Experimental Demonstration of Thermally Tunable Fano and EIT Resonances in Coupled Resonant System on SOI Platform

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Abstract: Thermally tunable Fano and electromagnetically induced transparency (EIT) resonances are theoretically and experimentally demonstrated based on a Mach–Zehnder interferometer (MZI)-assisted Bragg grating-microring coupled resonant system on SOI platform. In this work, the destructive and constructive coupling between the two resonators, the microring resonator and the Fabry-Perot resonator formed by two Bragg gratings, give rise to the Fano and EIT resonances respectively. The resonance lineshape can be controlled and converted by tuning the optical path length of the MZI arm. The device performance has been theoretically analyzed by using a specially developed numerical model. The coupled resonant system was designed, fabricated and characterized on a commercial silicon-on-insulator (SOI) platform. The tuning and conversion of the resonance lineshape by thermo-optical effect have been experimentally observed and verified, with good agreement between the experimental data and the simulations.

Index Terms: Silicon nanophotonics, integrated nanophotonic systems, electro-optical systems

1. Introduction

Fano resonances, characterized by sharp asymmetric lineshape, have been widely utilized in communication [1-3] and biochemical sensing [4-6] applications. Electromagnetically induced transparency (EIT) resonances, by virtue of low insertion loss and high time delay, have attracted significant attentions in the applications of signal processing [7-9]. So far most efforts are focusing on either tunable Fano resonances or tunable EIT resonances [10-23]. However, limited research work has been reported on the system that can switch between Fano and EIT resonances. In 2006, the conversion between the Fano-like transmission and the multi-peaks transmission was reported by W. Liang et al. through changing the coupling strength in a Fabry–Perot etalon-microtoroid resonator coupled system [24]. In 2009, the modifiable EIT-like and Fano-like transmissions were demonstrated by C. –H. Dong et al. based on the two-mode interference in a single silica microsphere by tuning the relative position of the fiber taper [25]. But for these two systems, the adoption of fiber techniques brings large feature sizes as well as the incompatibility with the planar waveguide fabrication process. If Fano and EIT resonances

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can be tuned and converted in a single on-chip system, the versatility, flexibility and compatibility can be much improved. And large volume integration on a single monolithic wafer then becomes possible. Recently, the conversion between Fano and EIT resonances was realized in an on-chip system consisting of a silicon ring resonator with two integrated tunable reflectors [26,27]. But the reported system is not so compact as the footprint is more than 1000 μm* 400 μm, which is more than 330 times larger than the proposed system in this manuscript (30 μm*40 μm).

In this manuscript, thermally tunable Fano and EIT resonances are theoretically and experimentally demonstrated based on a Mach–Zehnder interferometer (MZI)-assisted Bragg grating-microring coupled resonant system on SOI platform. By changing the optical path length of the MZI arm, the effective round-trip power attenuation of the MZI-assisted microring can be tuned, which leads to the change of the coupling status between the two resonators. When the coupling changes between destructive and constructive status, the resonance lineshape is converted between Fano and EIT lineshape. We theoretically calculated and analyzed the performance of the system with a specially developed numerical model based on the transfer matrix method. The system was designed, fabricated and characterized on a commercial 220 nm-top-silicon-layer silicon-on-insulator (SOI) platform. The tuning and conversion between Fano and EIT resonances by thermo-optical effect have been experimentally observed and verified with good agreement between the experimental data and the simulations.

2. Device Designs and Simulations

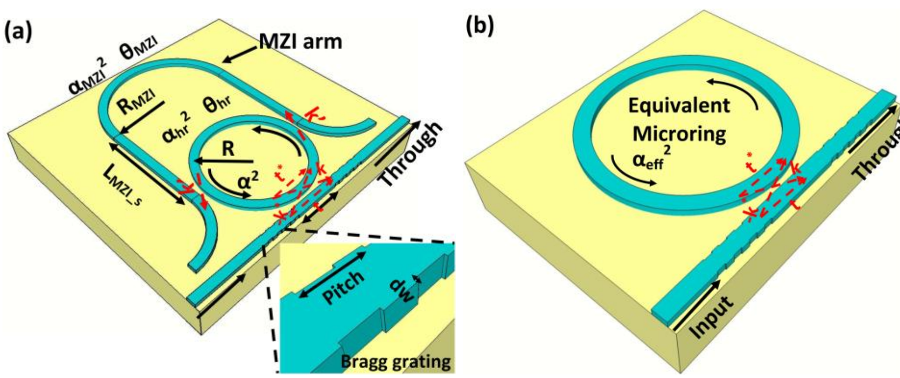

Fig. 1. (a) The schematic of the MZI-assisted Bragg grating-microring coupled resonant system. (b) The equivalent model of the MZI-assisted Bragg grating-microring coupled resonant system.

