

## Sharp Asymmetric Resonance Based on 4x4 Multimode Interference Coupler

<sup>1</sup>Duy-Tien Le, <sup>2</sup>The-Duong Do, <sup>3</sup>Van-Khoi Nguyen, <sup>4</sup>Anh-Tuan Nguyen and <sup>5\*</sup>Trung-Thanh Le

<sup>1</sup>Posts and Telecommunications Institute of Technology (PTIT) and Finance-Banking University, Hanoi, Vietnam.

<sup>2</sup>Academy of Policy and Development (APD), Hanoi, Vietnam.

<sup>3</sup>University of Transport and Communications (UTC), Hanoi, Vietnam.

<sup>4,5</sup>International School (VNU-IS), Vietnam National University (VNU), Hanoi, Vietnam.

### Abstract

We propose a method for generating the tunable Fano resonance line sharp by using only one 4x4 multimode interference (MMI) coupler. We show that our new device structure acting an interferometer and we employ a microring resonator and phase shifter to control the shape. The analytical analysis and FDTD simulations have been used for the first order design. The device has advantages of compactness, high tolerance fabrication and ease of fabrication on the same chip.

**Keywords:** Multimode interference couplers, silicon wire, CMOS technology, optical couplers, Fano resonance, EIT, FDTD, BPM

### INTRODUCTION

Devices based on optical microring resonators have attracted considerable attention recently, both as compact and highly sensitive sensors and for optical signal processing applications [1, 2]. The resonance line shape of a conventional microring resonator is symmetrical with respect to its resonant wavelength. However, microring resonator coupled Mach-Zehnder interferometers can produce a very sharp asymmetric Fano line shape that are used for improving optical switching and add-drop filtering [3, 4].

However, it is shown that for functional devices based on one-ring resonator such as optical modulators and switches, it is not possible to achieve simultaneously high extinction ratio and large modulation depth. To maximize the extinction ratio and modulation depth, we can use an asymmetric resonance such as the Fano resonance. Fano resonance is a result of interference between two pathways. One way to generate a Fano resonance is by the use of a ring resonator coupled to one arm of a Mach-Zehnder interferometer, with a static bias in the other arm. The strong sensitivity of Fano resonance to local media brings about a high figure of merit, which promises extensive applications in optical devices such as optical switches [5]. Fano resonances have long been recognized in grating diffraction and dielectric particles elastic scattering phenomena. The physics of the Fano resonance is explained by an interference between a continuum and discrete state [6]. The simplest realization is a one-dimensional discrete array with a side coupled defect. In such a system scattering waves can either bypass the defect or interact with it. Recently, optical Fano resonances have also been reported in various optical micro-cavities including integrated waveguide-coupled microcavities [7], prism-coupled square micro-pillar resonators, multimode tapered fiber coupled micro-spheres and Mach-Zehnder interferometer (MZI) coupled micro-cavities [8], plasmonic waveguide structure [9, 10]. It has been suggested that optical Fano resonances have

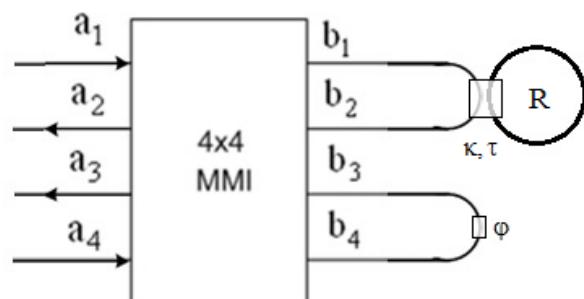
niche applications in resonance line shape sensitive bio-sensing, optical channel switching and filtering [11, 12].

In this paper, we propose a new structure based on only one 4x4 multimode interference coupler to produce Fano resonance line shape. The design of the devices is to use silicon waveguides that is compatible with CMOS technology. The proposed device is analyzed and optimized using the transfer matrix method, the beam propagation method (BPM) and FDTD [13].

### STRUCTURE AND OPERATING PRINCIPLES

A schematic of the structure is shown in Fig. 1. The proposed structure contains one 4x4 MMI coupler, where  $a_i$ ,  $b_i$  ( $i=1,\dots,4$ ) are complex amplitudes at the input and output waveguides. One single microring resonator and phase shifter  $\varphi$  are used in the arms.

Here, it is shown that by introducing the phase shifter to one arm, we can tune the Fano line shape. A microring resonator is introduced to create the phase difference between two arms and generating the asymmetric shape like Fano resonance.



