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Interference effect in a dual microresonator-coupled Mach–Zehnder interferometer

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We present a theoretical study of interference effect in a Mach–Zehnder interferometer in which two microresonators are side coupled to both arms of the interferometer. The results show that sharp asymmetric Fano resonance, coupled resonator induced transparency and absorption effects can be created in such a structure. We demonstrate that these effects arise from interference between a resonance mode and a continuing propagating mode with asymmetric phase difference, destructive interference between two overcoupled resonance modes, and constructive interference between an overcoupled resonance mode and an undercoupled mode or a continuing propagating mode with symmetric phase differences, respectively. These effects may offer a better understanding of the analogous effects in atomic medium and also make optical resonators a potential device to utilize these effects.

Keywords: microresonator, Mach–Zehnder interferometer, Fano resonance, coupled resonator induced transparency and absorption.

1. Introduction

Optical microring, microdisk and microsphere resonators have attracted considerable attention to device applications because of their high Q-factor and small modal volumes [1–4]. Recently, it has been demonstrated that the effects analogous to Fano resonance, electromagnetically induced transparency and absorption in atomic system can be established in microresonator system [5–17]. Such microresonator induced effects, which do not suffer from the specific light wavelength limitations in atomic system, have the advantages of improving the optical switching characteristics of microresonator-based devices and controlling dispersion and the group velocity of light.

In this paper, we investigate the interference effect in an alternative microresonator structure based on a Mach–Zehnder interferometer, as shown in Fig. 1. By interference between the propagating on-resonance (or non-resonance) modes in two arms, Fano resonance, coupled resonator-induced transparency (CRIT) and absorption (CRIA)

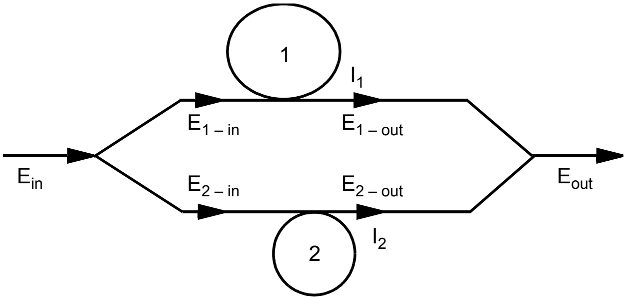

Fig. 1. Schematic diagram of a dual microresonator-coupled Mach–Zehnder interferometer; two microresonators are side coupled to both arms, respectively.

similar to quantum interference effects in atomic physics can be induced. Our system is different from the other two microresonator structures reported, as two microresonators respectively are coupled to separate arms of the interferometer and Fano resonance and CRIT can simultaneously appear in the transmission spectrum. Moreover, we show that CRIT arises from the interference between two resonance modes that have the same phase shifts and different amplitudes.

2. Theoretical analysis

Figure 1 shows the configuration of the dual microresonator-coupled Mach–Zehnder interferometer. We find transfer response in crossing the coupling zone of the upper arm and the lower arm,

$$\frac{E_{i-\mathrm{out}}}{E_{i-\mathrm{in}}} = \left|\frac{E_{i-\mathrm{out}}}{E_{i-\mathrm{in}}}\right| \exp(i\Phi_i) \tag{1}$$

where:

$$\left|\frac{E_{i-\mathrm{out}}}{E_{i-\mathrm{in}}}\right|^2 = \frac{\left[\sqrt{1-t_i^2} - \exp\left(-\frac{\alpha_i L_i}{2}\right)\right]^2 + 4\sqrt{1-t_i^2}\exp\left(-\frac{\alpha_i L_i}{2}\right)\sin^2\left(\frac{\phi_i}{2}\right)}{\left[1 - \sqrt{1-t_i^2}\exp\left(-\frac{\alpha_i L_i}{2}\right)\right]^2 + 4\sqrt{1-t_i^2}\exp\left(-\frac{\alpha_i L_i}{2}\right)\sin^2\left(\frac{\phi_i}{2}\right)}$$

$$\Phi_i = \arg\left[\frac{\sqrt{1-t_i^2} - \exp\left(i\phi_i - \frac{\alpha_i L_i}{2}\right)}{1 - \sqrt{1-t_i^2}\exp\left(i\phi_i - \frac{\alpha_i L_i}{2}\right)}\right]$$

E_i is the complex field amplitude (at the i-th port) normalized such that $|E_i|^2 = P_i$, the power entering or exiting that port, t_i is the real amplitude coupling coefficient,

α_i represents attenuation coefficient of the microcavity, $L_i = 2\pi a_i$, a_i is the radius of the microcavity and ϕ_i is the total phase shift acquired by the light during one round trip. $|E_{i-\mathrm{out}}/E_{i-\mathrm{in}}|$ and Φ_i represent the amplitude and the phase of $E_{i-\mathrm{out}}$ relative to $E_{i-\mathrm{in}}$, respectively.