The schematic of the MZI-assisted Bragg grating-microring coupled resonant system is shown in Fig. 1(a). Two Bragg gratings are located in the input-through bus waveguide at the two sides of the coupling region acting as two partially reflective elements to form a Fabry-Perot (F-P) resonator. In this work, the coupling between the resonances of the microring and the F-P resonator gives rise to the various EIT and Fano resonances. The two coupling points between the MZI arm and the microring are set at the two sides of the microring as shown in Fig. 1(a). L_{MZI_s} and R_{MZI} are the length of the straight section and the bending radius of the MZI arm respectively. The length of the MZI arm is defined as the total length between these two coupling points, which can be expressed as $L_{MZI} = 2 \cdot L_{MZI\_s} + \pi \cdot R_{MZI}$. The power attenuation coefficient and the phase shift of the MZI arm are $\alpha_{MZI}{}^2$ and θ_{MZI} respectively. Correspondingly, $\alpha_{hr}{}^2$ and θ_{hr} are the power attenuation coefficient and the phase shift of the half microring between the two coupling points. α^2 and R are the round-trip power attenuation coefficient and the radius of the microring resonator respectively. $t = \sqrt{1-|k|^2}$ is the transmission coefficient of the coupling region between the input-through bus waveguide and the microring, and t^* is the conjugation. k is the coupling coefficient of the coupling region between the input-through bus waveguide and the microring, and k^* is the conjugation. k' is the coupling coefficient of the two coupling points between the MZI arm and the microring. $pitch$ is the pitch of the Bragg gratings. dw is the depth of the corrugation. L_{cv} is the length of the F-P cavity, and N is the number of the periods of the Bragg gratings.

Based on the transfer matrix method, the transmission of the whole system can be expressed as [28]:

$$T_{input} = T_{Brag} \times T_{WG} \times T_{R\_eqv} \times T_{WG} \times T_{Brag} \times T_{output} \quad (1)$$

where the inverse expression is adopted; T_{Brag} is the matrix of the Bragg gratings; T_{WG} is the matrix of the straight waveguide; and T_{R_eqv} is the matrix of the equivalent microring resonator, which will be explained later. More detailed information can be found in [29].

In order to simplify the discussion, an add-drop bus waveguide with an effective coupling coefficient k_{eff} can be utilized to equivalently replace the MZI arm, where k_{eff} can be calculated by [30,31]:

$$k_{eff}^{\ 2} = k'^2(1-k'^2)\cdot(\alpha_{MZI}^{\ 2} + \alpha_{hr}^{\ 2} - 2\alpha_{MZI}\alpha_{hr}\cos(\theta_{MZI} - \theta_{hr})) \quad (2)$$

while the relative phase $\Delta\theta = \theta_{MZI} - \theta_{hr}$ is changed from 0 to π, $k_{eff}^{\ 2}$ can be tuned from 0 to $4k'^2(1-k'^2)$. Furthermore, as shown in Fig. 1(b), by considering the equivalent add-drop bus waveguide and the microring as a single microring, the system can be further simplified as an all-pass microring coupled with an F-P resonator. The effective round-trip power attenuation of this equivalent single microring can be expressed as $\alpha_{\mathrm{eff}}^{\ 2} = \alpha^2 - k_{eff}^{\ 2}$. So, $\alpha_{\mathrm{eff}}^{\ 2}$ can be tuned by changing $\Delta\theta$, which can be realized by changing the optical path length of the MZI arm by means of thermo-optical, electro-optical, or all-optical effects. In this experiment, the changing of the optical path length of the MZI arm is achieved by thermo-optical effect. Via tuning $\alpha_{\mathrm{eff}}^{\ 2}$, the coupling status between the microring and the F-P resonator can be changed as well as the resonance lineshape. When $\alpha_{\mathrm{eff}} > t$, the microring resonator operates in the over-coupling regime. The phase curve of the microring resonator is continuous and the coupling between the microring resonator and the F-P resonator is constructive, which results in the EIT peak. However, when $\alpha_{\mathrm{eff}} = t$, the microring resonator operates at the critical-coupling point. An abrupt π shift of the microring phase curve occurs [32], and the coupling between the two resonators turns to completely destructive, which generates a sharp Fano lineshape with the largest extinction ratio (ER). When $\alpha_{\mathrm{eff}} < t$, the microring resonator operates in the under-coupling regime. The phase shifting is maintained but with smaller values. The two light paths of the two resonators undergo partially destructive interference, which results in Fano lineshapes with smaller ERs. More detailed discussions can be referred in [33].