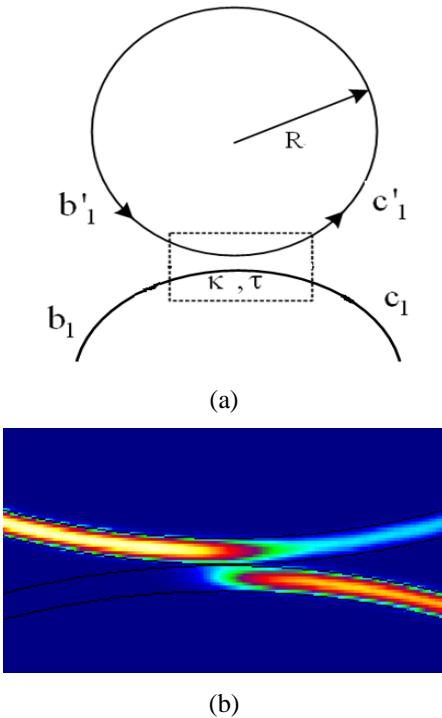
**Figure 1:** Schematic diagram of a 4x4 MMI coupler based device

Let consider a single ring resonator in the first arm of the structure of Fig. 1, the field amplitudes at input and output of the microring resonator can be expressed by using the transfer matrix method [14]

$$\begin{pmatrix} b_2 \\ c'_1 \end{pmatrix} = \begin{pmatrix} c_1 \\ c'_1 \end{pmatrix} = \begin{pmatrix} \tau & j\kappa \\ j\kappa & \tau \end{pmatrix} \begin{pmatrix} b_1 \\ b'_1 \end{pmatrix} \quad (1)$$

$$b'_1 = \alpha \exp(j\theta) c'_1 \quad (2)$$

Where  $\tau$  and  $\kappa$  are the amplitude transmission and coupling coefficients of the coupler, respectively; for a lossless coupler,  $|\kappa|^2 + |\tau|^2 = 1$ . The transmission loss factor  $\alpha$  is  $\alpha = \exp(-\alpha_0 L)$ , where  $L = \pi R$  is the length of the microring waveguide,  $R$  is the radius of the microring resonator and  $\alpha_0$ (dB/cm) is the transmission loss coefficient.  $\theta = \beta_0 L$  is the phase accumulated over the microring waveguide, where  $\beta_0 = 2\pi n_{\text{eff}} / \lambda$ ,  $\lambda$  is the optical wavelength and  $n_{\text{eff}}$  is the effective refractive index.



**Figure 2:** Schematic diagram of a microring resonator (a) directional coupler and (b) simulation of directional coupler with gap  $g=70\text{nm}$  and width  $w=500\text{nm}$

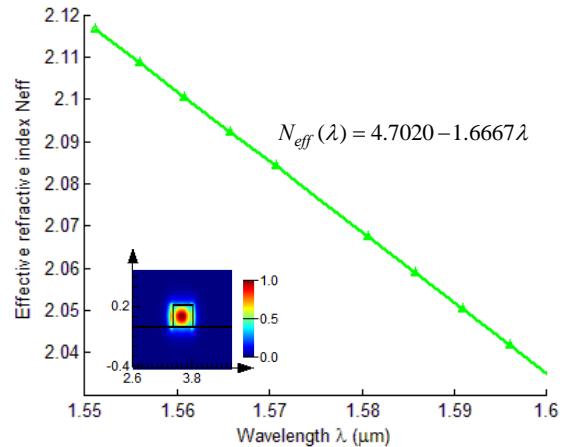
The effective index of the waveguide at different operating wavelength is calculated by numerical method (FDM method) shown in Fig. 3. In this research we use silicon waveguide for the design. The parameters used in the designs are as follows: the waveguide has a standard silicon thickness of  $h_{\text{co}} = 220\text{nm}$  and access waveguide widths are  $W_a = 0.5\text{ }\mu\text{m}$  for single mode operation. It is assumed that the designs are for the TE polarization at a central optical wavelength  $\lambda = 1550\text{nm}$ .

