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Microring Resonator Based on 3x3 General Multimode Interference Structures Using Silicon Waveguides for Highly Sensitive Sensing and Optical Communication Applications

Trung-Thanh Le *

Faculty of Information Technology, Hanoi University of Natural Resources and Environment, Ha Noi, Viet Nam 41A, Phu Dien road, Tu Liem, Ha Noi, Viet Nam

Abstract: In this paper, the realization and design of a novel waveguide microring resonator for biological and chemical sensing are presented. The structure of the proposed sensor uses a 3x3 multimode interference (MMI) coupler based on silicon waveguides for highly sensitivity, compactness and CMOS compatibility. The Fano resonances based on this structure can be achieved. As a result, sensors based on the proposed device can provide high sensitivity. In addition, many useful optical functions such as all-optical switches, filters and single-mode lasers can be realized using the proposed Fano-type transmission device. The transfer matrix method (TMM) and beam propagation method (BPM) are used to optimally design the sensor structure.

Keywords: Optical sensor; optical biosensing; microring resonator; multimode interference coupler; silicon waveguide.

1. Introduction

Optical sensors have been used widely in many applications such as biomedical research, healthcare and environmental monitoring. Typically, 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]. 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.

Recently, optical microring resonators are becoming versatile components for communication and sensing applications. Many optical devices based on microring resonators such as optical filters, optical multiplexers and optical switches have been reported [3]. Optical sensors based on microring resonators have attracted considerable attention due to their compactness and high sensitivity. However, only optical sensors using microring resonators based on 2x2 directional couplers or 2x2 multimode interference (MMI) couplers have been reported. In this study, the realization of a novel optical sensor based on a 3x3 multimode interference coupler is presented.

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* Corresponding author; e-mail: thanh.le@hunre.edu.vn

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The proposed sensor has advantages of compactness and high sensitivity compared with the reported sensors.

It has been suggested that optical Fano resonances have many important applications in highly sensitive chemical and biological sensing, optical switching, modulating and filtering [4, 5]. However, such structures need complex fabrication processes or complicated configurations. In this study, it is showed that the proposed microring resonator based on 3x3 general multimode interference couplers (GI-MMI) can provide the Fano like transmission. Therefore, the sensitivity of the sensor based on this structure can be greatly enhanced by steeping the slope of the transmission.

In addition, in the literature, ring resonator sensors have been made in some materials such as silicon on insulator (SOI), polymer and silicon nitride materials [3]. However, not much work on microring resonator sensors based on silicon nanowire waveguides [6], which have ultra-small bends due to its high refractive index contrast and are compatible with the existing CMOS (Complementary Metal-Oxide-Semiconductor) fabrication technologies. This has attracted much attention for realizing ultra-compact and cheap optical sensors. Therefore, another aim of this study is to use silicon nanowire waveguides for designing the proposed sensor structure.

2. Principle of operation

2.1. Optical sensor based on a 2x2 microring resonator

The MMI coupler consists of a multimode optical waveguide that can support a number of modes. In order to launch and extract light from the multimode region, a number of single mode access waveguides are placed at the input and output planes. If there are N input waveguides and M output waveguides, then the device is called an NxM MMI coupler.

The operation of optical MMI coupler is based on the self-imaging principle [7, 8]. Self-imaging is a property of a multimode waveguide by which as the 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 [9]

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\left[\frac{2\pi n(x,y)}{\lambda}\right]^2\psi=\beta^2\psi \tag{1}$$

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

There are a number of different interference mechanisms in the MMI coupler that can be employed. These mechanisms, namely general interference (GI), restricted interference (RI), and symmetric interference (SI) mechanisms, depend upon the locations of the access waveguides.

A typical microring resonator based on a 2x2 coupler is shown in Figure 1. The coupling element can be a 2x2 directional coupler or a 2x2 multimode interference coupler. Light is coupled into the input access waveguide (input port 1). Part of it is coupled into the microring resonator via the coupling element and then back into the access waveguide.

