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Fano Resonance and EIT-like effect based on 4x4 Multimode Interference Structures

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Abstract

We propose a new structure for creating the Fano resonance and electromagnetically induced transparency (EIT) effect. The structure is based on 4x4 multimode interference couplers. The proposed devices have advantages of compactness, large tolerance fabrication. The transfer matrix method (TMM) and numerical methods are used for analytical analysis and design of the device.

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

INTRODUCTION

Devices based on optical microring resonators hare attracted considerable attention recently, both as compact and highly sensitive sensors and for optical signal processing applications [1]. 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 [2, 3].

The strong sensitivity of Fano resonance to local media brings about a high figure of merit (FOM), which promises extensive applications in optical devices such as optical switches [4]. 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 [5]. 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 [6], prism-coupled square micro-pillar resonators, multimode tapered fiber coupled micro-spheres and Mach Zehnder interferometer (MZI) coupled micro-cavities [7], plasmonic waveguide structure [8, 9]. It has been suggested that optical Fano resonances have niche applications in resonance line shape sensitive bio-sensing, optical channel switching and filtering [10].

In addition, electromagnetically induced transparency (EIT) has been intensively investigated in recent decades [11, 12]. Extensive research efforts have been made in fundamental physics and exciting applications. These include quantum information, lasing without inversion, optical delay, slow light or storing light, nonlinearity enhancement and precise spectroscopy, pushing frontiers in quantum mechanics and photonics [12].

EIT was first observed in atomic media [13]. EIT-like effects are identified as a universal phenomenon in coupled resonant systems in optics [14], mechanics and electrical circuits [15], plasmonics, metamaterials and hybrid configurations [16].

In this paper, we propose a new structure based on 4x4 multimode interference couplers to produce Fano resonances and EIT like effect. We further develop the EIT structure by cascading the two Fano resonances based on our recent research [17]. 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 [18].

STRUCTURE AND OPERATING PRINCIPLES

A schematic of the structure is shown in Fig. 1. The proposed structure contains one 4x4 MMI coupler connected to a second 4x4 MMI coupler via four arms, where a_i, b_i, c_i, d_i (i=1,...,4) are complex amplitudes at the input and output waveguides. Two microring resonators are introduced to two upper arms and phase shifters φ_1, φ_2 are in the others.

Here, it is shown that by introducing two phase shifters to two arms, we can achieve two independent tunable Fano resonance line shapes over a very narrow frequency range. By cascading the two independent Fano resonance line shapes, we achieve the EIT like effect as shown in Fig.1.

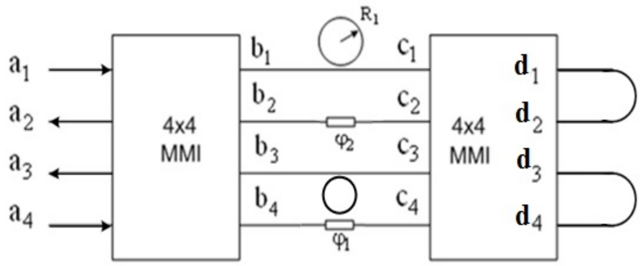


Figure 1: Schematic diagram of a microring resonator coupled 4x4 GMZI structure

Let consider a single ring resonator in the first arm of GMZI structure of Fig.1, the field amplitudes at input and output of the microring resonator can be expressed by using the transfer matrix method [19]

$$\begin{pmatrix} c_1 \\ c'_1 \end{pmatrix} = \begin{pmatrix} \tau_1 & j\kappa_1 \\ j\kappa_1 & \tau_1 \end{pmatrix} \begin{pmatrix} b_1 \\ b'_1 \end{pmatrix} \quad (1)$$

$$b'_1 = \alpha_1 \exp(j\theta_1) c'_1 \quad (2)$$

Where τ_1 and κ_1 are the amplitude transmission and coupling coefficients of the coupler, respectively; for a lossless coupler, $|\kappa_1|^2 + |\tau_1|^2 = 1$. The transmission loss factor α_1 is $\alpha_1 = \exp(-\alpha_0 L_1)$, where $L_1 = \pi R_1$ is the length of the microring waveguide, R_1 is the radius of the microring resonator and $\alpha_0 (\mathrm{dB/cm})$ is the transmission loss coefficient. $\theta_1 = \beta_0 L_1$ is the phase accumulated over the microring waveguide, where $\beta_0 = 2\pi n_{eff} / \lambda$, λ is the optical wavelength and n_{eff} is the effective refractive index.