The simulations are conducted on a 220 nm-top-silicon-layer SOI platform with 2 μm buried oxide (BOX) layer, based on the transfer matrix method. For an initial design, we chose the parameters as $pitch$ = 315 nm, N = 100, dw = 10 nm, R = 10 μm, R_{MZI} = 10.715 μm (the gap widths between the MZI arm and the microring are set as 115 nm), $k' = 0.4i$, $k = 0.45i$, $t = 0.8930$, $L_{cv} = 10.5 \cdot pitch$. Since the simulations are conducted in a narrow band, the dispersion of the group index can be ignored and the value of the group index is set as 4.067. As shown in Fig. 2(a), the curve of α_{eff} is periodical. By heating up the MZI arm, the curve of α_{eff} is blue-shifted, which is consistent with [25]. $\Delta\varphi$ is the additional phase difference between the MZI arm and the half microring caused by the increased temperature of the MZI arm. The value of t is marked out with a horizontal black long-dashed line as 0.8930. When the curve of α_{eff} is blue-shifted, the value of α_{eff} at the wavelength of the Fano dip or EIT peak changes as well as the coupling status between the two resonators. The transmission spectra under different $\Delta\varphi$ are shown in Fig. 2(b). A magnified image of the black dashed-line circled region is presented in Fig. 2(c). As seen, when the MZI arm is at room temperature (red line), α_{eff} is much larger than t

hence an EIT resonance is generated. While we heat up the MZI arm to increase $\Delta\varphi$ from 0 to 0.257π (blue line), the ER of the EIT peak drops from 16.1 dB to 4.63 dB, and the insertion loss (IL) increases from 3.5 dB to 16.4 dB. At the same time, the full-width-at-half-maximum (FWHM) of the EIT peak becomes smaller from ~ 0.03 nm to ~ 0.213 nm, which corresponds to the decrease of the quality factor (Q factor) from ~ 51200 to ~ 7200. So while $\alpha_{\text{eff}} > t$ and with the decreasing difference between α_{eff} and t, the ER, the IL and the sharpness of the EIT peak are all degraded. For the application in a photonics integrated circuit, the IL can be fine-tuned to achieve an acceptable value and meet the requirement. When the temperature of the MZI arm is increased until $\Delta\varphi=0.456\pi$, α_{eff} is equal to t and critical coupling occurs, which acts as a threshold point between Fano and EIT lineshapes. At that point, the transmission spectrum is converted from EIT lineshape to Fano lineshape. It is also noteworthy that the Fano resonance obtains the largest ER of 55 dB at the same time. When we continue raising the temperature of the MZI arm until $\Delta\varphi=0.706\pi$, the Fano resonance lineshape remains but the ER significantly decreases to only 7.8 dB. Besides, the required wavelength shifting between the dip and the peak of the Fano lineshape also increases from ~ 0.405 nm to ~ 0.59 nm. So while $\alpha_{\text{eff}} \le t$ and with the increasing difference between t and α_{eff}, not only the ER of the Fano resonance drops but also the sharpness degrades.