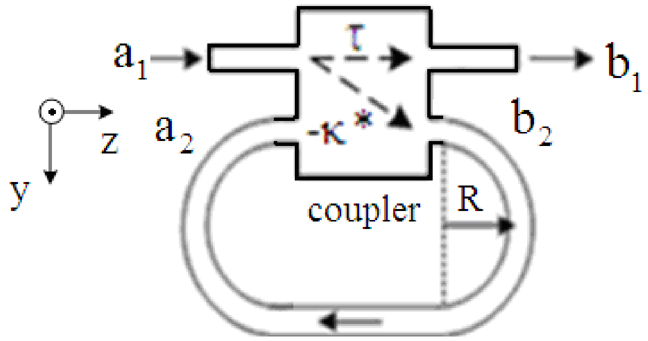


Figure 1. Scheme of an optical sensor based on a microring resonator using a 2x2 coupler

The relations between the input complex amplitudes a_1, a_2 and output complex amplitudes b_1, b_2 can be expressed as [10]

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \tau & \kappa \\ -\kappa^* & \tau^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{2}$$

$$a_2 = \alpha e^{j\varphi} b_2 \tag{3}$$

where κ and τ are the cross coupling coefficient and transmission coupling coefficient of the coupler; α is the loss factor of the field after one round trip through the microring resonator; $\varphi = 2\pi n_{eff} L / \lambda$ is the round trip phase, n_{eff} is the effective index and L is the microring resonator length. The normalized transmitted power at the output waveguide is:

$$T = \left| \frac{b_1}{a_1} \right|^2 = \frac{\alpha^2 - 2\alpha\tau\cos(\varphi) + \tau^2}{1 - 2\alpha\tau\cos(\varphi) + \alpha^2\tau^2} \tag{4}$$

When light is passed through the input port of the microring resonator, all of the light are received at the through port except for the wavelength which satisfies the resonance condition:

$$\lambda_r = \frac{n_{eff} L}{m} \tag{5}$$

where λ_r is the resonance wavelength and m is an integer representing the order of the resonance. The operation of the sensor using microring resonators is based on the shift of resonance wavelength. A small change in the effective index n_{eff} will result in a change in the resonance wavelength. The change in the effective index is due to a variation of ambient refractive index (n_a) caused by the presence of the analytes in the microring. The sensitivity of the microring resonator sensor is defined as [11]

$$S = \frac{\partial \lambda_r}{\partial n_a} = \frac{\partial \lambda_r}{\partial \lambda_{eff}} \frac{\partial \lambda_{eff}}{\partial n_a} = \frac{\partial \lambda_r}{\partial \lambda_{eff}} S_W \tag{6}$$

where n_a is the refractive index of the analyte and $S_W = \frac{\partial n_{eff}}{\partial n_a}$ is the waveguide sensitivity, that depends on the waveguide design and is a constant for a given waveguide structure.

Another important figure of merit for sensing applications is the detection limit δn_a. It can be defined as

$$\delta n_a \sim \frac{\lambda_r}{SQ} \tag{7}$$

where Q is the quality factor of the microring resonator [10]. It is desirable to have a small refractive index resolution, in which a small ambient index change can be detected. Therefore, high Q factor and sensitivity S are necessary.

2.2. Optical sensor based on a 3x3 GI-MMI microring resonator

Microring structures based on a 3x3 GI-MMI coupler for optical filtering, modulating and switching applications have been proposed in the literature [12-14]. The aim of this study is to show that this structure can be used for highly sensitive sensors. The schematic of a microring resonator based on a 3x3 MMI coupler is shown in Figure 2.

