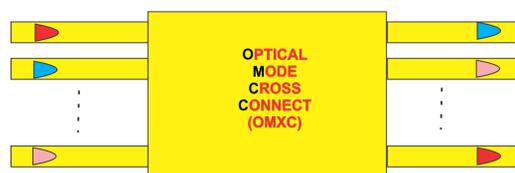


Fig. 1: General diagram of optical mode cross connector OMXC.

To build a switch that supports more channels in the MDM system illustrated in Fig. 1, we designed a single-mode OMXC 3x3 in this paper. The advantage of the MMI component is its compact size and ease of fabrication, so the design of the OMXC device using the MMI component will reduce the size of the device compared to the previous proposals. By changing the appropriate phase values to control the path of the signal, each signal at the input is selected to any output without overlap at the output.

2. Structure Design

The OMXC is designed and shown in Fig. 2. The device consists of four MMIs divided into two pairs (MMI1; MMI4) at the device's beginning and end, and a pair (MMI2; MMI3) in the middle. Each of these MMI pairs is the same completely. In addition, the

Ho Duc Tam Linh is with Hue University of Sciences, Vietnam (e-mail: hdtlinh@husc.edu.vn).

Vo Duy Phuc is with the University of Danang - University of Science and Technology, Danang, Vietnam (e-mail: vdphuc@dut.udn.vn).

Nguyen Quang Viet is with the University of Danang - University of Science and Technology, Danang, Vietnam (e-mail: vietdlmc@gmail.com).

Nguyen Duc Hien is with the University of Danang - Vietnam - Korea University of Information and Communication Technology, Danang, Vietnam (e-mail: ndhien@vku.udn.vn).

Nguyen Tan Hung is with the University of Danang - Advanced Institute of Science and Technology, Vietnam; The University of Danang - University of Science and Technology, Danang, Vietnam (e-mail: hung.nguyen@ac.udn.vn)

*Corresponding author: Ho Duc Tam Linh (e-mail: hdtlinh@husc.edu.vn)
Manuscript received April 13, 2022; revised May 10, 2022; accepted June 15, 2022.

Digital Object Identifier 10.31130/ud-jst.2022.160ICT

device structure has five phase shifters located at the appropriate input and output positions of MMI. In addition, we will use a quadrilateral taper to improve optical signal transmission performance between MMI and access waveguide, with $L_{TP} = 4 \mu\text{m}$ and $W_{TP} = 0.8 \mu\text{m}$ corresponding to its length and width.

The Silicon core material layer with a refractive index of $n = 3.47$ is covered by upper and lower layers made of silicate material. These two shells have a refractive index of 1.44. The height of this channel waveguide is chosen at $H = 0.22 \mu\text{m}$.

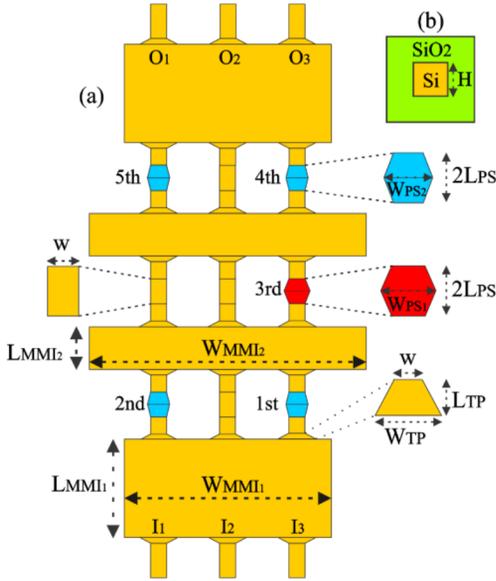


Fig. 2: Structure of OMXC 3x3.

