Realization of a Multichannel Chemical and Biological Sensor Using 6x6 Multimode Interference Structures

Trung-Thanh Le

***Abstract*—A new mirroring resonators (MRR) based on 6x6 multimode interference (MMI) couplers for multichannel and highly sensitive chemical and biological sensors is proposed in this paper. The proposed sensor structure has advantages of compactness, high sensitivity compared with the reported sensing structures. By using the transfer matrix method (TMM) and numerical simulations, the designs of the sensor based on silicon nanowires are optimized and demonstrated in detail.**

***Index Terms*— Biological sensors, chemical sensors, optical microring resonators, high sensitivity, multimode interference, transfer matrix method, beam propagation method**

I. Introduction

Current approaches to the real time analysis of chemical and biological sensing applications utilize systematic approaches such as mass spectrometry for detection. Such systems are expensive, heavy and cannot monolithically integrated in one single chip [1]. Electronic sensors use metallic probes which produces electro magnetic noise, which can disturb the electro magnetic field being measured. This can be avoided in the case of using optical sensors. Optical sensors are very attractive due to their advantages of high sensitivity and ultra-wide bandwidth.

A large class of optical sensors based on optical fibre and waveguides uses evanescent wave to monitor the presence of the analyte in the environment. Detection can be made by the optical absorption of the analytes, optic spectroscopy or the refractive index change [1]. The two former methods can be directly obtained by measuring optical intensity. The third method is to monitor various chemical and biological systems via sensing of the change in refractive index [2]. Optical waveguide devices can perform as refractive index sensors particularly when the analyte becomes a physical part of the device, such as waveguide cladding. In this case, the evanescent portion of the guided mode within the cladding will overlap and interact with the analyte. The measurement of the refractive index change of the guided mode of the optical waveguides requires a special structure to convert the refractive index change into detectable signals. A number of refractive index sensors based on optical waveguide structures have been reported, including Bragg grating sensors, directional coupler sensors, Mach- Zehnder interferometer (MZI) sensors, microring resonator sensors and surface plasmon resonance sensors [1-5].

Manuscript received August 25, 2011; revised October 25 2011

The author is with Hanoi University of Natural Resources and Environment, Hanoi, Vietnam. He is the Vice Dean in charge of the Faculty of Information Technology, 41A, Phu Dien, Tu Liem, Hanoi, Vietnam. (e-mail: thanh.le@hunre.edu.vn).

Recently, the use of optical microring resonators as sensors [4] is becoming one of the most attractive candidates for optical sensing applications because of its ultra-compact size and easy to realize an array of sensors with a large scale integration [6]. When detecting target chemicals by using microring resonator sensors, one can use a certain chemical binding on the surface. There are two ways to measure the presence of the target chemicals. One is to measure the shift of the resonant wavelength and the other is to measure the optical intensity with a fixed wavelength.

In the literature, some highly sensitive resonator sensors based on polymer microring and disk resonators have been developed. However, not much work on microring resonator sensors based on silicon nanowires [7, 8], which have ultra-small bends due to the high refractive index contrast and are compatible with the existing CMOS fabrication technologies. This has attracted much attention for realizing ultra-compact and cheap optical sensors. In addition, the reported sensors can be capable of determining only one chemical or biological element. Also, the sensing structures based on one microring resonator or Mach Zender interferometer can provide small sensitivity.

Therefore, in this paper, we focus on achieving a high sensitivity to the change of ambient refractive index by using a novel sensor structure based on multimode interference (MMI) coupler assisted microring resonators. The proposed sensors provide very high sensitivity compared with the conventional MZI sensors. In addition, it can measure three different and independent target chemicals and biological elements simultaneously.

Our research is differentiated from prior works in the way that our design is to employ multimode interference (MMI) couplers [9] as coupling elements instead of using directional couplers in microring resonators. MMI couplers have shown to have relaxed fabrication requirements, simplicity, and compactness and are less sensitive to the wavelength. The design of the proposed sensors will use silicon nanowire waveguides in order to take the advantages of the CMOS fabrication technologies [10]. The analytical description of output spectrum response of the proposed sensor is analyzed and derived. The transfer matrix method (TMM) [11] and beam propagation method (BPM) [12] are used to optimally design the sensor structure.