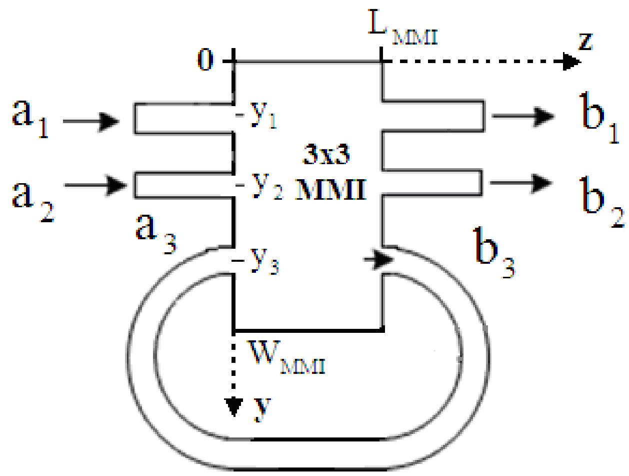


Figure 2. Microring resonators based on a 3x3 MMI coupler

The 3x3 GI-MMI coupler can be described by a transfer matrix $\mathbf{M}$ which describes the relationships between the input and output complex amplitudes (fields) of the coupler. However, in order for this microring resonator to operate correctly, the width, length and access waveguide positions need to be chosen carefully. It is assumed that the access waveguides are located at the positions: $y_1 = W_e/6$, $y_2 = W_e/2$, $y_3 = 5W_e/6$. The length of the MMI coupler is to be $L_{MMI} = L_\pi$. The relationship between the output complex amplitudes b_j (j=1,2,3) and the input complex amplitudes a_i (i=1,2,3) of the coupler can be expressed by

$$\mathbf{b} = \mathbf{M}\,\mathbf{a} \tag{8}$$

where $\mathbf{a} = [a_1\ a_2\ a_3]^T$, $\mathbf{b} = [b_1\ b_2\ b_3]^T$ and $\mathbf{M} = [m_{ij}]_{3x3}$ (i, j=1, 2, 3).

Equation (8) can be rewritten as

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} -e^{-j2\pi/3} & e^{-j2\pi/3} & -1 \\ e^{-j2\pi/3} & -1 & e^{-j2\pi/3} \\ -1 & e^{-j2\pi/3} & -e^{-j2\pi/3} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \tag{9}$$

where $$\mathbf{M} = \frac{1}{\sqrt{3}} \begin{pmatrix} -e^{-j2\pi/3} & e^{-j2\pi/3} & -1 \\ e^{-j2\pi/3} & -1 & e^{-j2\pi/3} \\ -1 & e^{-j2\pi/3} & -e^{-j2\pi/3} \end{pmatrix} \tag{10}$$

and $\phi_0 = -\beta_0 L_{MMI} + \frac{9\pi}{24}$, $a_3 = [\alpha \exp(j\theta)]b_3$, and $\alpha = \exp(-\alpha_0 L)$ is the transmission loss along the ring waveguide, where $L = 2\pi R + L_{MMI}$ and α_0 (dB/cm) is the loss coefficient in the core of the optical waveguide; $\theta = \beta_0 L$ is the phase accumulated over the racetrack waveguide, where $\beta_0 = 2\pi n_{eff} / \lambda$, and n_{eff} is the effective refractive index.

Therefore, the complex amplitudes at output ports 1 and 2 are given by

$$b_1 = (m_{11} + \frac{m_{13} m_{31} \alpha e^{j\theta}}{1 - m_{33} \alpha e^{j\theta}}) a_1 + (m_{12} + \frac{m_{13} m_{32} \alpha e^{j\theta}}{1 - m_{33} \alpha e^{j\theta}}) a_2 \tag{11}$$

$$b_2 = (m_{21} + \frac{m_{23} m_{31} \alpha e^{j\theta}}{1 - m_{33} \alpha e^{j\theta}}) a_1 + (m_{22} + \frac{m_{23} m_{32} \alpha e^{j\theta}}{1 - m_{33} \alpha e^{j\theta}}) a_2 \tag{12}$$

As a result, the transmissions at these output ports are given by:

For the input signal presented at input port 1 ($a_2 = 0$):

$$T_1 = \left| \frac{b_1}{a_1} \right|^2, \tag{13}$$

and $$T_2 = \left| \frac{b_2}{a_1} \right|^2 \tag{14}$$

For the input signal presented at input port 2 ($a_1 = 0$):

$$T_3 = \left| \frac{b_1}{a_2} \right|^2, \tag{15}$$

and $$T_4 = \left| \frac{b_2}{a_2} \right|^2 \tag{16}$$

3. Simulation results and discussion

It is now shown that the proposed device can be used for highly sensitive sensors. The aim of the designs is to use silicon nanowire waveguides due to its compatibility with existing CMOS technologies. The cross-section of the waveguide is shown in Figure 3. The core thickness is $h_{co} = 220nm$ and the access waveguide width is $W_a = 500nm$ for single mode operation and low loss [15, 16]. The width W_{MMI} of the MMI coupler is large enough to limit crosstalk between two adjacent waveguides. In this design, the width of the MMI coupler is chosen to be $W_{MMI} = 6\mu m$. The length of the MMI coupler is optimised by the 3D-BPM method and is found to be $L_{MMI} = 99.8\ \mu m$ at the operating wavelength of $\lambda = 1550nm$. The access waveguides are connected to the MMI waveguide via linear tapers having the same length of $L_{tp} = 5\mu m$ to reduce excess losses [9].