2.1. Multimode Interference (MMI) Coupler

The MMI device consists of two parts: a rectangular multimode waveguide in the center, and access waveguides that only support a single mode placed in the rectangular waveguide's input and output positions. We designed them using the self-imaging principle, as shown in [9], [10], and the relationship between signal amplitude and phase, as shown in [11]. Based on that theory, we choose a width of $W_{MMI1} = 3.9 \mu\text{m}$ and a length of $L_{MMI1} = 64.2 \mu\text{m}$ for the MMI coupler, with the positions of the three access waveguides corresponding to $\pm W_{MMI1}/3$ and the central location of the MMI1 region. For two MMI2 and MMI3 couplers, they also have an access waveguide placed in the central position, and the two remaining waveguides are arranged at two positions $W = \pm 2 \mu\text{m}$. The rectangular MMI2 and MMI3 have lengths and widths chosen $W_{MMI2} = W_{MMI3} = 5.0 \mu\text{m}$ and $L_{MMI2} = L_{MMI3} = 25.8 \mu\text{m}$, respectively.

For MMI1, we have two properties as follows: when sending a signal to the input port 2 of MMI1, the signal will go straight to the output port 2. Another characteristic of MMI1 is that when we only transmit one signal to port 1 or port 3, we will simultaneously get two signals of equal amplitude at ports 1 and 3,

but the phase of the two signals at these two ports is different by an amount of 90 degrees.

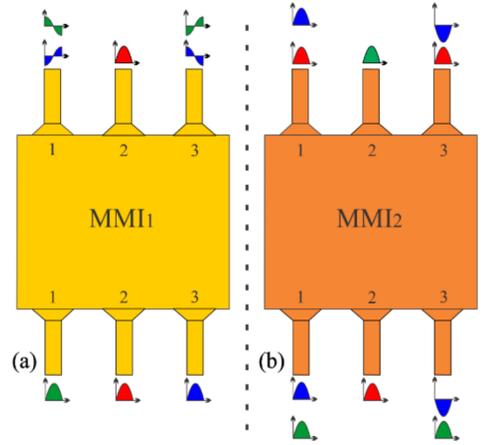


Fig. 3: The operating principle of two couplers MMI1 and MMI2.

In contrast to the nature of MMI1, when a signal is transmitted to the input port 2 of MMI2, two signals with the same phase and amplitude at two output ports, 1 and 3, will be obtained at the same time. In addition, if we send two signals exactly the same on ports 1 and 3, we will get a composite signal at output port 2. On the other hand, at the two inputs 1 and 3, two signals are transmitted simultaneously with equal amplitudes but out of phase by 180 degrees. Then the two output ports 1 and 3 of MMI2 also receive the correct amplitude and phase of the two input ports.

2.2. Phase shifter

For simulations, instead of using thermo-optic [12]–[15] or electric-optic [16]–[25] phase shifters, a passive phase shifter in which the length $L_{PS1} = 8.4 \mu\text{m}$ and the width $W_{PS1} = 0.35 \mu\text{m}$ of tapered waveguide is used to shift amount of phase of 180 degrees. Another phase shifter with the length $L_{PS1} = 8.4 \mu\text{m}$ and the width $W_{PS2} = 0.38 \mu\text{m}$ will shift a phase of 90 degrees (Figure 4). We will use these two phase shifters to control the signals in the proposed phase.

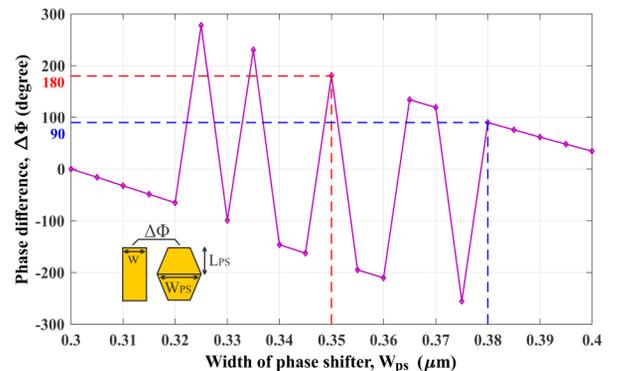


Fig. 4: Phase shifting value as functions of the central width W_{PS} .

