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Conversion between EIT and Fano spectra in a microring-Bragg grating coupled-resonator system

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A conversion between the electromagnetically induced transparency (EIT) transmission and Fano transmission is theoretically and experimentally demonstrated in an all-pass microring-Bragg grating (APMR-BG) coupled-resonator system. In this work, the coupling between the two resonators (the microring resonator and the Fabry-Perot resonator formed by two Bragg gratings) gives rise to the EIT and Fano transmissions. The resonant status strongly depends on the round-trip attenuation of the microring and the coupling strength. By tuning the coupling strength, the EIT and Fano transmissions can be controlled and converted. The device performance has been theoretically calculated and analyzed with a specially developed numerical model based on the transfer matrix method. The APMR-BG coupled-resonator systems with different gap widths were designed, fabricated, and characterized on a silicon-on-insulator (SOI) platform. The conversion of resonance was experimentally observed and verified. In addition, this on-chip system has the advantage of a small footprint, and the fabrication process is compatible with the planar waveguide fabrication process. Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.4990486>]

The electromagnetically induced transparency (EIT) transmission and Fano transmission in silicon photonics have attracted considerable research interest in the past few decades. The EIT transmission has a narrow optical transparency peak residing in a broader absorption valley,¹ which is useful in the applications of signal processing² and on-chip time delay lines.³ The Fano transmission possesses a sharp asymmetric lineshape and is widely used in sensing⁴ and modulation applications.⁵ The EIT and Fano transmissions can be either generated from the interaction of a non-resonant continuum and a resonant channel or from the coupling between multiple resonant modes.^{6–11} Many works have been done on either EIT or Fano transmission.^{12–14} In 2011, Li reported a series of research on the Fano transmission in a single whispering-gallery microresonator and indirectly coupled whispering-gallery microresonators.^{15,16} In 2013, Yu obtained a Fano transmission in a waveguide F-P resonator side-coupled lossy nanobeam cavity.¹⁷ Xiao utilized a single polydimethylsiloxane-coated silica microtoroid to realize an EIT-like transmission.¹⁸ In 2014, Huang observed an EIT-like transmission in a two-bus waveguide coupled microdisk resonator.^{19,20} However, the conversion between the EIT and Fano transmission, which is very interesting, was rarely reported. In 2006, Liang experimentally claimed the conversion between the Fano-like transmission and the multi-peaks transmission by changing the coupling strength in a Fabry-Perot etalon-microtoroid resonator coupled system,²¹ but that the existence of EIT transmission was not confirmed, and the mechanism behind the conversion is not thoroughly discussed. In 2009, Dong experimentally demonstrated modified transmission spectra, including EIT-like and Fano-like lineshapes, based on the two-mode interference in a single

silica microsphere by tuning the relative position of the fiber taper.²² However, the common drawback of these two devices is based on the fiber technique, which leads to a much larger footprint and is incompatible with planar waveguide fabrication process.

In this paper, we reveal the mechanism behind the conversion between the EIT and Fano transmissions in an on-chip all-pass microring-Bragg grating (APMR-BG) coupled-resonator system. Both the EIT and Fano transmissions originate from the coupling between the light paths of the two resonators [a microring resonator and a Fabry-Perot (F-P) resonator], which is similar to the quantum interference in a multi-level atomic system. By tuning the coupling strength between the microring resonator and the F-P resonator formed by two Bragg gratings, an abrupt π phase shift of the light in the microring resonator occurs, leading to the transformation from constructive interference to destructive interference between the two resonators. Consequently, it triggers the transformation of the transmission from the EIT lineshape to the Fano lineshape. We theoretically analyzed the conversion of the transmission by using the transfer matrix method. The conversion between the EIT and Fano transmission was also experimentally demonstrated using the coupled-resonator system designed and fabricated on a silicon-on-insulator (SOI) platform, and the measured results show good agreement with the theoretical prediction. This system also has the advantage of a small footprint consisting of only one microring resonator and one bus waveguide with Bragg gratings, and the fabrication process is compatible with the planar waveguide fabrication process. The capability to have different transmission lineshapes can pave the way for the future active tuning applications, such as optical switching, modulation, sensing, and on-chip time delay lines.

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Figure 1(a) shows the schematic of the APMR-BG coupled-resonator system. Two Bragg gratings are located in the bus waveguide at the two sides of the microring coupling region, which perform as two partially reflective elements to form an F-P resonator. As shown, dw is the depth of the Bragg grating corrugations, R is the radius of the microring, L is the cavity length of the F-P resonator, N is the number of periods of each Bragg grating, k is the coupling coefficient, k^* is the conjugation, $t = \sqrt{1 - |k|^2}$ is the transmission coefficient, and t^* is the conjugation. $\alpha^2 = e^{-\delta_r L_r}$ is the round-trip-power-attenuation in which the δ_r is the propagation loss of microring waveguide per unit length, and $L_r = 2\pi \times R$ is the cavity length of the microring. Based on the transfer matrix method, this system can be expressed as

$$T_{in} = T_{Bg} \times T_{wg} \times T_{ring} \times T_{wg} \times T_{Bg} \times T_{out}, \quad (1)$$

where T_{in} and T_{out} are the vectors containing the amplitudes of the forward and backward propagating light at the input port and the through port, respectively, T_{ring} is the matrix of the microring with taking the reflected light into account, and T_{Bg} is the transfer matrix of the Bragg grating. Here, we regard the Bragg grating as a periodic structure consisting of wide waveguide segments, narrow segments, and reflective interfaces.²³ The detailed definitions of relative parameters can be found in our previous work.²⁴ The effective indices

for the waveguides of different widths and wavelengths are calculated with the BeamPROP module of Rsoft software by taking the dispersion into account.