II. Sensor Design

A. Conventional Sensors Based on MZI Structure

It is shown that conventional MZI configuration can be used as a refractive index sensor [1]. The conventional MZI sensor configuration is shown in Fig. 1. It consists of two waveguides lied between two 3dB directional couplers. A window in the upper cladding isolation layer over one arm of the MZI is opened to create an active sensing region of length L_a , in which the evanescent tail of the waveguide mode may interact with an analyte. The other arm of the MZI is optically isolated from the analyte and serves as a reference arm.

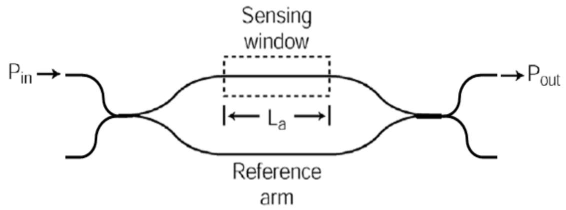


Fig. 1. Schematic of a conventional MZI sensor

The relative phase shift $\Delta\varphi$ between two *MZI* arms and the optical power transmitted through the MZI can be made a function of the environmental refractive index, via the modal effective index n_{eff} . The transmission at the bar port of the MZI structure can be given by [1]

$$T_{MZI} = \frac{P_{out}}{P_{in}} = \cos^2(\frac{\Delta\varphi}{2}) \quad (1)$$

where P_{in} and P_{out} are input and output powers; $\Delta\varphi$ is the phase difference between two arms of the MZI, $\Delta\varphi = \frac{2\pi}{\lambda} L_a(n_{eff,a} - n_{eff,ref})$. Where $n_{eff,a}$ and $n_{eff,ref}$ are the refractive index of mode propagating in sensing arm and reference arm, respectively.

The sensitivity S_{MZI} of the MZI ssensor is defined as the change in normalized transmission per unit change in the refractive index and can be expressed as

$$S_{MZI} = \frac{\partial T_{MZI}}{\partial n_c} \quad (2)$$

where n_c is the cover medium refractive index or the refractive index of the analyte. The sensitivity of the MZI sensor can be rewritten by

$$S_{MZI} = \frac{\partial T_{MZI}}{\partial n_c} = \frac{\partial T_{MZI}}{\partial n_{eff,a}} \frac{\partial n_{eff,a}}{\partial n_c} \quad (3)$$

The waveguide sensitivity parameter $\frac{\partial n_{eff,a}}{\partial n_c}$ can be calculated using the variation theorem for optical waveguides [1]:

$$\frac{\partial n_{eff,a}}{\partial n_c} = \frac{\frac{n_c}{n_{eff,a}} \iint_{analyte} |E_a(x,y)|^2 dxdy}{\iint_{\infty} |E_a(x,y)|^2 dxdy} \quad (4)$$

where $E_a(x, y)$ is the transverse field profile of the optical mode within the sensing region, calculated assuming a dielectric material with index n_c occupies the appropriate part of the cross-section. The integral in the numerator is carried out over the fraction of the waveguide cross-section occupied by the analyte and the integral in the denominator is carried out over the whole cross-section.

For sensing applications, sensor should have steeper slopes on the transmission and phase shift curve for higher sensitivity. From (2), (3) and (4), one can see that the sensitivity of the MZI sensor is maximized at phase shift $\Delta\varphi = \frac{\pi}{2}$. Therefore, the sensitivity of the MZI sensor can be enhanced by increasing the sensing window length L_a or increasing the waveguide sensitivity factor $\frac{\partial n_{eff,a}}{\partial n_c}$, which can be obtained by properly designing optical waveguide structure. In this design, we propose a new sensor structure based on microring resonators for very high sensitive and multi-channel sensing applications.

B. Realization of Novel Sensors Based on 6x6 MMI Structures

The proposed sensor based on 6x6 multimode interference and microring resonator structures is shown in Fig. 2 . The two MMI couplers are identical. The two 6x6 MMI couplers have the same width W_{MMI} and length L_{MMI} . In this structure, there are four sensing windows having lengths $L_{a1}, L_{a2}, L_{a3}, L_{a4}$. As with the conventional MZI sensor device, segments of four MZI arms having lengths $L_{a1}, L_{a2}, L_{a3}, L_{a4}$ overlap with the flow channel, forming four separate sensing regions. The other four MZI arms isolated from the analyte by the micro fluidic circuit's substrate.