In order for the signals at the inputs to switch to the desired outputs, the phase shifters must be placed at the

appropriate positions. With three inputs and outputs, six general cases will describe all switching cases, as shown in the Table 1.

TABLE 1: Setting of phase shifters for all situations of the OMXC.

Switching cases	Phase shifter				
	1st	2nd	3rd	4th	5th
$I_1 - O_1$ $I_2 - O_2$ $I_3 - O_3$	0^0	90^0	0^0	0^0	90^0
$I_1 - O_1$ $I_2 - O_3$ $I_3 - O_2$	0^0	90^0	180^0	0^0	90^0
$I_1 - O_2$ $I_2 - O_3$ $I_3 - O_1$	90^0	0^0	180^0	0^0	90^0
$I_1 - O_2$ $I_2 - O_1$ $I_3 - O_3$	90^0	0^0	180^0	90^0	0^0
$I_1 - O_3$ $I_2 - O_2$ $I_3 - O_1$	0^0	90^0	0^0	90^0	0^0

3. Performance Evaluation And Discussion

With the theory mentioned in Section II, the wavelength $\lambda = 1.55 \mu\text{m}$ is chosen to survey the proposed device. Because there are so many switching cases, we only choose one general case to explain the working principle of optical cross-connectors, and the remaining general cases are explained in a similar way.

From the Fig. 2a, assuming the signal at input port I_1 is the first priority to select the output port, it has three output choices (O_1, O_2, O_3). If the input signal I_1 switches to output O_1 , two inputs (I_2, I_3) have only two choices to output (O_2, O_3). If the signal is switched from input I_2 to O_2 , the remaining input I_3 is required to select O_3 output. With the above selection ($I_1 \rightarrow O_1, I_2 \rightarrow O_2, I_3 \rightarrow O_3$), based on the table in Section II, Part B, two phase shifters of 90 degrees are placed at the positions (2nd and 5th). Conversely, if the input signal I_1 still selects O_1 output but the signal at input I_2 to switch to output O_3 , then the O_2 output will surely receive the signal when the input signal is input I_3 . Based on Table 1, we can see that, for switching ($I_1 \rightarrow O_1, I_2 \rightarrow O_3, I_3 \rightarrow O_2$), all three phase shifters will be used, with two 90-degree phase shifters located at the positions (2nd and 5th) and the remaining 180-degree phase shifter will be placed in the 3rd position. In particular, the signaling order at the inputs is not important for output selection.

To illustrate the case of clear and detailed switching, the images of the field distribution at the input switches to the desired outputs with the beam propagation method (3D-BPM) [26] are shown in Figs. (5, 6 and 7).

For more accurate evaluation of optical power conversion efficiency, we use two insertion loss (IL) and crosstalk (CT) parameters to investigate and evaluate conversion efficiency (dB) between the signal inputs and the output signals at optical band C. The IL and CT are given by the formula:

$$IL(\text{dB}) = 10\log_{10}\left(\frac{P_{\text{out-desirable}}}{P_{\text{in}}}\right) \quad (1)$$

$$CT(\text{dB}) = 10\log_{10}\left(\frac{P_{\text{out-desirable}}}{\sum P_{\text{out-unwanted}}}\right) \quad (2)$$

where $P_{\text{out-desirable}}$ is the received power at the desired output, $P_{\text{out-unwanted}}$ is the unwanted power at other outputs and P_{in} is the transmit power of the input signals.