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

$$\frac{c_1}{b_1} = \frac{\tau_1 - \alpha_1 \exp(j\theta_1)}{1 - \tau_1 \alpha_1 \exp(j\theta_1)} \quad (3)$$

The effective phase ϕ_1 caused by the microring resonator is defined as the phase argument of the field transmission factor, which is

$$\phi_1 = \pi + \theta_1 + \arctan\left(\frac{\tau_1 \sin\theta_1}{\alpha_1 - \tau_1 \cos\theta_1}\right) + \arctan\left(\frac{\alpha_1 \tau_1 \sin\theta_1}{1 - \alpha_1 \tau_1 \cos\theta_1}\right) \quad (4)$$

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

$$\begin{aligned} \Delta\varphi_1 &= \phi_1 - \varphi_1 \\ &= \pi + \theta_1 + \arctan\left(\frac{\tau_1 \sin\theta_1}{\alpha_1 - \tau_1 \cos\theta_1}\right) \\ &\quad + \arctan\left(\frac{\alpha_1 \tau_1 \sin\theta_1}{1 - \alpha_1 \tau_1 \cos\theta_1}\right) - \varphi_1 \end{aligned} \quad (5)$$

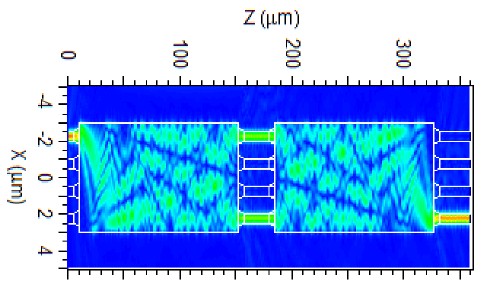
By the same analysis, the phase difference between two arms 2 and 3 of the GMZI is expressed by

$$\begin{aligned} \Delta\varphi_2 &= \varphi_2 - \phi_2 \\ &= \varphi_2 - \left(\pi + \theta_2 + \arctan\left(\frac{\tau_2 \sin\theta_2}{\alpha_2 - \tau_2 \cos\theta_2}\right) \right. \\ &\quad \left. + \arctan\left(\frac{\alpha_2 \tau_2 \sin\theta_2}{1 - \alpha_2 \tau_2 \cos\theta_2}\right)\right) \end{aligned} \quad (6)$$

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 [20, 21]. 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.

It is assumed that two 4x4 MMI couplers have the same width W_{MMI} and length $L_{MMI} = \frac{3L_\pi}{2}$. The silicon waveguide is used for the design. The parameters used in the designs are as follows: the waveguide has a standard silicon thickness of $h_{co} = 220\mathrm{nm}$ and access waveguide widths are $W_a = 0.5\ \mu\mathrm{m}$ for single mode operation. It is assumed that the designs are for the TE polarization at a central optical wavelength $\lambda = 1550\mathrm{nm}$. By using the BPM simulation, we showed that the width of the MMI is optimized to be W_{MMI} =6μm 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 $L_{MMI} = 141.7\ \mu\mathrm{m}$.



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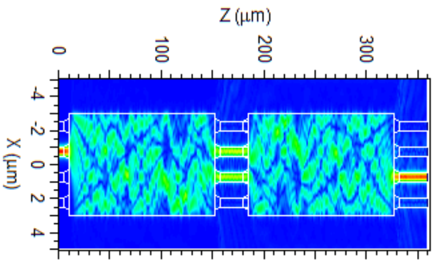


Figure 2: BPM simulations for 4x4 cascaded MMI coupler used for microring resonator coupled MZI for input 1 and 2

The relations between the complex amplitudes at the input ports and output ports can be expressed in terms of the transfer matrices of the 3dB MMI couplers and the phase shifters as follows

$$\begin{bmatrix} d_1 \\ d_4 \end{bmatrix} = \begin{bmatrix} \sin(\Delta\varphi_1/2) & \cos(\Delta\varphi_1/2) \\ \cos(\Delta\varphi_1/2) & -\sin(\Delta\varphi_1/2) \end{bmatrix} \begin{bmatrix} a_1 \\ a_4 \end{bmatrix} \quad (7)$$