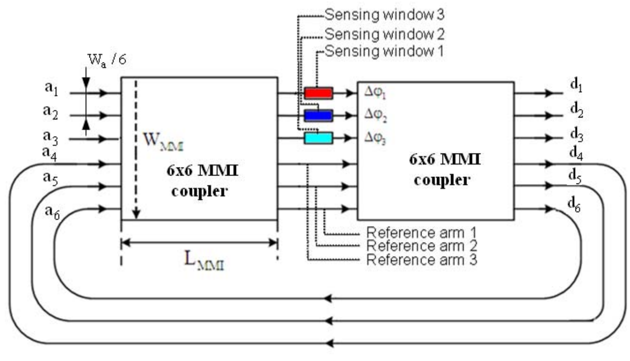


Fig. 2. Schematic of the new sensor using 6x6 MMI couplers and microring resonators. Four arms of the MZI is exposed to the analyte within the interaction regions of lengths $L_{a1}, L_{a2}, L_{a3}, L_{a4}$

The operation of optical MMI coupler is based on the self-imaging principle [13]. Self-imaging is a property of a multimode waveguide by which as an input field is reproduced in single or multiple images at periodic intervals along the propagation direction of the waveguide. The central structure of the MMI filter is formed by a waveguide designed to support a large number of modes. In the MMI section, the 2-D scalar Helmholtz wave equation is defined as

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\left[\frac{2\pi n(x,y)}{\lambda}\right]^2\psi=\beta^2\psi \tag{5}$$

where $\psi(x,y,z)=\sum_{\nu=0}^{M-1}c_\nu\psi_\nu(x,y)\exp(j(\omega t-\beta_\nu z))$; x is the lateral dimension; y is the transverse dimension; z is the propagation direction; c_ν is the field excitation coefficient; $\psi_\nu(x,y)$ is the modal field distribution; $n(x,y)$ is the refractive index profile, ν =0, 1,…, $M-1$ are the mode numbers of the waveguide supporting M modes; λ is the optical wavelength and β is the propagation constant.

If we choose the MMI coupler having a length of $L_{MMI}=2L_2=\frac{3L_\pi}{2}$, where L_π is the beat length of the MMI coupler, $L_\pi=\frac{\pi}{\beta_1-\beta_2}$; the MMI coupler is characterized by a transfer matrix M. We can prove that the overall transfer matrix S of both the MMI coupler and combiner in Fig. 2 is expressed by

$$\mathbf{S}=\frac{1}{\sqrt{2}}\begin{bmatrix} e^{j\frac{\pi}{4}} & 0 & 0 & 0 & 0 & e^{j\frac{3\pi}{4}} \\ 0 & e^{j\frac{\pi}{4}} & 0 & 0 & e^{j\frac{3\pi}{4}} & 0 \\ 0 & 0 & e^{j\frac{\pi}{4}} & e^{j\frac{3\pi}{4}} & 0 & 0 \\ 0 & 0 & e^{j\frac{3\pi}{4}} & e^{j\frac{\pi}{4}} & 0 & 0 \\ 0 & e^{j\frac{3\pi}{4}} & 0 & 0 & e^{j\frac{\pi}{4}} & 0 \\ e^{j\frac{3\pi}{4}} & 0 & 0 & 0 & 0 & e^{j\frac{\pi}{4}} \end{bmatrix} \tag{6}$$

This matrix can be considered as consisting of four separate sub-matrices which describe four 2x2 3dB MMI couplers, both having the transfer matrix

$$\mathbf{M_2}=\frac{1}{\sqrt{2}}\begin{bmatrix} e^{j\frac{\pi}{4}} & e^{j\frac{3\pi}{4}} \\ e^{j\frac{3\pi}{4}} & e^{j\frac{\pi}{4}} \end{bmatrix}=\frac{1}{\sqrt{2}}e^{j\frac{\pi}{4}}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \tag{7}$$