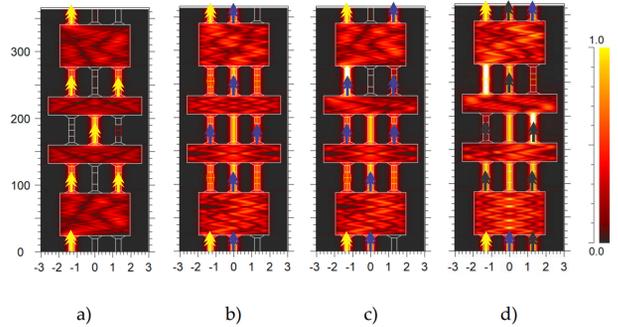


Fig. 5: The image of the optical field distribution of the signal at input port I_1 is the first priority to select the output port. (a) I_1 input - O_1 output; (b) Input I_1, I_2 - Output O_1, O_2 ; (c) Input I_1, I_2 - Output O_1, O_3 ; (d) Inputs I_1, I_2, I_3 - Outputs O_1, O_3, O_2 .

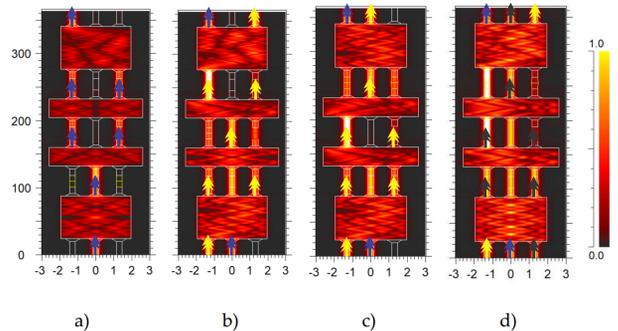


Fig. 6: The image of the optical field distribution of the signal at input port I_2 is the first priority to select the output port. (a) I_2 input - O_1 output; (b) Input I_2, I_1 - Output O_1, O_3 ; (c) Input I_2, I_1 - Output O_1, O_2 ; (d) Inputs I_2, I_1, I_3 - Outputs O_1, O_2, O_3 .

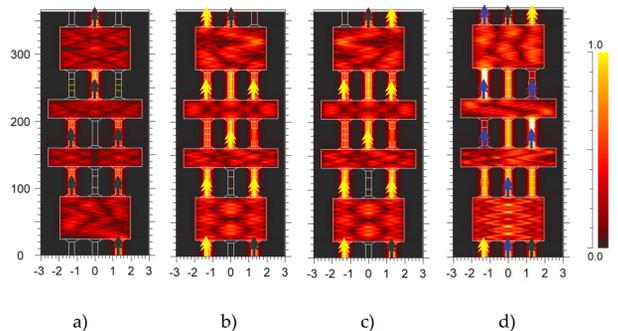


Fig. 7: The image of the optical field distribution of the signal at input port I_3 is the first priority to select the output port. (a) I_3 input - O_2 output; (b) Input I_3, I_1 - Output O_2, O_1 ; (c) Input I_3, I_1 - Output O_2, O_3 ; (d) Inputs I_3, I_1, I_2 - Outputs O_2, O_3, O_1 .

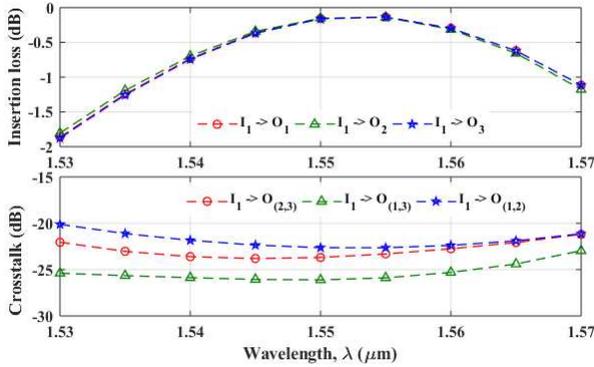


Fig. 8: Insertion Loss and Crosstalk as a function of wavelength for input signal I_1 .