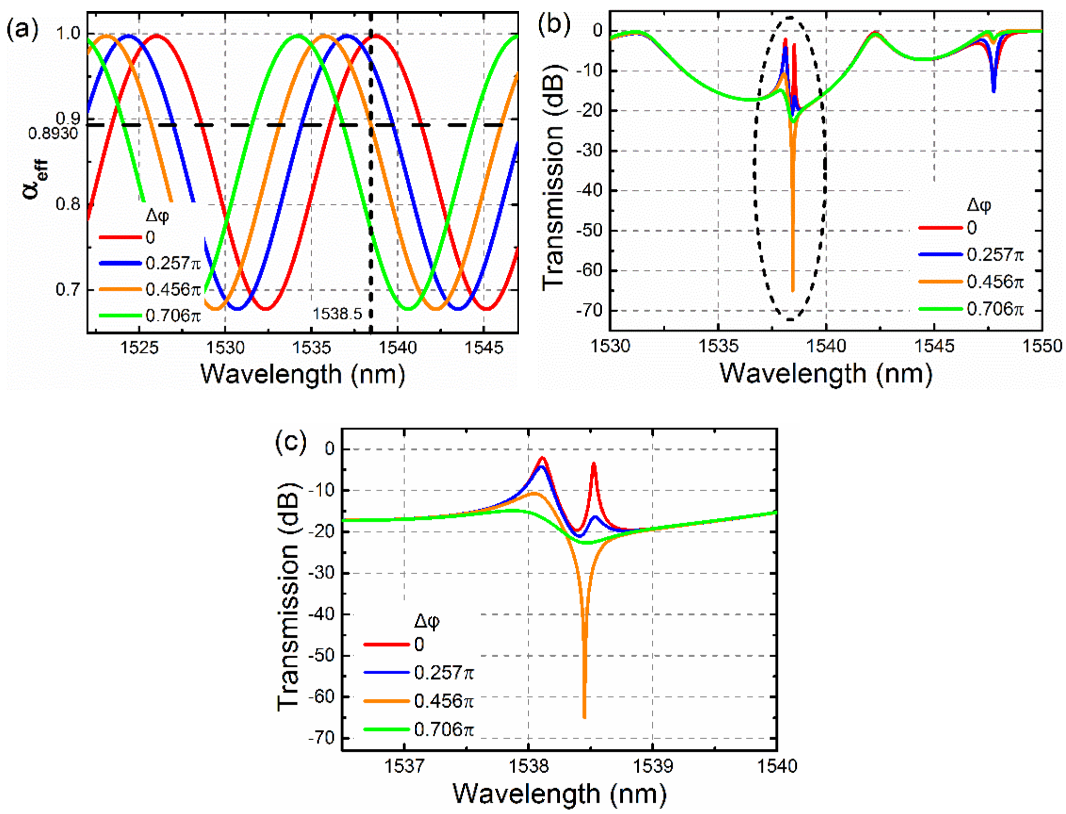

Fig. 2. (a) The curves of α_{eff} versus wavelength under different $\Delta\varphi$ when $t = 0.8930$. (b) The transmission spectra under different $\Delta\varphi$ when $t = 0.8930$. (c) The magnified spectra of the transmissions circled by the black dashed line in Fig. 2(b).

3. Device Fabrication and Characterizations

The fabricated device is shown in Fig. 3. The grating layer and the waveguide layer were both patterned with electron beam lithography (EBL). The grating layer was etched down to a depth of 70 nm with reactive ion etching (RIE). The waveguide layer was etched down to the BOX layer with deep reactive ion etching (DRIE). Then the sample was coated with a cladding layer of 1 μm

SiO_2. A layer of 110 nm Ti was deposited and partially lifted off on the SiO_2 cladding to form the heating wires. Then a 20 nm Ti layer and a 300 nm Au layer were deposited. The metal at the patterned area is kept and the unwanted metal is lifted off to form the conducting wires and the electrode pads. The designed parameters were: $pitch$ = 315 nm, N = 100, dw = 15 nm, R = 10 μm, R_{MZI} = 10.715 μm, $L_{cv} = 10.5 \cdot pitch$. The gap widths between the MZI arm and the microring were set as 115 nm. The gap width between the input-through bus waveguide and the microring was 85 nm. The width of waveguide was 500 nm. L_{MZI_s} was 21.5 μm. The width of the Ti heating wires was 1.5 μm. Two specially designed grating couplers are applied at the input and output ports to couple light into and out from the system, which can also avoid the reflection caused by the ending of waveguide.