Similarly, the complex amplitudes at input and output ports 2 and 3 can be expressed by

$$\begin{bmatrix} d_2 \\ d_3 \end{bmatrix} = \begin{bmatrix} \sin(\Delta\varphi_2/2) & \cos(\Delta\varphi_2/2) \\ \cos(\Delta\varphi_2/2) & -\sin(\Delta\varphi_2/2) \end{bmatrix} \begin{bmatrix} a_2 \\ a_3 \end{bmatrix} \quad (8)$$

Here, the transmission loss factor $\alpha_2 = \exp(-\alpha_0 L_2)$, where $L_2 = \pi R_2$ is the length of the microring waveguide in arm 2, R_2 is the radius of the microring resonator and $\alpha_0(\mathrm{dB/cm})$ is the transmission loss coefficient. $\theta_2 = \beta_0 L_2$ is the phase accumulated over the microring waveguide.

As a result, the transmissions at the bar and cross output ports of the structure in Fig.1 are given by

$$T\_bar = \left| \cos(\frac{\Delta\varphi_2}{2})\sin(\frac{\Delta\varphi_2}{2}) + \cos(\frac{\Delta\varphi_1}{2})\sin(\frac{\Delta\varphi_1}{2}) \right|^2 \quad (9)$$

$$T\_cross = \left| \cos^2(\frac{\Delta\varphi_2}{2}) - \sin^2(\frac{\Delta\varphi_2}{2}) \right|^2 \quad (10)$$

It will be shown that the transmissions have the Fano resonance line shape and the shape can be tuned by tuning the phase shifters φ_1 and φ_2.

SIMULATION RESULTS AND DISCUSSION

Without loss of generality, we choose the microring radius $R_1 = 5\mu m$ for compact device but still low loss [22], effective refractive index calculated to be $n_{eff} = 2.2559$, $\tau_1 = 0.707$ (3dB coupler) and $\alpha_1 = 0.98$. We vary the phase shift φ_1 from 0 to 1.5π. 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 [23]. 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 φ_1. 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 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 κ_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 [24]. Fig.5 shows the controlling of the coupling and transmission coefficients by changing the gap and the length of the directional coupler.

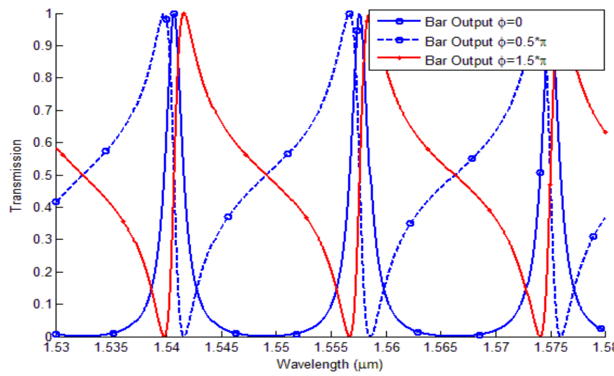


Figure 3: Transmission spectra via the device at the bar port for $\varphi_1 = 0$, $\varphi_1 = 0.5\pi$, $\varphi_1 = 1.5\pi$

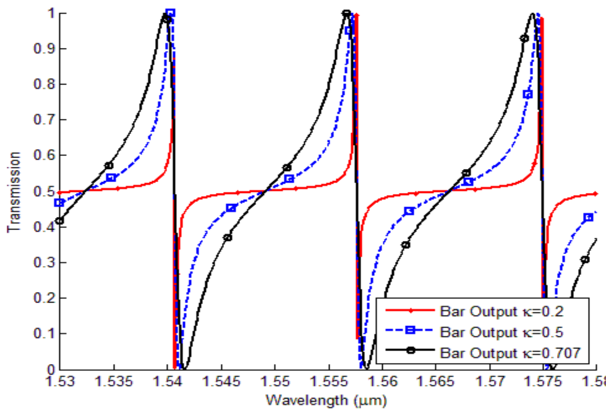


Figure 4: Transmission spectra via the device at the bar port for $\kappa_1 = 0.2$, $\kappa_1 = 0.5$, $\kappa_1 = 0.707$