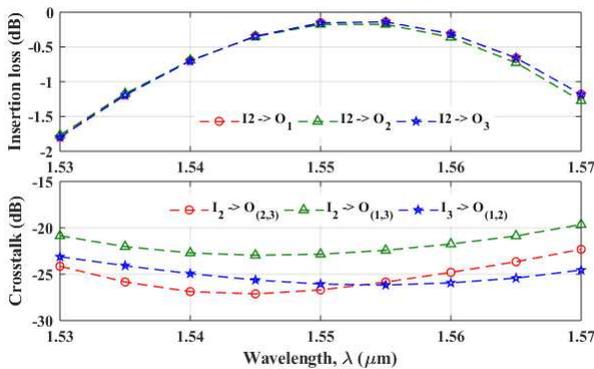


Fig. 9: Insertion Loss and Crosstalk as a function of wavelength for input signal I_2 .

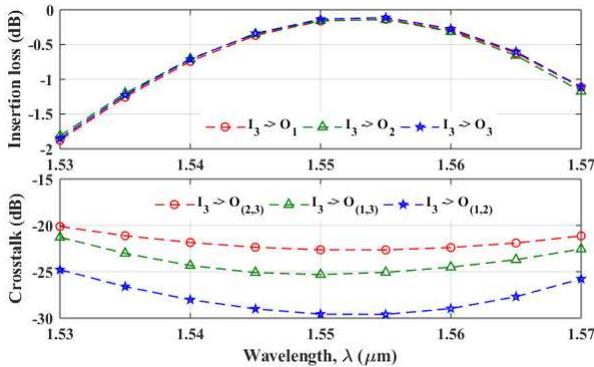


Fig. 10: Insertion Loss and Crosstalk as a function of wavelength for input signal I_3 .

The simulation results are shown in Figs. (8, 9 and 10). In the entire C band, insertion loss is always less than 1.8 dB, especially at the center wavelength of 1.55 μm , this value is always less than 0.5 dB. We also consider that within this wavelength range, the value of crosstalk in all conversion cases is from -30 dB to -20 dB. When transferring signal from I_3 to O_3 at center wavelength, this desirable signal is leaked through two unwanted outputs O_2 and O_3 is -30 dB. The largest

noise is the case of converting the signal from I_2 to O_2 at a wavelength of 1.57 μm , approximately -20 dB. However, at this wavelength, the optical conversion efficiency from the input to the desired output is also quite high, approximately 67%.

4. Conclusion

An OMXC optical mode cross connector with the ability to switch signals at any input to arbitrary output has been proposed in this article. The device's achieving insertion loss is always less than 0.5 dB corresponding to the received power of over 90% at 1.55 μm wavelength. In particular, in the entire C band, cross-channel noise always reaches values from -30 dB to -20 dB.

Acknowledgment

This research was supported by the University of Danang - Fund for Science and Technology Development under project number B2020-DN02-82.