Therefore, the transfer response of the single microring resonator can be given by

$$\frac{b_2}{b_1} = \frac{\tau - \alpha \exp(j\theta)}{1 - \tau \alpha \exp(j\theta)} \quad (3)$$

The effective phase  $\phi$  caused by the microring resonator is defined as the phase argument of the field transmission factor, which is

$$\phi = \pi + \theta + \arctan\left(\frac{\tau \sin \theta}{\alpha - \tau \cos \theta}\right) + \arctan\left(\frac{\alpha \tau \sin \theta}{1 - \alpha \tau \cos \theta}\right) \quad (4)$$



**Figure 3:** Effective refractive index calculated by FDM method

As a result, the phase difference between two arms 1 and 4 of the structure is expressed by

$$\Delta\phi = \phi - \phi = \pi + \theta + \arctan\left(\frac{\tau \sin \theta}{\alpha - \tau \cos \theta}\right) + \arctan\left(\frac{\alpha \tau \sin \theta}{1 - \alpha \tau \cos \theta}\right) - \phi \quad (5)$$

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  $N \times M$  MMI coupler.

The operation of optical MMI coupler is based on the self-imaging principle [15, 16]. Self-imaging is a property of a multimode waveguide by which as 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 this paper, the access waveguides are identical single mode waveguides with width  $W_a$ . The input and output waveguides are located at

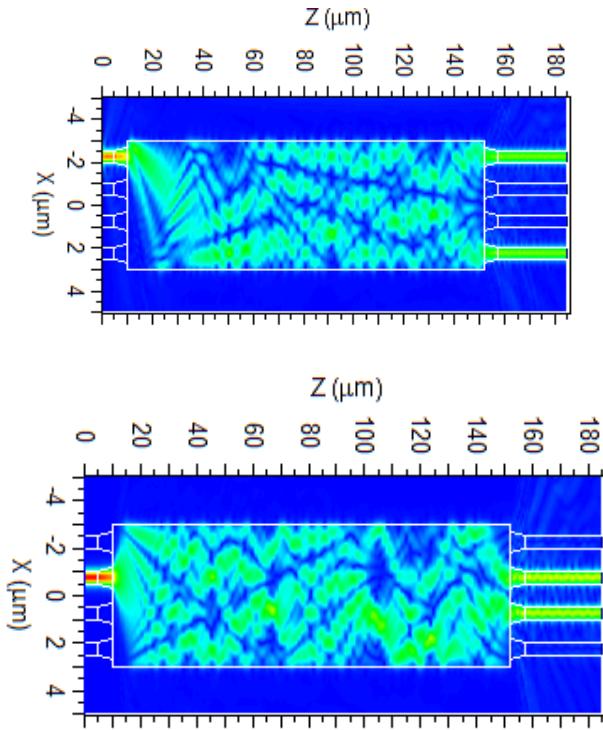
$$x = \left(i + \frac{1}{2}\right) \frac{W_{\text{MMI}}}{N}, \quad (i=0,1,\dots,N-1) \quad (6)$$

The electrical field inside the MMI coupler can be expressed by [17]

$$E(x, z) = \exp(-jkz) \sum_{m=1}^M E_m \exp\left(j \frac{m^2 \pi}{4\Lambda} z\right) \sin\left(\frac{m\pi}{W_{\text{MMI}}} x\right) \quad (7)$$

By using the mode propagation method, the length of  $4 \times 4$  MMI coupler with the width of  $W_{\text{MMI}}$  is to be  $L_{\text{MMI}} = \frac{3L_\pi}{2}$ . Then by using the BPM simulation, we showed that the width of the MMI is optimized to be  $W_{\text{MMI}} = 6\mu\text{m}$  for compact and high performance device. The 3D-BPM simulations for this

cascaded 4x4 MMI coupler are shown in Fig. 2(a) for the signal at input port 1 and Fig. 2(b) for the signal at input port 2. The optimised length of each MMI coupler is found to be  $L_{MMI} = 141.7 \mu\text{m}$ .



**Figure 2:** BPM simulations for 4x4 MMI coupler for input 1 and 2

After some calculations, we obtain the transmissions at the output port 2 and 3 of Fig.1 are given by

$$T_{\text{bar}} = \left| \cos\left(\frac{\Delta\varphi}{2}\right) \right|^2 \quad (8)$$

$$T_{\text{cross}} = \left| \sin\left(\frac{\Delta\varphi}{2}\right) \right|^2 \quad (9)$$

It will be shown that the transmissions have the Fano resonance line shape and the shape can be tuned by tuning the phase shifters  $\varphi$