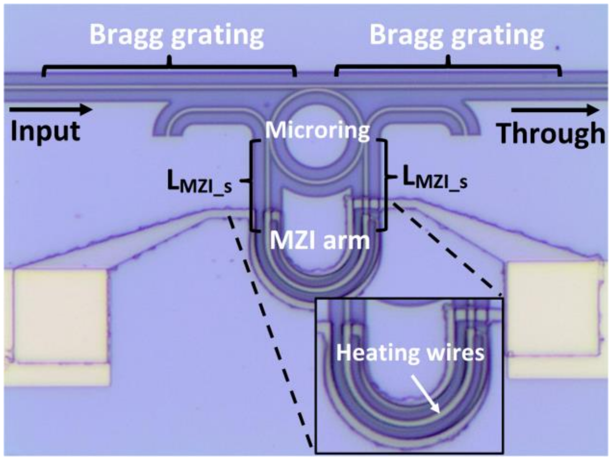

Fig. 3. The fabricated thermal-optic switch between Fano and EIT resonances based on a MZI-assisted Bragg grating-microring coupled system.

The experimental results under a series of bias voltages of 0 V, 4 V and 8 V are shown in Fig. 4(a). It can be clearly seen that while the bias voltage increases from 0 V to 8 V, the transmission spectrum gradually converts from EIT lineshape to Fano lineshape. In Fig. 4(b), 4(c), 4(d), the experimental results of the bias voltage of 0V, 4V and 8V are fitted with our numerical model respectively and the corresponding curves of α_{eff} are also plotted. As seen, all the experimental results and the simulation results are in good agreement. Because the widths of the gaps are kept constant, the values of k and k' are fitted and fixed as 0.45i and 0.4i respectively in all these devices. Besides, in all the fittings, N , dw , R_{MZI} and $pitch$ are kept constant and fitted as 100, 9.5 nm, 10.715 μm and 314.4 nm respectively. The difference between the designed value (15 nm) and fitted value (9.5 nm) of dw is because the fabricated corrugations of the Bragg grating are not in ideal rectangular shape. The fabricated Bragg gratings are comparable with the ideal rectangular Bragg grating with a corrugation depth of 9.5 nm. The value of t is marked as 0.8930 with horizontal black long-dashed lines and the wavelengths of the EIT peak or the Fano dip are marked with vertical black short-dashed lines. While the bias voltage increases from 0 V to 4V, $\Delta\varphi$ increases from 0 to 0.077π and α_{eff} decreases from 0.9846 to 0.9654. In the meantime, the EIT resonance lineshape maintains but the ER of the EIT peak drops more than a half from 8.73 dB to 3.6 dB and the FWHM increases from ~ 0.07 nm to ~ 0.25 nm (corresponding to the decrease of Q factor from ~ 21900 to ~ 6150). Both the ER and the sharpness are degraded, which are in good agreement with the above simulations. Next, with the increase of bias voltage to 8 V, $\Delta\varphi$ increases from 0.077π to 0.308π as expected and α_{eff} drops from 0.9654 to 0.8716. As a result, the Fano transmission is generated. As measured, the ER is 27.4 dB and the required wavelength shifting between the dip and the peak is 0.557 nm. The small ripples of the curves are probably due to the weak optical reflection at the input and output facets. Besides, it is noteworthy that the wavelength of the EIT peak or the Fano dip is slightly red-shifted while the bias voltage increases. It is because the distance between the Ti heating wire and the microring waveguide is not large enough and the microring waveguide is also heated up by the heater, which results in the red-shifting of the microring resonance peak. The thermal isolation can be improved by etching deep trenches between the microring and the MZI arm. Alternatively, the additional phase difference $\Delta\varphi$ can be achieved by employing the phase-changing materials, such as VO_2 and $Ge_2Sb_2Te_5$ [34, 35]. At the same time, the influence on the performance and the lifetime of the device from the thermal heating wires can be avoided. Furthermore, the Bragg grating can be replaced by a Sagnac-loop mirror (SLM) [36] or an offset in the bus waveguide [37] for obtaining a broader operation bandwidth and ease the controlling of fabrication process. However, compared with the SLM, the Bragg grating is much more compact and suitable for high density integration. And the advantage of the Bragg grating over the offset in the bus waveguide is that, the transmission spectrum can be flexibly and conveniently tuned by changing parameters of the Bragg grating. So these three kinds of partially reflective elements can be utilized for the applications with different requirements.