References

- [1] D. T. H. Tan, K. Ikeda, S. Zamek, A. Mizrahi, M. Nezhad, and Y. Fainman, "Wavelength selective coupler on silicon for applications in wavelength division multiplexing," *2010 IEEE Photonics Soc. Summer Top. Meet. Ser. PHOSST 2010*, pp. 203–204, 2010.
- [2] T. Augustsson, "Proposal of a wavelength-selective switch based on an MMIMZI configuration with wavelength-selective phase-tuning circuits," *J. Light. Technol.*, vol. 20, no. 1, pp. 120–125, 2002.
- [3] H. Kishikawa, K. Kimiya, N. Goto, and S. I. Yanagiya, "All-optical wavelength-selective switch consisting of asymmetric X-junction couplers and Raman amplifiers for wide wavelength range," *J. Light. Technol.*, vol. 28, no. 1, pp. 172–180, 2010.
- [4] H. Kishikawa and N. Goto, "Proposal of All-Optical Wavelength-Selective Switching Using Waveguide-Type Raman Amplifiers and 3-dB Couplers," *Lightwave*, vol. 23, no. 4, pp. 1631–1636, 2005.
- [5] T. L. Tsai and J. C. Wu, "Low-complexity and high-flexibility design of a wavelength-selective switch using Raman amplifiers and directional couplers," *J. Light. Technol.*, vol. 26, no. 10, pp. 1226–1233, 2008.
- [6] X. Zi, L. Wang, K. Chen, and K. S. Chiang, "Mode-Selective Switch Based on Thermo-Optic Asymmetric Directional Coupler," *IEEE Photonics Technol. Lett.*, vol. 30, no. 7, pp. 618–621, 2018.
- [7] Y. Xiong, R. B. Priti, and O. Liboiron-Ladouceur, "High-speed two-mode switch for mode-division multiplexing optical networks," *Optica*, vol. 4, no. 9, p. 1098, 2017.
- [8] M. Hayashi, N. P. Diamantopoulous, Y. Yoshida, A. Maruta, and K. Kitayama, "Novel Mode-selective Packet Switching," *Photonic Switch.*, no. Topic 3, pp. 306–308, 2015.
- [9] M. P. B. Soldano, "Optical Multi-Mode Interference Devices Based on Self-Imaging: Principles and Applications," *J. Light. Technol.*, vol. 13, no. 4, p. 615, 1995.
- [10] D. D. Tu, H. D. T. Linh, V. Q. Phuoc, D. D. Thang, T. C. Dung, N. T. Hung, "Optical mode conversion based on silicon-on-insulator material Ψ -junction coupler and multimode interferometer," *Optics and Laser Technology*, Volume 142, 2021, 107177, ISSN 0030-3992.
- [11] M. Bachmann, P. A. Besse, and H. Melchior, "General self-imaging properties in NxN multimode interference couplers including phase relations," *Appl. Opt.*, vol. 33, no. 18, pp. 3905–3911, 1994.
- [12] A. Ribeiro and W. Bogaerts, "Digitally controlled multiplexed silicon photonics phase shifter using heaters with integrated diodes," *Opt. Express*, vol. 25, no. 24, p. 29778, 2017.

- [13] A. Masood et al., "Comparison of heater architectures for thermal control of silicon photonic circuits," *IEEE Int. Conf. Gr. IV Photonics GFP*, vol. 2, pp. 83–84, 2013.
- [14] N. C. Harris et al., "Efficient, Compact and Low Loss Thermo-Optic Phase Shifter in Silicon," *Opt. Express*, vol. 22, no. 9, pp. 83–85, 2014.
- [15] M. Mendez-Astudillo, M. Okamoto, Y. Ito, and T. Kita, "Compact thermo-optic MZI switch in silicon-on-insulator using direct carrier injection," *Opt. Express*, vol. 27, no. 2, p. 899, 2019.
- [16] F. Rosa et al., "Design of a carrier-depletion Mach-Zehnder modulator in 250 nm silicon-on-insulator technology," *Adv. Radio Sci*, vol. 15, pp. 269–277, 2017.
- [17] A. Samani et al., "A low-voltage 35-GHz silicon photonic modulator-enabled 112-Gb/s transmission system," *IEEE Photonics J.*, vol. 7, no. 3, 2015.
- [18] K. Debnath et al., "All-silicon carrier accumulation modulator based on a lateral metal-oxide-semiconductor capacitor," *Photonics Res.*, vol. 6, no. 5, p. 373, 2018.
- [19] J. Wang et al., "Optimization and demonstration of a large-bandwidth carrier-depletion silicon optical modulator," *J. Light. Technol.*, vol. 31, no. 24, pp. 4119–4125, 2013.
- [20] M. Okano, G. Cong, Y. Maegami, K. Yamada, and M. Ohno, "Strip-loaded waveguide-based optical phase shifter for high-efficiency silicon optical modulators," *Photonics Res.*, vol. 4, no. 6, p. 222, 2016.
- [21] M. Nedeljkovic, R. Soref, and G. Z. Mashanovich, "Free-carrier electrorefraction and electroabsorption modulation predictions for silicon over the 1-14- μm infrared wavelength range," *IEEE Photonics J.*, vol. 3, no. 6, pp. 1171–1180, 2011.
- [22] G. T. Reed, G. Mashanovich, F. Y. Gardes, and D. J. Thomson, "Silicon optical modulators," *Nat. Photonics*, vol. 4, no. 8, pp. 518–526, 2010.
- [23] I. Goykhman, B. Desiatov, S. Ben-Ezra, J. Shappir, and U. Levy, "Optimization of efficiency-loss figure of merit in carrier-depletion silicon Mach-Zehnder optical modulator," *Opt. Express*, vol. 21, no. 17, p. 19518, 2013.
- [24] S. Sakamoto et al., "Silicon-based phase shifters for high figure of merit in optical modulation," *Silicon Photonics XI*, vol. 9752, no. March, p. 975202, 2016.
- [25] C. Lacava et al., "496 Gb/s direct detection DMT transmission over 40 km single mode fibre using an electrically packaged silicon photonic modulator," *Opt. Express*, vol. 25, no. 24, p. 29798, 2017.
- [26] C. Vbquez and F. J. Mustieles, "Three-Dimensional method for Simulation of Multimode Interference Couplers," *J. Light. Technol.*, vol. 13, no. 11, pp. 2296–2299, 1995.