Relations between the complex amplitudes $a_1, a_2,..., a_6$ at the input ports and $d_1, d_2,..., d_6$ at the output ports can be expressed in terms of the transfer matrices of the 3dB MMI couplers and the phase shifters as follows

$$\begin{bmatrix} d_1 \\ d_6 \end{bmatrix}=je^{j\frac{\Delta\varphi_1}{2}}\begin{bmatrix} \tau_1 & \kappa_1 \\ \kappa_1^* & -\tau_1^* \end{bmatrix}\begin{bmatrix} a_1 \\ a_6 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} d_2 \\ d_5 \end{bmatrix}=je^{j\frac{\Delta\varphi_2}{2}}\begin{bmatrix} \tau_2 & \kappa_2 \\ \kappa_2^* & -\tau_2^* \end{bmatrix}\begin{bmatrix} a_2 \\ a_5 \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} d_3 \\ d_4 \end{bmatrix}=je^{j\frac{\Delta\varphi_1}{2}}\begin{bmatrix} \tau_3 & \kappa_3 \\ \kappa_3^* & -\tau_3^* \end{bmatrix}\begin{bmatrix} a_3 \\ a_4 \end{bmatrix} \tag{10}$$

where $\tau_1=\sin(\frac{\Delta\varphi_1}{2}),\kappa_1=\cos(\frac{\Delta\varphi_1}{2})$, $\tau_2=\sin(\frac{\Delta\varphi_2}{2}),\kappa_2=\cos(\frac{\Delta\varphi_2}{2})$; $\tau_3=\sin(\frac{\Delta\varphi_3}{2}),\kappa_3=\cos(\frac{\Delta\varphi_3}{2})$; $\Delta\varphi_1$, $\Delta\varphi_2$, $\Delta\varphi_3$ are the phase differences between two arms of the MZI, respectively.

One can prove that the normalized optical powers transmitted through the proposed sensor at wavelengths on resonance with the microring resonators are given by

$$T_1=\left|\frac{d_1}{a_1}\right|^2=\left[\frac{\alpha_1-\left|\cos(\frac{\Delta\varphi_1}{2})\right|}{1-\alpha_1\left|\cos(\frac{\Delta\varphi_1}{2})\right|}\right]^2 \tag{11}$$

$$T_2=\left|\frac{d_2}{a_2}\right|^2=\left[\frac{\alpha_2-\left|\cos(\frac{\Delta\varphi_2}{2})\right|}{1-\alpha_2\left|\cos(\frac{\Delta\varphi_2}{2})\right|}\right]^2 \tag{12}$$

$$T_3=\left|\frac{d_3}{a_3}\right|^2=\left[\frac{\alpha_3-\left|\cos(\frac{\Delta\varphi_3}{2})\right|}{1-\alpha_3\left|\cos(\frac{\Delta\varphi_3}{2})\right|}\right]^2 \tag{13}$$

Here α_1, α_2, and α_3 are round trip transmissions of light propagation through the four microring resonators [14] depending the losses of light propagation from output ports d_4, d_5, d_6 back to input ports a_4, a_5, a_5 ; for a lossless resonator $\alpha=1$. The proposed structure can be viewed as a sensor with four channel sensing windows, which are separated with four power transmission characteristics T_1, T_2, and T_3 and four sensitivities S_1, S_2 and S_3. This means that the proposed sensor is able to monitor four target chemicals simultaneously. Their sensitivities can be expressed by:

$$S_1=\frac{\partial T_1}{\partial n_c},\ S_2=\frac{\partial T_2}{\partial n_c},\ S_3=\frac{\partial T_3}{\partial n_c} \tag{14}$$

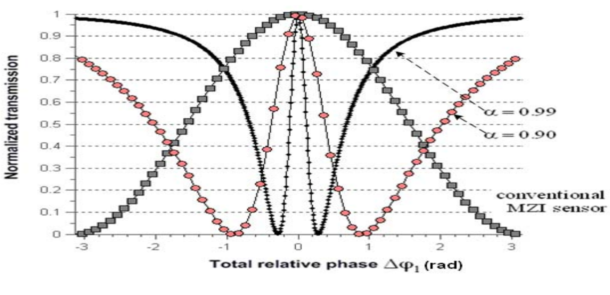


Fig. 3. Normalized optical transmissions as functions of total relative phase for the proposed sensor with $\alpha_1=0.99$ and 0.90 and conventional MZI sensor.