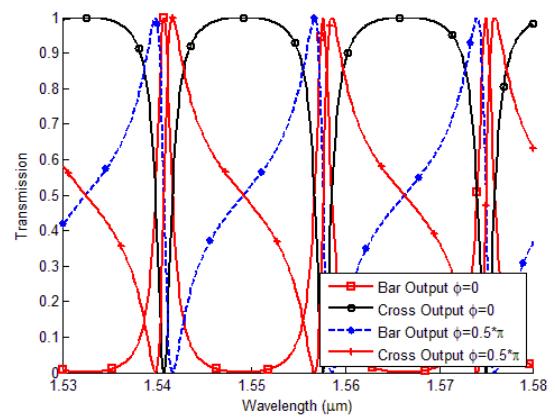
## SIMULATION RESULTS AND DISCUSSION

Without loss of generality, we choose the microring radius  $R = 5\mu\text{m}$  for compact device but still low loss [18], effective refractive index calculated to be  $n_{\text{eff}} = 2.2559$ ,  $\tau = 0.707$  (3dB coupler) and  $\alpha = 0.98$ . We vary the phase shift  $\varphi$  from 0 to  $0.5\pi$ . The transmission at bar port of the device are shown in Fig. 3.

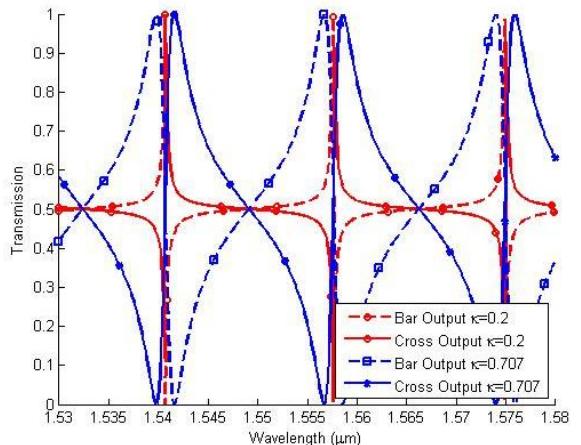
The phase shifter can be made from thermos-optic effect or free carrier effect in silicon waveguide [19]. These Fano resonance occur from interference between the optical resonance in the arm coupled with microring resonator and the propagating mode in the other arm. From the simulation results, we can see that the continuous transition from an asymmetric to symmetric

and toward a reverse line shape can be achieved by changing the phase shifter in the straight waveguide  $\varphi$ . Therefore, we can control a Fano resonance by adjusting the phase shift. In addition, by choosing the phase shift appropriately, a sharp Fano line shape can be obtained. This means that the transmitted power at the output port is very sensitive to the resonance wavelength and thus optical sensors based on this property can provide a high sensitivity.

Fig. 4 shows the transmission spectra of the device at the bar port and cross port for different coupling ratio of the microring resonator with the MZI arm. It can be seen that a very sharp Fano line can be achieved if the coupling coefficient of the coupler  $\kappa_1$  is small. The coupling coefficient of the coupler can be tuned by adjusting the length of the directional coupler or by using the MMI coupler [20]. Fig. 5 shows the controlling of the coupling and transmission coefficients by changing the gap and the length of the directional coupler.



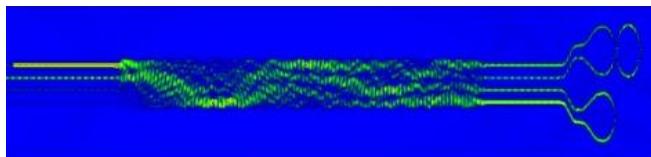
**Figure 3.** Transmission at port 2 and 3 through the device for  $\varphi = 0, \varphi = 0.5\pi$



**Figure 4.** Transmission at port 2 and 3 through the device for  $\kappa = 0.2, \kappa = 0.707$

Finally, we use FDTD method to simulate the whole device and then make a comparison with the analytical theory. In our FDTD simulation, we take into account the wavelength dispersion of the silicon waveguide. We employ the design of the directional coupler presented in the previous section as the input for the FDTD. A Gaussian light pulse of 15fs pulse width

is launched from the input to investigate the transmission characteristics of the device. The grid size  $\Delta x = \Delta y = 0.02\text{nm}$  and  $\Delta z = 0.02\text{nm}$  are chosen in our simulations. The FDTD simulations have a good agreement with the analytic analysis.



**Figure 5:** FDTD simulations of the whole device

## CONCLUSION

This paper has presented a new structure for achieving tunable Fano resonance line shapes. The proposed structure is based on only one  $4 \times 4$  multimode interference coupler. The design of the proposed device is based on silicon waveguide. The whole device structure can be fabricated on the same chip using CMOS technology. The transfer matrix method (TMM) and beam propagation method (BPM) are used for analytical analysis and design of the device. Then the FDTD method is used to compare with the analytic method. The proposed structure is useful for potential applications such as highly sensitive sensors and low power all-optical switching.