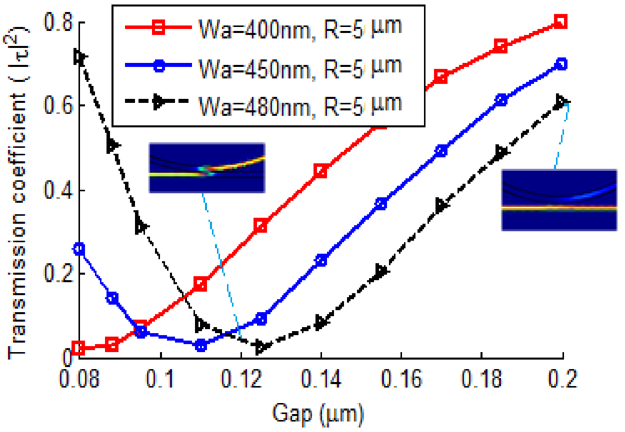


Figure 5: Power transfer between the straight and ring waveguides dependence gap and waveguide width, R=5µm

Now we investigate the behavior of the device when cascading the two 4x4 MMI coupler. The EIT effect can be created as shown in Fig.6.

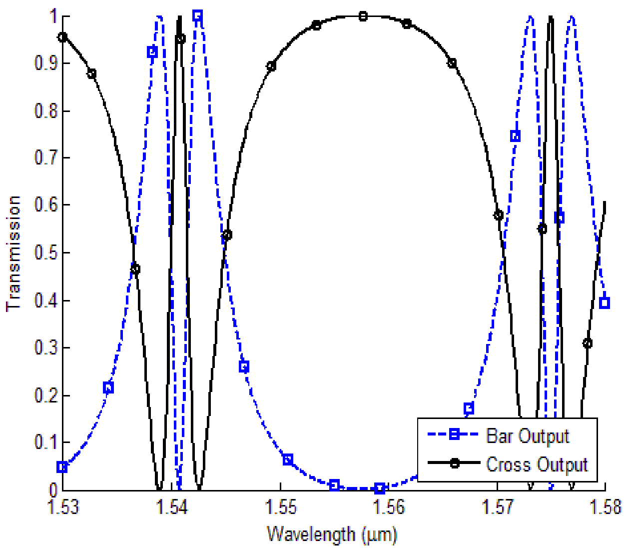
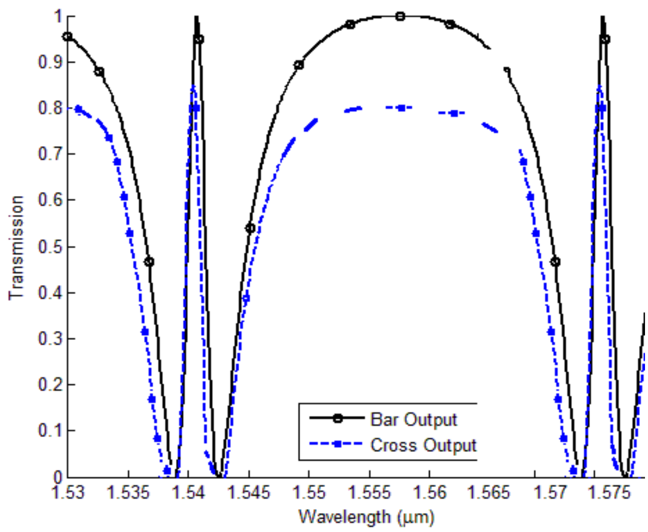


Figure 6: EIT effect created from the structure

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.



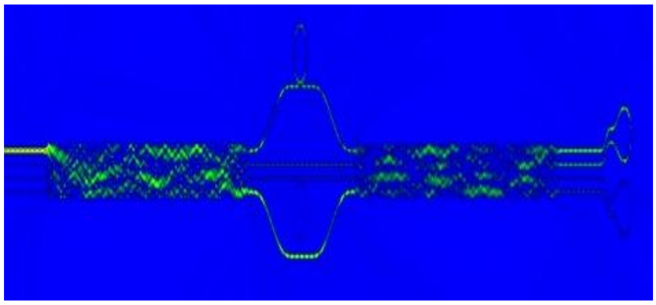


Figure 7: FDTD simulations of the device

CONCLUSION

This paper has presented a new structure for achieving tunable Fano resonance line shapes and EIT like effect. The proposed structure is based on 4x4 multimode interference couplers. By cascading the two independent Fano resonances, the EIT effect is achieved. This 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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