Fig. 3 compares the normalized transmission for the proposed sensor with $\alpha_1=0.99$ and 0.90 to that for the conventional MZI, as functions of the total relative phase $\Delta\varphi$. Given that the sensitivity is linearly proportional to the slope of the power transfer characteristics. Fig. 3 shows that the proposed sensor should have a higher sensitivity to a change in the refractive index of the analyte than the conventional MZI, when biased for operation with the region of large slope near $\Delta\varphi_1 = 0$.

From (2) and (16), the ratio of the sensitivities of the proposed sensor and the conventional MZI sensor can be numerically evaluated. The sensitivity enhancement factor S_1 / S_{MZI} can be calculated for values of α_1 between 0 and 1 is plotted in Fig. 4. For $\alpha_1 = 0.99$, an enhancement factor of approximately 10 is obtained. The similar results can be achieved for other sensing arms.

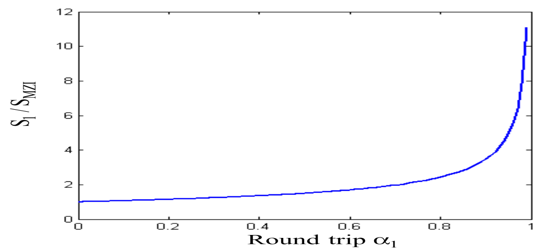


Fig. 4. Sensitivity enhancement factor for the proposed sensor, calculated with the first sensing arm.

III. Simulation Results and Discussion

It is now shown that the proposed sensor can be realized using silicon nanowire waveguides. The cross-section of the waveguide is shown in Fig. 5 [15]. The width of the MMI is $W_{MMI} = 8.4\mu m$ and the core thickness is h_{co} =220nm. The access waveguide is tapered to a width of 0.8 µm to improve device performance. It is assumed that the designs are for the transverse electric (TE) polarization at a central optical wavelength $\lambda = 1550nm$.

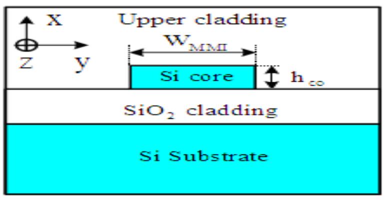
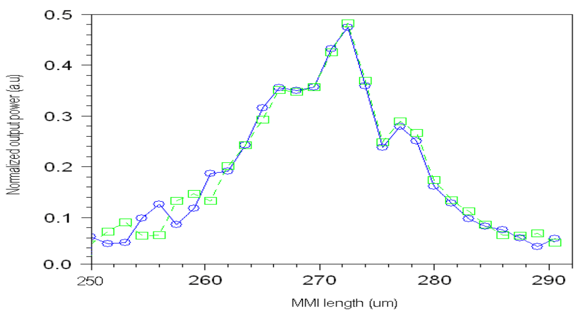
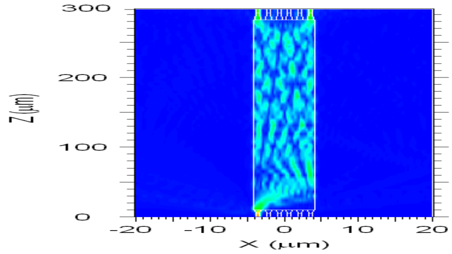


Fig. 5.Waveguide cross-section used in the designs of the device

The first 6x6 MMI coupler is now optimized by using the 3D BPM. Fig. 6(a) shows the normalized output powers at the bar and cross ports at different MMI lengths for a signal presented at input port 1 of the MMI coupler. From this simulation result, the optimized length of MMI calculated to be $L_{MMI} = 273.5\mu m$. The field propagation through the 6x6 MMI coupler at this optimized length is plotted in Fig. 6(b).