As shown in Fig. 1(b), when $L = (m + \frac{1}{2}) \times \text{pitch}$ (m is a natural number, and pitch is the pitch of Bragg grating), the transmission spectrum of the F-P resonator is in a “W” lineshape. While the resonance dips of the microring overlap with the “W” lineshape of the F-P resonator, the resonances are formed in both resonators simultaneously. The coupling between them gives rise to the EIT and Fano transmission as shown in Fig. 2(a). In order to set the resonance wavelengths of the F-P resonator at $1.55 \mu\text{m}$, we chose these parameters as an initial design: $\text{pitch} = 320.5 \text{ nm}$, $N = 70$, $dw = 20 \text{ nm}$, and $\alpha = 0.9803$.

While increasing the gap width between the bus waveguide and the microring resonator, the coupling strength between the F-P resonator and the microring resonator becomes weaker. Consequently, the coupling coefficient k decreases, and the transmission coefficient t increases. The region circled by the black dashed line is zoomed-in as shown in Fig. 2(b). It can be clearly seen that when $t = 0.7141 < \alpha$, an EIT transmission is generated. With increasing t to 0.8660 , the extinction ratio (ER) of the EIT peak drops from 17 dB to 10 dB, and the insertion loss (IR) increases from 13 dB to 20 dB. Meanwhile, the dip at the right side of the EIT peak becomes narrower. By increasing the value of t to $t = 0.9803 = \alpha$, the transmission spectrum

FIG. 1. (a) The schematic of the APMR-BG coupled-resonator system. (b) The normalized transmission spectra of the F-P resonator and the microring resonator.

FIG. 2. (a) The EIT and Fano transmission spectra of different t under $\text{pitch} = 320.5 \text{ nm}$, $N = 70$, $dw = 20 \text{ nm}$, and $\alpha = 0.9803$. (b) The zoomed-in spectra of the EIT and Fano transmission spectra circled by the black dashed line.

transforms to a sharp Fano lineshape, and it is noteworthy that the Fano transmission has the largest ER ~ 43 dB at this point. With a further increase in t to $t = 0.9950 > \alpha$, the transmission spectrum keeps the Fano lineshape, but the extinction ratio (ER) of Fano transmission dramatically decreases from 43 dB to 7 dB, and the required wavelength shift $\Delta\lambda$ between the dip and the peak decreases from 0.15 nm to 0.11 nm.

We consider that it is the abrupt π phase shift of the transmission of the microring resonator under the critical coupling condition ($t = \alpha$),²⁵ which leads to the transformation of the lineshape. The transmission of the APMR-BG coupled-resonator system (blue solid line) and the corresponding phase of the microring resonator (red dashed line) have been plotted in Fig. 3. As shown in Fig. 3(a), when $t = 0.7141$, the phase curve of the microring resonator becomes steeper at the wavelength of the EIT peak (marked with black dashed line). When we increased the gap width until $t = 0.8660$, as it can be seen in Fig. 3(b), the gradient of the phase at the wavelength of the EIT peak becomes larger than $t = 0.7141$. For these two scenarios, no abrupt phase shift happens, which means that the coupling between two resonators keeps constructive, and the transmission maintains as the EIT lineshape. When $t = 0.9803 = \alpha$ (critical coupling), it is noteworthy that an abrupt π phase shift of the light in the microring resonator occurs at the same wavelength of the Fano lineshape as plotted in Fig. 3(c). This abrupt π phase shift contributes to the transformation from constructive interference (EIT transmission) to destructive interference (Fano transmission). The opposite phases of these two light paths lead to the completely destructive interference and gives rise to the extremely low transmission at the dip of the Fano lineshape and the largest ER. In addition, as shown in Fig. 3(d), if t is further increased to 0.9950, the phase shift maintains but the shifting value is smaller than π . This smaller phase shift results in a partially counteraction of the light between the microring resonator and the F-P resonator, corresponding to the smaller ER (~ 7 dB) of the Fano lineshape. In summary, for the over-coupling ($t < \alpha$) and the under-coupling ($t > \alpha$) regime of the microring resonator,

FIG. 3. (a) The normalized transmission spectra and the phase of microring when $t = 0.7141$. (b) The normalized transmission spectra and the phase of microring when $t = 0.8660$. (c) The normalized transmission spectra and the phase of microring when $t = 0.9803$. (d) The normalized transmission spectra and the phase of microring when $t = 0.9950$. (Figs. 3(a)–3(d) are under conditions: pitch = 320.5 nm, $N = 70$, $dw = 20$ nm, and $\alpha = 0.9803$.)

the phase shift is continuous but in opposite direction,²⁶ which leads to the continuous change of the EIT and Fano transmissions, respectively. The critical coupling regime ($t = \alpha$) is the threshold point for the conversion between the EIT and Fano transmissions.

