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Coupled Resonator Induced Transparency (CRIT) Based on Interference Effect in 4x4 MMI Coupler

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Abstract

We present a study of coupled resonator induced transparency (CRIT) and of coupled resonator induced absorption (CRIA) using only one 4x4 multimode interference coupler and two microring resonators. The structure has advantages of compactness, ease of fabrication on the same chip and no crossover. Our analysis shows that sharp Fano resonance, CRIT and CRIA can be achieved simultaneously.

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

I. 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, 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].

Our proposed structure is presented for the first time and it is different from the other two microresonator structures reported. Our structure has advantages of compactness, ease of fabrication on the same chip. Our analysis shows that sharp Fano resonance, CRIT and CRIA can be achieved simultaneously.

II. Theoretical Analysis

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,...,4) are complex amplitudes at the input and output waveguides. Two microring resonators are used in two output ports.

Here, it is shown that this structure can create Fano resonance, CRIT and CRIA at the same time. We also can control the Fano line shape by changing the radius R1 and R2 or the coupling coefficients of the couplers used in microring resonators.

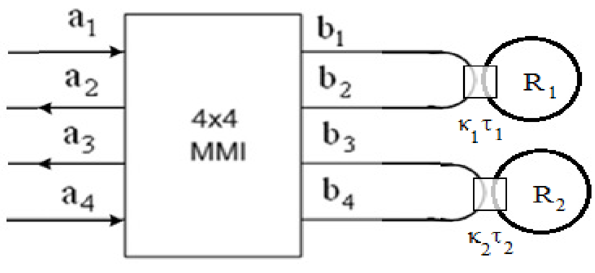


Fig. 1 Schematic diagram of a 4x4 MMI coupler based device

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 [14]

$$\begin{pmatrix} b_2 \\ c'_1 \end{pmatrix} = \begin{pmatrix} c_1 \\ c'_1 \end{pmatrix} = \begin{pmatrix} \tau_1 & j\kappa_1 \\ j\kappa_1 & \tau_1 \end{pmatrix} \begin{pmatrix} b_1 \\ b'_1 \end{pmatrix} \quad (1)$$

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

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 $\alpha_0 (dB/cm)$ 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

$$\frac{b_2}{b_1} = \frac{\tau_1 - \alpha_1 \exp(j\theta_1)}{1 - \tau_1 \alpha_1 \exp(j\theta_1)} \quad (3)$$

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

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

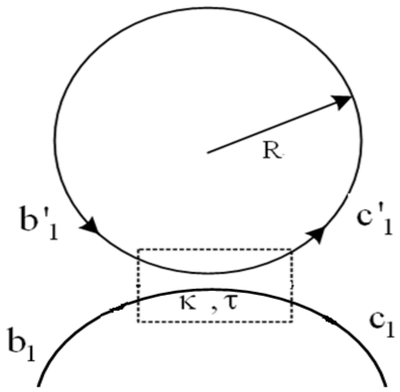
By using the same analysis, we can obtain the transfer response of the second single microring resonator

$$\frac{b_4}{b_3} = \frac{\tau_2 - \alpha_2 \exp(j\theta_2)}{1 - \tau_2 \alpha_2 \exp(j\theta_2)} \quad (5)$$

The effective phase ϕ_2 caused by the microring resonator is defined as the phase argument of the field transmission factor, which is

$$\phi_2 = \pi + \theta_2 + \arctan(\frac{\tau_2 \sin\theta_2}{\alpha_2 - \tau_1 \cos\theta_2}) + \arctan(\frac{\alpha_2 \tau_2 \sin\theta_2}{1 - \alpha_2 \tau_2 \cos\theta_2}) \quad (6)$$

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 $h_{co} = 220nm$ and access waveguide widths are $W_a = 0.5\ \mu m$ for single mode operation. It is assumed that the designs are for the TE polarization at a central optical wavelength $\lambda = 1550nm$.



(a)

Fig. 2 Schematic diagram of a microring resonator

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

$$\Delta\varphi = \phi_2 - \phi_1 \quad (7)$$

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 [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

$$x = (i + \frac{1}{2})\frac{W_{MMI}}{N}, \text{ (i=0,1,…,N-1)} \quad (8)$$

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

$$E(x,z) = \exp(-jkz)\sum_{m=1}^{M} E_m \exp(j\frac{m^2\pi}{4\Lambda}z)\sin(\frac{m\pi}{W_{MMI}}x) \quad (9)$$

By using the mode propagation method, the length of 4x4 MMI coupler with the width of W_{MMI} is to be $L_{MMI} = \frac{3L_\pi}{2}$. Then 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 calculated length of each MMI coupler is found to be $L_{MMI} = 141.7\ \mu m$. The FDTD simulation of the whole device is shown in Fig. 3. We take into account the wavelength dispersion of the silicon waveguide. A Gaussian light pulse of 15fs pulse width is launched from the input to investigate the transmission characteristics of the device. The grid size $\Delta x = \Delta y = 0.02nm$ and

$\Delta z = 0.02\text{nm}$ are chosen in our simulations. The FDTD simulations have a good agreement with the analytic analysis.