Incident light is equally distributed into two arms at the dividing Y junction and subsequently recombined at the output by an adding Y junction. Both arms have the same physical length L_a. At the combing Y junction the light in the arm coupling with the microcavity acquires an optical phase $\Phi_1 + \beta L_a$ (β is propagation constant), while in the other arm the phase accumulated is given by $\Phi_2 + \beta L_a$. Therefore, the output transmitted power is determined by

$$\left|\frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}\right|^2 = \frac{1}{4}\left[\left|\frac{E_{1-\mathrm{out}}}{E_{1-\mathrm{in}}}\right|^2 + 2\left|\frac{E_{1-\mathrm{out}}}{E_{1-\mathrm{in}}}\right|\left|\frac{E_{2-\mathrm{out}}}{E_{2-\mathrm{in}}}\right|\cos(\Phi_1 - \Phi_2) + \left|\frac{E_{2-\mathrm{out}}}{E_{2-\mathrm{in}}}\right|^2\right] \tag{2}$$

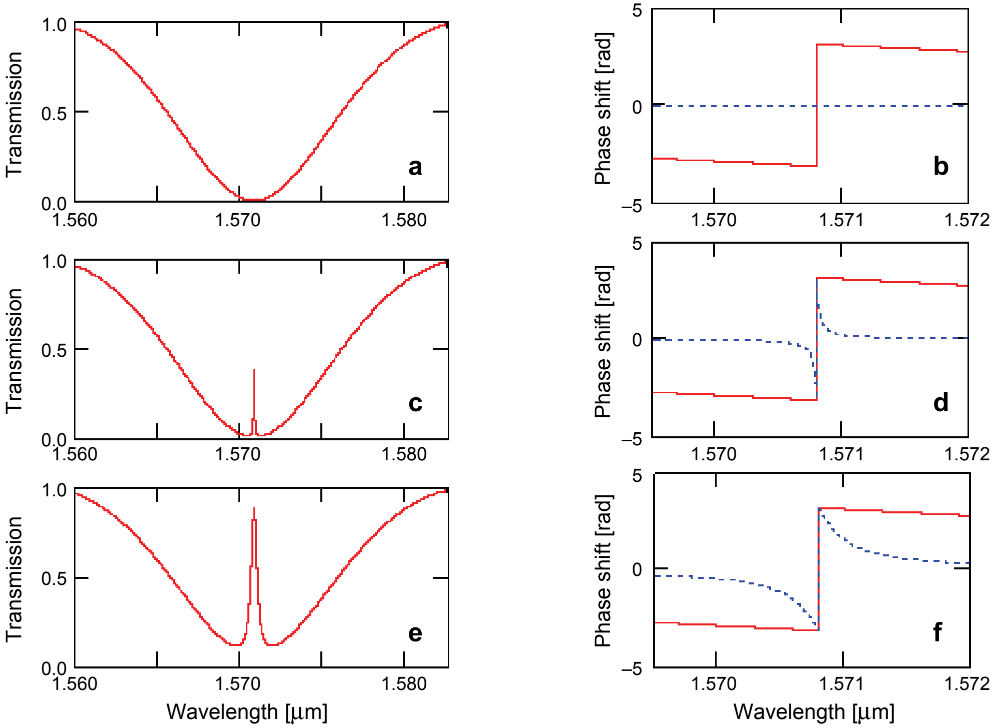

Fig. 2. Intensity transmission spectra through optical system as shown in Fig. 1, with $a_1 = a_2 = 10$ µm, refractive index contrast $n = 1.5$, $t_1 = 0.99$, $\alpha_{1,2} = 10^{-4}$ µm^{-1} for $t_2 = 0$ (**a**), $t_2 = 0.1$ (**c**), $t_2 = 0.3$ (**e**). The phase shifts of the transmitted mode passing the coupling zone between the microresonator and the arm (**b**, **d** and **f**). The solid curves are the phase shifts of the mode in the upper arm and the dashed curves are the phase shifts of the mode in the lower arm. The parameters used in **b**, **d** and **f** are same as those in **a**, **c** and **e**, respectively.