The APMR-BG coupled-resonator systems of different gap widths were fabricated on a SOI wafer with a 220 nm-thick top silicon layer and a 2 μm-thick buried oxide (BOX) layer. Both the grating layer and the waveguide layer were patterned with electron beam lithography (EBL). The grating layer was etched to the 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) in order to have straight and smooth sidewalls. After removing the photoresist, the sample was coated with a cladding layer of 1 μm SiO₂ using the plasma enhanced chemical vapor deposition (PECVD) system. The radius of the microring and the width of the strip waveguides are designed to be 10 μm and 500 nm, respectively. The pitch and dw are fixed at 320 nm and 20 nm, respectively. The duty cycle is 50%. The N of each Bragg grating is 100. The L of 3.36 μm is chosen which was equal to 10.5 times of the pitch. The gap width between the bus waveguide and the microring is swept from 60 nm to 300 nm. Figures 4(a) and 4(b) show the SEM images of the fabricated APMG-BG system. As shown in Fig. 5(a), when the width of the gap is 110 nm ($t < \alpha$), the coupling between the two resonators is strong, and the EIT transmission is generated. For the EIT transmission circled by the black dashed

FIG. 4. (a) The SEM image of the APMR-BG coupled-resonator system. (b) The zoomed-in SEM image of the Bragg grating.

FIG. 5. (a) The measured EIT transmission spectrum when the gap width is 110 nm. (b) The measured Fano transmission spectrum when the gap width is 170 nm. (c) The zoomed-in EIT transmission spectrum and the corresponding phase of the microring resonator. (d) The zoomed-in Fano transmission spectrum and the corresponding phase of the microring resonator.

lines, the full-width-at-half-maximum (FWHM) is measured as 0.155 nm, which corresponds to the quality factor (Q factor) of 10020. Based on the theoretical fitting data, the Q factor of the fabricated loaded microring is 2160. The Q factor of the F-P resonator formed by Bragg gratings is 1100. The ER is about 8.5 dB. The fitting parameters are: $pitch = 318.85$ nm, $N = 100$, $dw = 8.5$ nm, $R = 10.4$ μ m, $k = 0.6i$, $t = 0.8$, and $\alpha = 0.9799$. With the fitting parameters, the corresponding phase of the microring resonator has been plotted with the zoomed-in EIT transmission spectrum in Fig. 5(c), which is consistent with the scenarios in Figs. 3(a) and 3(b). As shown in Fig. 5(b), when the width of the gap is 170 nm ($t \geq \alpha$), a sharp asymmetric Fano transmission is generated. It is noteworthy that the ER of the Fano transmission is as large as 26 dB. The fitting parameters are as follows: $pitch = 320.35$ nm, $N = 100$, $dw = 8$ nm, $R = 10.199$ μ m, $k = 0.208i$, $t = 0.9781$, and $\alpha = 0.9745$. As seen, in this device, t is very close to α , which means the coupling status is close to the critical coupling status. So, a large ER of 26 dB can be obtained, which agrees well with the simulation result shown in Fig. 3(c). As shown in Fig. 5(d), the corresponding phase of the microring resonator has an abrupt shift at the wavelength of the Fano lineshape (marked with black dashed line), which is consistent with the simulation results shown in Figs. 3(c) and 3(d). It can be clearly seen that the experimental results and the simulation results are in good agreement. The difference between the designed (20 nm) and the fitted dw (8 and 8.5 nm) is because the fabricated Bragg grating corrugations are not in the desired rectangular shape.

The actual fabricated Bragg gratings are comparable with an ideal rectangular Bragg grating with $dw = 8$ nm and 8.5 nm. So we utilize more periods ($N = 100$) of Bragg grating to increase the reflectivity and compensate the influence of the smaller actual corrugation depth. The small ripples are due to the weak optical reflection at the input and output facets. The active tuning of the coupling coefficient k can be realized by utilizing the MEMS method to change the gap between the bus waveguide and the microring (need to remove the oxide cladding layer).^{27–29} Besides, tuning the round-trip-power-attenuation α^2 can be achieved by adding an MZI (Mach-Zehnder interferometer)-assisted structure with a thermal heater.^{30,31}

In this paper, we reported the conversion between the EIT and the Fano transmission in an APMR-BG coupled-resonator system. The transformation of the transmission lineshape is achieved by tuning the coupling strength between the F-P resonator and the microring resonator as an abrupt π phase shift of the light in the microring resonator occurs and leads to the transformation from the constructive interference to the destructive interference between the two resonators. For the over-coupling ($t < \alpha$) and the under-coupling ($t > \alpha$) status of the microring resonator, the phase shift is continuous but in opposite direction, which leads to the continuous changing of the EIT transmission and the Fano transmission, respectively. The experimental results are well fitted with the specially developed numerical model. This system has the advantage of a small footprint, and the fabrication process is compatible with the planar waveguide fabrication process.