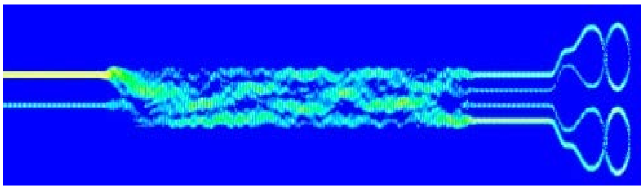


Fig. 3 FDTD simulations for 4x4 MMI coupler for input 1, output port is at port 2

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

$$T\_bar = \left|\cos(\frac{\Delta\varphi}{2})\right|^2 \quad (10)$$

$$T\_cross = \left|\sin(\frac{\Delta\varphi}{2})\right|^2 \quad (11)$$

III. SIMULATION RESULTS AND DISCUSSION

In this section, we investigate the behavior of the proposed device structure. First, we choose the microring radius $R_1 = R_2 = 5\mu m$ for compact device but still low loss [18], effective refractive index calculated to be $n_{eff} = 2.2559$, $\tau_2 = 0.707$ (3dB coupler) and $\alpha = 0.98$. We change the transmission coefficient of the first microring resonator τ_1 for critical coupling, under-coupling and over-coupling [19]. Figure 4 and 5 show the spectra of the proposed structure at output port 2 and port 3. When the coupling coefficient of the first microring resonator κ_1 increases, a narrow transparent peak is appeared, which is similar to the EIT effect in atomic systems. The CRIT peak is created.

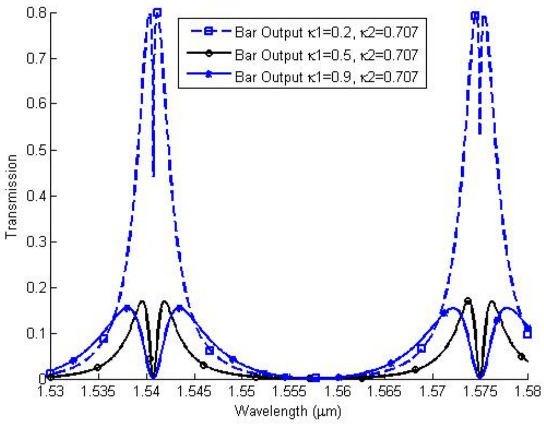


Fig. 4. Transmission at port 2 through the device at different coupling coefficients κ_1 , $R_1 = R_2 = 5\mu m$

Now we investigate the behavior of our devices when the radius of two microring resonators is different. For example, we choose $R_1 = 5\mu m$ and $R_2 = 5\mu m$, $\alpha = 0.98$. It is assumed that a 3dB coupler is used at the microring resonator 2, we change the coupling coefficient of the microring resonator 1, the CRIT is created as shown in Fig. 6. In addition, a peak like notch filter is also achieved.

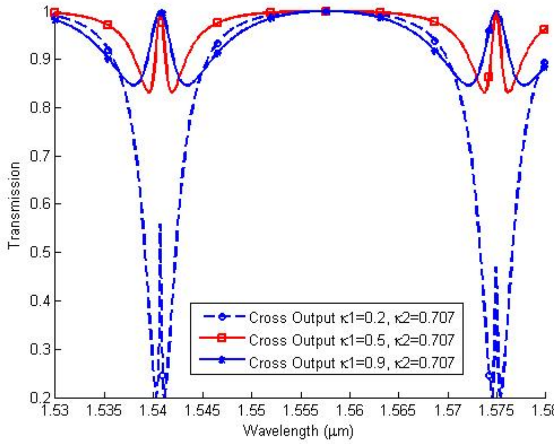


Fig. 5. Transmission at port 2 through the device at different coupling coefficients κ_1 , $R_1 = R_2 = 5\mu m$

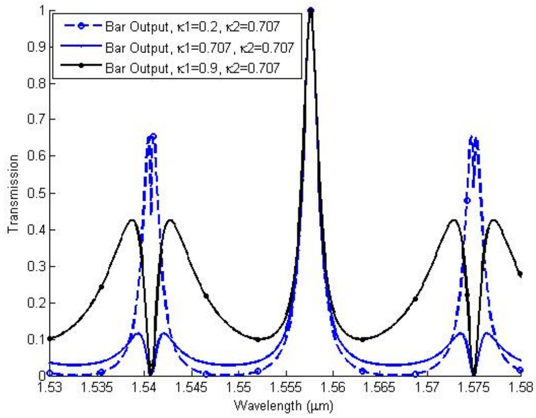


Fig. 6. Transmission at port 2 through the device at different coupling coefficients κ_1 , $R_1 = 5\mu m$, $R_2 = 10\mu m$

By choosing the proper radius of two ring waveguides, the Fano resonance can occur from interference between the optical resonance in the arm coupled with microring resonator and the propagating mode in the other arm.

IV. CONCLUSION

We have presented a new structure based on only one 4x4 MMI coupler and two microring resonators for creating the CRIT, CRIA and Fano resonance simultaneously. 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, optical modulation and low power all-optical switching.

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