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## REFERENCES

- [1] D.G. Rabus, *Integrated Ring Resonators – The Compendium*: Springer-Verlag, 2007.
- [2] Trung-Thanh Le, *Multimode Interference Structures for Photonic Signal Processing: Modeling and Design*: Lambert Academic Publishing, Germany, ISBN 3838361199, 2010.
- [3] Ying Lu, Jianquan Yao, Xifu Li *et al.*, "Tunable asymmetrical Fano resonance and bistability in a microcavity-resonator-coupled Mach-Zehnder interferometer," *Optics Letters*, vol. 30, pp. 3069-3071, 2005.
- [4] Linjie Zhou and Andrew W. Poon, "Fano resonance-based electrically reconfigurable add-drop filters in silicon microring resonator-coupled Mach-Zehnder interferometers," *Optics Letters*, vol. 32, pp. 781-783, 2007.
- [5] Andrey E. Miroshnichenko, Sergej Flach, and Yuri S. Kivshar, "Fano resonances in nanoscale structures," *Review Modern Physics*, vol. 82, pp. 2257-, 2010.
- [6] Yi Xu and Andrey E. Miroshnichenko, "Nonlinear Mach-Zehnder-Fano interferometer," *Europhysics Letters*, vol. 97, pp. 44007-, 2012.
- [7] Shanhui Fan, "Sharp asymmetric line shapes in side-coupled waveguide-cavity systems," *Applied Physics Letters*, vol. 80, pp. 908 - 910, 2002.
- [8] Kam Yan Hon and Andrew Poon, "Silica polygonal micropillar resonators: Fano line shapes tuning by using a Mach -Zehnder interferometer," in *Proceedings of SPIE Vol. 6101, Photonics West 2006, Laser Resonators and Beam Control IX*, San Jose, California, USA, 25-26 January, 2006.
- [9] CHEN Zong-Qiang, QI Ji-Wei, CHEN Jing *et al.*, "Fano Resonance Based on Multimode Interference in Symmetric Plasmonic Structures and its Applications in Plasmonic Nanosensors," *Chinese Physics Letters*, vol. 30, 2013.
- [10] Bing-Hua Zhang, Ling-Ling Wang, Hong-Ju Li *et al.*, "Two kinds of double Fano resonances induced by an asymmetric MIM waveguide structure," *Journal of Optics*, vol. 18, 2016.
- [11] S. Darmawan, L. Y. M. Tobing, and D. H. Zhang, "Experimental demonstration of coupled-resonator-induced-transparency in silicon-on-insulator based ring-bus-ring geometry," *Optics Express*, vol. 19, pp. 17813-17819, 2011.
- [12] J. Heebner, R. Grover, and T. Ibrahim, *Optical Microresonators: Theory, Fabrication, and Applications*: Springer, 2008.
- [13] W.P. Huang, C.L. Xu, W. Lui *et al.*, "The perfectly matched layer (PML) boundary condition for the beam propagation method," *IEEE Photonics Technology Letters*, vol. 8, pp. 649 - 651, 1996.
- [14] A. Yariv, "Universal relations for coupling of optical power between microresonators and dielectric waveguides," *Electronics Letters*, vol. 36, pp. 321–322, 2000.
- [15] M. Bachmann, P. A. Besse, and H. Melchior, "General self-imaging properties in  $N \times N$  multimode interference couplers including phase relations," *Applied Optics*, vol. 33, pp. 3905-, 1994.
- [16] L.B. Soldano and E.C.M. Pennings, "Optical multimode interference devices based on self-imaging :principles and applications," *IEEE Journal of Lightwave Technology*, vol. 13, pp. 615-627, Apr 1995.
- [17] 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, Feb 1999 1999.
- [18] Qianfan Xu, David Fattal, and Raymond G. Beausoleil, "Silicon microring resonators with  $1.5\text{-}\mu\text{m}$  radius," *Optics Express*, vol. 16, pp. 4309-4315, 2008.
- [19] Sang-Yeon Cho and Richard Soref, "Interferometric microring-resonant  $2 \times 2$  optical switches," *Optics Express*, vol. 16, pp. 13304-13314, 2008.
- [20] T.T Le, L.W. Cahill, and D. Elton, "The Design of  $2 \times 2$  SOI MMI couplers with arbitrary power coupling ratios," *Electronics Letters*, vol. 45, pp. 1118-1119, 2009.