(a) Normalized output powers vs MMI length



(b) Field propagation

Fig. 6. BPM simulation results: (a) Normalized output powers vs the length of the 6x6 MMI coupler and (b) field propagation at the optimized MMI length

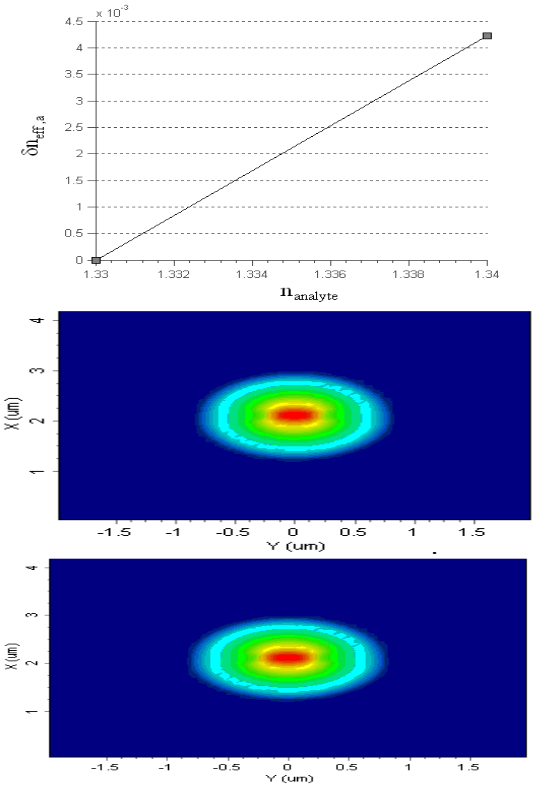


Fig. 6. (a) The change of the effective index as the increase of refractive index of the analyte for silicon nanowire waveguides, (b) optical field profile for $n_{analyte} = 1.33$ and (c) optical field profile for $n_{analyte} = 1.34$

From the simulation results of Fig. 6, the sensitivities of the proposed sensor and the conventional MZI with the active region length of $L_a = 100\mu m$ and $L_a = 500\mu m$ are plotted in Fig. 7. The simulations obviously show that the sensitivity of the proposed sensor is much higher than the sensitivity of the conventional MZI sensor.

It is obvious that the simulation results in Fig. 6 predict accurately our theory expressed by (5). From (1) and (3), one can obtain the sensitivity of the conventional MZI sensor by using $S_{MZI} = \frac{\partial T_{MZI}}{\partial n_c} = \frac{2\pi}{\lambda} L_a \frac{\partial n_{eff,a}}{\partial n_c}$. The relation between the effective index $n_{eff,a}$ and the ambient index or cladding index $n_{analyte} = n_c$ is achieved by using the beam propagation method (BPM). From this relationship, one can obtain the waveguide sensitivity factor $\frac{\partial n_{eff,a}}{\partial n_c}$. Fig. 6 shows the effective index change $\delta n_{eff,a}$ due to the ambient change for silicon nanowire waveguides having a width of 500nm.

From this simulation, one can see that the effective index $n_{eff,a}$ increases almost linearly in the change in the refractive index of ambient material, i.e., the waveguide sensitivity factor is almost a constant.

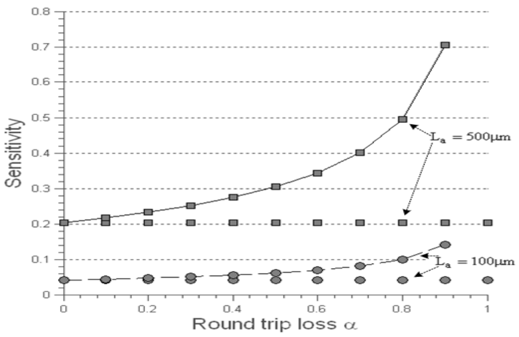


Fig. 7. Sensitivity of the proposed sensor for sensing window S1 and the conventional MZI sensor versus the round trip loss of the first microring resonator.

IV. CONCLUSION

We have presented a novel sensor structure based on 6x6 multimode interference structure and microring resonators. The design of the proposed sensors used silicon waveguides; therefore the sensor has advantages of compatibility with CMOS fabrication technology and compactness. It has been shown that the proposed sensors can provide a very high sensitivity compared with the conventional MZI sensor. In addition, by using 6x6 multimode interference couplers, our sensor structure can detect three separate target chemicals or biological elements simultaneously. The transfer matrix method and the beam propagation method have been used to verify the principle of operation and optimally design the proposed sensor structure.