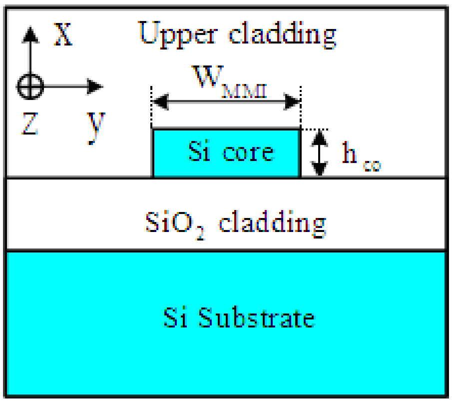
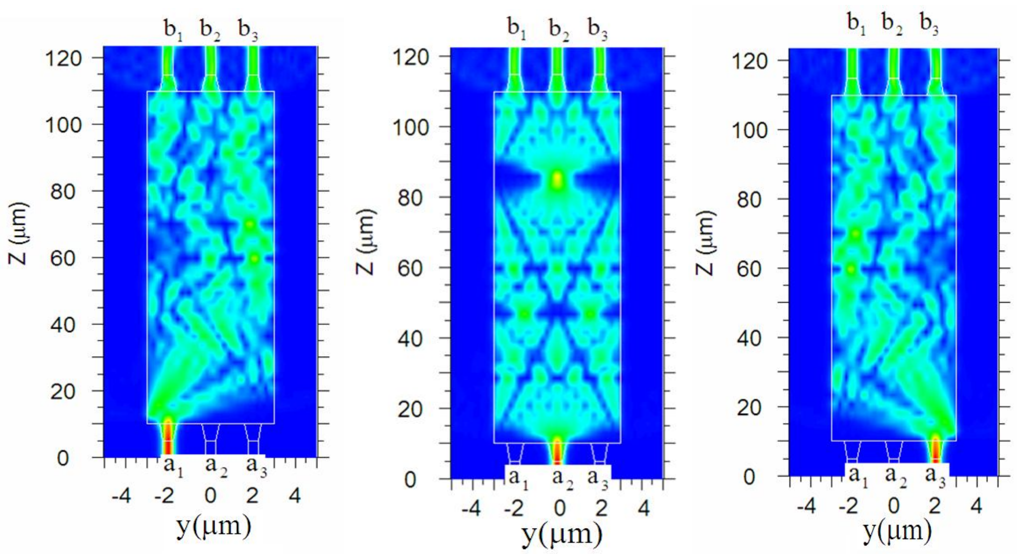


Figure 3. Waveguide cross-section used in the designs of the proposed device



(a) (b) (c)

Figure 4. 3D-BPM simulations of the 3x3 GI-MMI coupler for an input signal (a) at input port 1, (b) at input port 2, and (c) at input port 3

The BPM simulations for the signals presented at input ports 1, 2 and 3 are shown in Figure 4(a), 4(b) and 4(c), respectively. The normalized output power at each of the output ports is 0.31. As a result, 1x3 MMI splitters are formed. The 3D-BPM shows that there is a small excess loss of 0.31dB.

Figure 5 shows the transmission characteristics of the microring resonator based on 3dB 2x2 MMI (T) and 3x3 GI-MMI couplers (T_1). For the 3x3 GI-MMI based microring resonator, the input signal is excited at input port 1. The simulation parameters used in the designs are following: the loss factor is $\alpha = 0.98$ and the length of the microring waveguide is $L = 700\mu m$. The simulation results show that the slope of the 3x3 GI-MMI microring resonator structure is steeper than that of the 2x2 MMI microring resonator structure. As a result, a chemical or biological sensor based on the 3x3 GI-MMI structure can provide a higher sensitivity compared with the sensors based on 2x2 MMI microring resonators. In addition, the on-off ratio of the 3x3 GI-MMI based microring resonator is 34dB compared with an on-off ratio of 30 dB of the 2x2 MMI based microring resonator. Therefore, the sensor based on the 3x3 GI-MMI coupler has higher performance than that of the sensor based on the 2x2 MMI coupler.