3. Results and discussion

Figure 2 shows the transmission spectra of the dual microresonator-coupled Mach–Zehnder interferometer and the phase shifts of the transmitted mode passing the coupling zone between the microresonator and the arm in the case where the sizes of microresonators are equal. Figure 2**a** shows the transmission spectrum for a single microresonator coupled Mach–Zehnder interferometer where the coupling coefficient between the second resonator and the arm is $t_2 = 0$. A broad absorption dip appears at

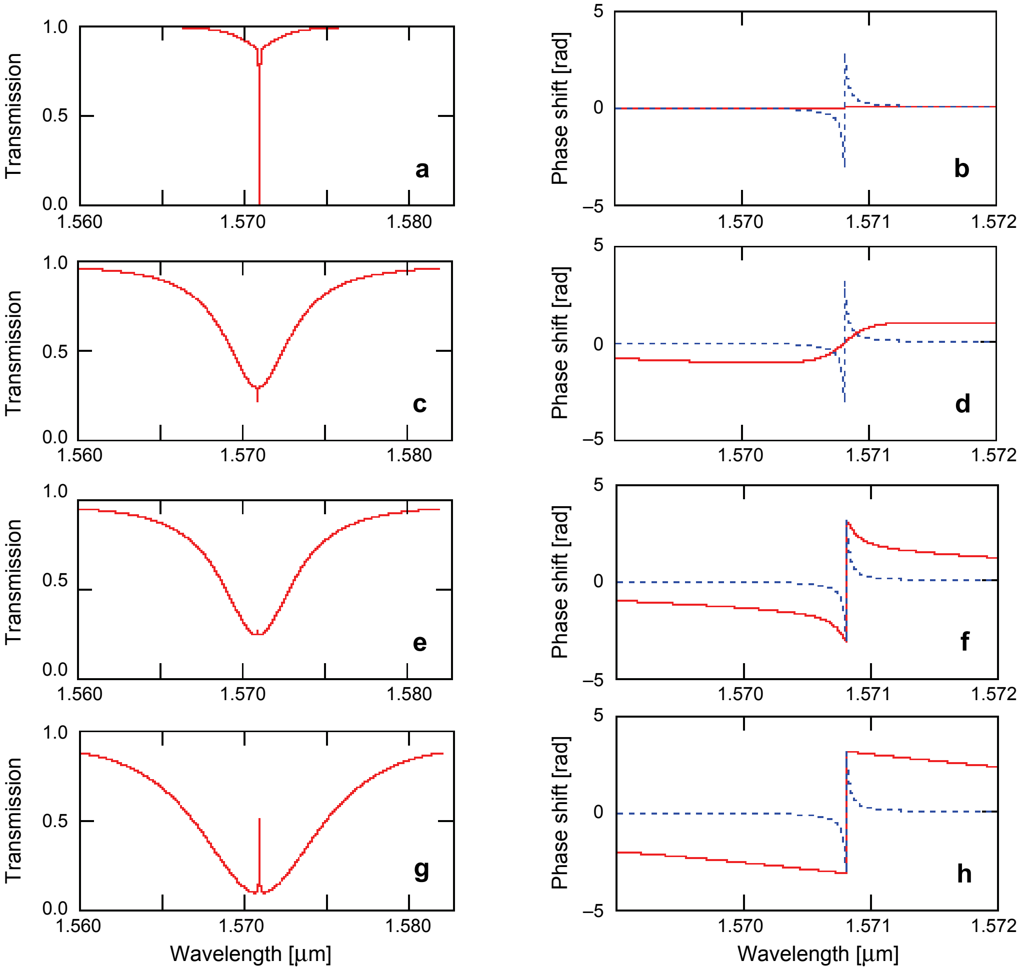

Fig. 3. Intensity transmission spectra through optical system as shown in Fig. 1, with $a_1 = a_2 = 10$ µm, refractive index contrast $n = 1.5$, $t_1 = 0.1$, $\alpha_1 = 10^{-6}$ µm^{-1}, $\alpha_2 = 10^{-2}$ µm^{-1} for $t_2 = 0.2$ (**a**), $t_2 = 0.65$ (**c**), $t_2 = 0.7$ (**e**), $t_2 = 0.9$ (**g**). The phase shifts of the transmitted mode passing the coupling zone between the microresonator and the arm (**b**, **d**, **f** and **h**). The solid curves are the phase shifts of the mode in the upper arm and the dashed curves are the phase shifts of the mode in the lower arm. The parameters used in **b**, **d**, **f** and **h** are the same as those in **a**, **c**, **e** and **g**, respectively.

the resonance wavelength. When t_2 increases and the second resonator is also coupled into the arm, a narrow transparent peak appears in the broad absorption dip, which is similar to the EIT effect in an atomic system. This CRIT peak results from the destructive interference between the two on-resonance modes: the mode in the lower arm has narrower resonance than the one in the upper arm and their phase difference is around 0, as seen in Fig. 2**d**. As t_2 increases, the transparency peak grows, as shown in Figs. 2**c** and 2**e**.