Vo Duy Phuc was born in Danang, Vietnam, in 1988. He received the B.E. degree from National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kiev, Ukraine in 2012, and the M.E. and Ph.D. degrees from National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kiev, Ukraine in 2014 and 2018. From 2014 to 2018, he was a Ph.D. student with Faculty of Radio Engineering, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kiev, Ukraine. He is currently a Teacher in the Department of Electronic and Telecommunication Engineering, the University of Danang - University of Science and Technology. His research interests include antennas theory, wireless communications, optical communications and networking, and photonic integrated circuits.



Nguyen Quang Viet was born in Danang, Vietnam, in 1973. He received a B.E. and is now pursuing an M.E. degree in Electronics and Telecommunications at the University of Danang - University of Science and Technology. He is currently working at Danang Urban Infrastructure Management Center. His main research is in photonic integrated circuits.



Nguyen Duc Hien is an Information Technology lecturer-researcher at the University of Danang (UDN) for over ten years. He is a faculty of Computer Science, the University of Danang - Vietnam-Korea University of Information and Communication Technology. He got a Ph.D. degree in Computer science in 2019. Before that, he spent two years in Pre-Ph.D program at Yuan Ze University (YZU) - Taiwan. His research interests are Algorithm Theory, Fuzzy Set Theory,

Fuzzy Modeling, Predictive Modeling. His strengths are researching, teaching, and managing at the College of Information Technology, the University of Danang - Vietnam-Korea University of Information and Communication Technology.



Nguyen Tan Hung was born in Danang, Viet Nam, in 1980. He received the B.E. degree from the University of Danang - University of Science and Technology, Da Nang, Vietnam, in 2003, and the M.E. and Ph.D. degrees from the University of Electro- Communications, Tokyo, Japan, in 2009 and 2012, respectively. From 2012 to 2016, he was a Researcher with the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan,

where he worked on ultrafast and spectrally efficient all-optical network technologies, and development of an all-optical wavelength converter. In 2016, he joined the University of Danang, Danang, Vietnam, where he is currently an Associate Professor and the Vice-Director of the University of Danang - Advanced Institute of Science and Technology. His research interests include optical communications and networking, all-optical signal processing and photonic integrated circuits.



Ho Duc Tam Linh was born in Hue, Vietnam, in 1986. He received the B.E. degree from Hue University of Science, Hue, Vietnam in 2009, and the M.E. degree from Vietnam National University-University of Engineering and Technology, Hanoi, Vietnam, in 2014. He is currently pursuing a PhD degree at The University of Danang-University of Science and Technology, Danang, Vietnam. His research interests include optical communications and

networking, all optical signal processing and photonic integrated circuits.