The transmissions through the proposed device at output port 1 and port 2 are shown in Figure 6. The simulation shows that the sharp Fano line shapes can be achieved. This transmission characteristic can be useful for optical communication and sensing applications such as all-optical switches, sensors and single-mode lasers.

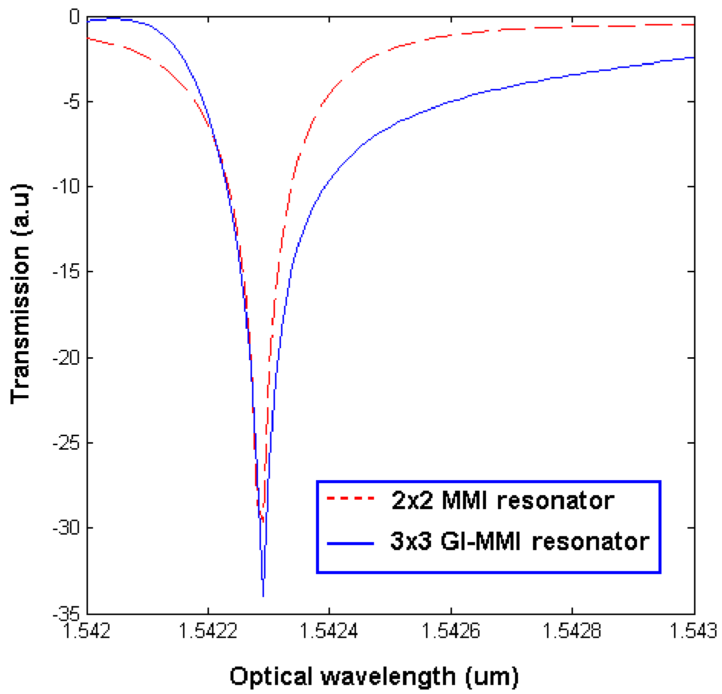


Figure 5. Transmission through the device for a microring resonator based on a 2x2 MMI coupler and a 3x3 GI-MMI coupler

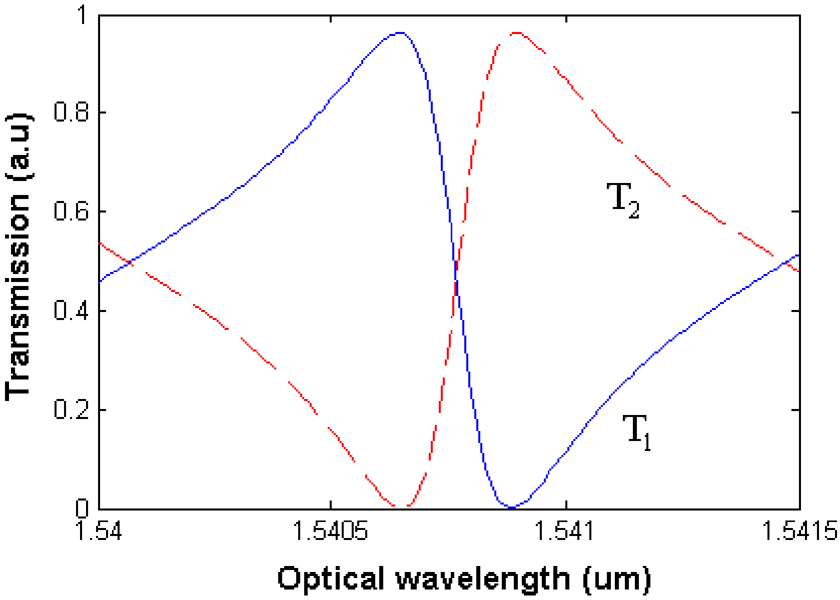


Figure 6. Transmission through the device at output port 1 and 2

4. Conclusion

A new sensor structure based on 3x3 GI-MMI coupler using silicon waveguides have been proposed. The proposed device can provide a steeper slope compared with the conventional sensor based on 2x2 MMI coupler and therefore the proposed sensor device can provide a high sensitivity. In addition, the proposed device can generate Fano shapes, that can be useful for all-optical switches, optical filters and single-mode lasers.

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