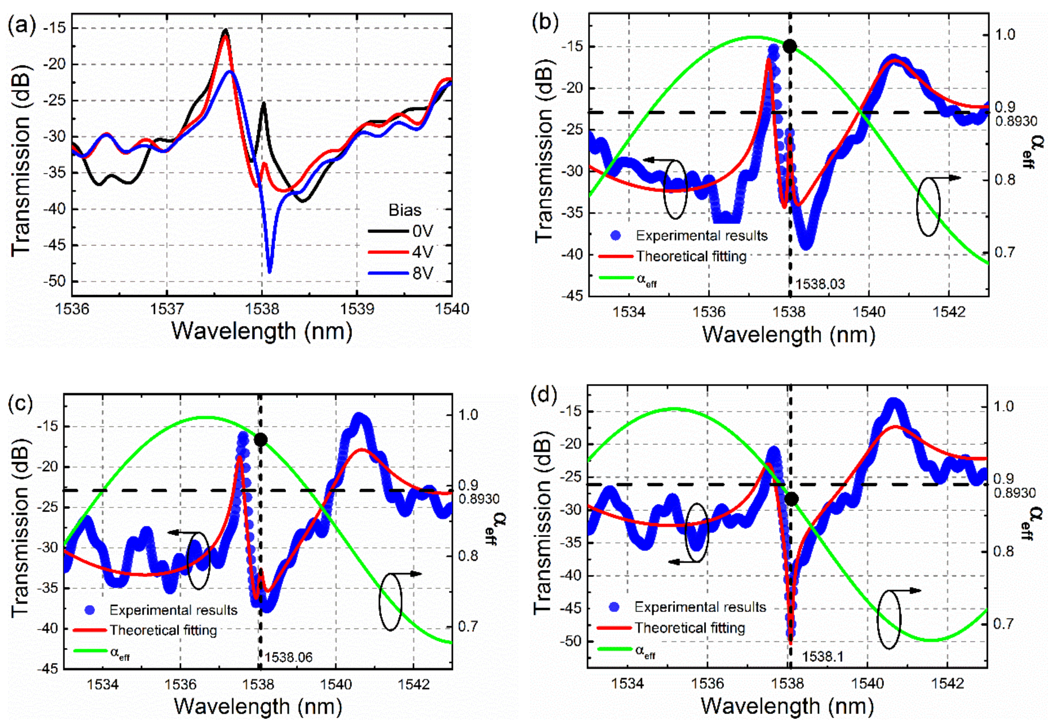

Fig. 4. (a) The experimental transmission spectra when the bias voltage is 0 V, 4 V and 8 V. (b) The fitted transmission spectrum when the bias voltage is 0 V and the corresponding curve of α_{eff}. (c) The fitted transmission spectrum when the bias voltage is 4 V and the corresponding curve of α_{eff}. (d) The fitted transmission spectrum when the bias voltage is 8 V and the corresponding curve of α_{eff}.

4. Conclusion

In summary, a thermal-optic switch between Fano and EIT resonances is theoretically and experimentally demonstrated based on a MZI-assisted Bragg grating-microring coupled resonant system. In this work, the coupling between the MZI-assisted microring resonator and the F-P resonator gives rise to the EIT and Fano resonances. By changing the optical path length of the MZI arm, the resonant status of the MZI-assisted microring can be tuned as well as the resonance lineshape. The performance of the system is theoretically calculated and analyzed with a specially developed numerical model. Active tuning with thermo-optical effect is experimentally verified to be able to achieve the conversion of the resonance lineshape. The experimental and simulation results are in good agreement. With the capability of on-chip tuning and converting the resonance between Fano and EIT lineshapes, great improvements in the versatility, flexibility and compatibility of the system as well as the possibility of high volume monolithic integration become possible. As a result, it is envisaged that more related potential applications in communication, biochemical sensing and on-chip signal processing can be realized.

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