REFERENCE

[1] V. M. N. Passaro, F. Dell'Olio, B. Casamassima, and F. D. Leonardis, "Guided-Wave Optical Biosensors," "*Sensors"*, vol. 7, pp. 508-536, 2007.

[2] L. Shi, Y. Xu, W. Tan, and X. Chen, "Simulation of Optical Microfiber Loop Resonators for Ambient Refractive Index Sensing," "*Sensors"*, vol. 7, pp. 689-696, 2007.

[3] H. Yi, D. S. Citrin, and Z. Zhou, "Highly sensitive silicon microring sensor with sharp asymmetrical resonance," "*Optics Express"*, vol. 18, pp. 2967-2972, 2010.

[4] Z. Xia, Y. Chen, and Z. Zhou, "Dual Waveguide Coupled Microring Resonator Sensor Based on Intensity Detection," "*IEEE Journal of Quantum Electronics"*, vol. 44, pp. 100-107, 2008.

[5] V. M. Passaro, F. Dell'Olio, and F. Leonardis, "Ammonia Optical Sensing by Microring Resonators," "*Sensors"*, vol. 7, pp. 2741-2749, 2007.

[6] C. L. Arce, K. D. Vos, T. Claes, K. Komorowska, D. V. Thourhout, and P. Bienstman, "Silicon-on-insulator microring resonator sensor integrated on an optical fiber facet," "*IEEE Photonics Technology Letters"*, vol. 23, pp. 890 - 892, 2011.

[7] K. De Vos, J. Girones, T. Claes, Y. De Koninck, S. Popelka, E. Schacht, R. Baets, and Bienstman, "Multiplexed Antibody Detection With an Array of Silicon-on-Insulator Microring Resonators," "*IEEE Photonics Journal"*, vol. 1, pp. 225 - 235, 2009.

[8] D. Dai, "Highly sensitive digital optical sensor based on cascaded high-Q ring-resonators," "*Optics Express"*, vol. 17, pp. 23817-23822, 2009.

[9] L. B. Soldano and E. C. M. Pennings, "Optical multi-mode interference devices based on self-imaging :principles and applications," "*IEEE Journal of Lightwave Technology"*, vol. 13, pp. 615-627, Apr 1995.

[10] N. A. Yebo, Taillaert, D. Roels, and D. Lahem, "Silicon-on-Insulator (SOI) Ring Resonator-Based Integrated Optical Hydrogen Sensor," "*IEEE Photonics Technology Letters"*, vol. 21, pp. 960 - 962, 2009.

[11] J. M. Heaton and R. M. Jenkins, " General matrix theory of self-imaging in multimode interference(MMI) couplers," "*IEEE* Photonics *Technology Letters"*, vol. 11, pp. 212-214, 1999.

[12] W. P. Huang, C. L. Xu, W. Lui, and K. Yokoyama, "The perfectly matched layer (PML) boundary condition for the beam propagation method," "*IEEE Photonics Technology Letters"*, vol. 8, pp. 649 - 651, 1996.

[13] M. Bachmann, P. A. Besse, and H. Melchior, "General self-imaging properties in N x N multimode interference couplers including phase relations," "*Applied Optics"*, vol. 33, pp. 3905-, 1994.

[14] W. Green, R. Lee, and G. D. e. al., "Hybrid InGaAsP-InP Mach-Zehnder Racetrack Resonator for Thermooptic Switching and Coupling Control," "*Optics Express"*, vol. 13, pp. 1651-1659, 2005.

[15] L. T. Thanh and L. Cahill, "The Design of 4×4 Multimode Interference Coupler Based Microring Resonators on an SOI Platform," "*Journal of Telecommunications and Information Technology, Poland"*, pp. 98-102, 2/2009.

Trung-Thanh Le received the B.Sc. and M.Sc. degrees in electronic and telecommunication engineering from Hanoi University of Technology, Vietnam in 2003 and 2005, respectively. He received the PhD degree in electronic and telecommunications engineering from La Trobe University, Australia in 2009. Since 2003, he has been a lecturer at National University of Transports and Communications. He is now with Hanoi University of Natural Resources and Environment, Vietnam and is the Vice Dean in charge of the Faculty of Information Technology.