In Figures 3**a**, 3**c**, 3**e** and 3**g**, we show transmission spectra for the system as we tune the second resonator from undercoupled to overcoupled, showing the progression from CRIA to CRIT. When the first resonator is overcoupled and the second is undercoupled, the phase difference between the guiding modes in the upper and lower arms is around π at the resonance wavelength, as shown in Fig. 3**b** and 3**d**. Two modes interfere constructively to enhance absorption. The result is that a sharp drop induced by the mode in the upper arm with narrower resonance appears in a broad absorption dip induced by the mode in the lower arm, producing CRIA, as shown in

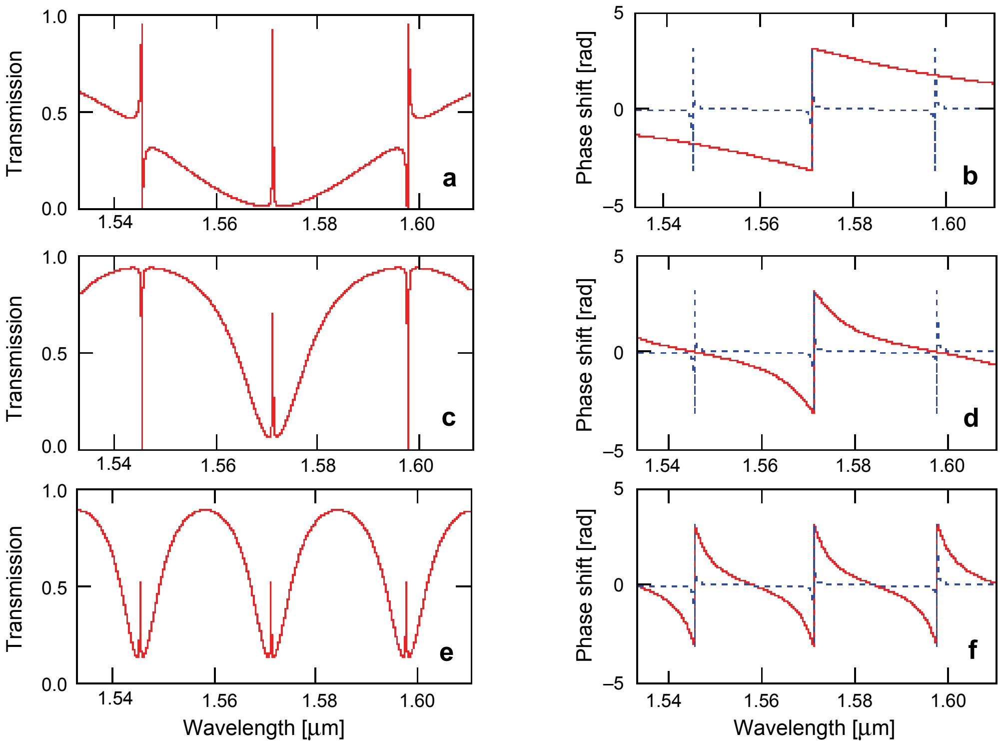

Fig. 4. Intensity transmission spectra through optical system as shown in Fig. 1, with $a_1 = 10$ µm, refractive index contrast $n = 1.5$, $t_1 = 0.2$, $t_2 = 0.9$, $\alpha_1 = 10^{-6}$ µm^{-1}, $\alpha_2 = 10^{-2}$ µm^{-1} for $a_2 = 10$ µm (**a**), $a_2 = 5$ µm (**c**) $a_2 = 1$ µm (**e**). The phase shifts of the transmitted mode passing the coupling zone between the microresonator and the arm (**b**, **d** and **f**). The solid curves are the phase shifts of the mode in the upper arm and the dashed curves are the phase shifts of the mode in the lower arm. The parameters used in **b**, **d** and **f** are the same as those in **a**, **c** and **e**, respectively.

Figs. 3**a** and 3**c**. When the second resonator turns to overcoupled, the phase difference between two guiding modes is around 0 at the resonance wavelength, as shown in Figs. 3**f** and 3**h**. Destructive interference between two modes decreases absorption to produce a narrow CRIT peak in the broad absorption dip, as shown in Figs. 3**e** and 3**g**.

Now, we investigate the transmission spectra in the case when the sizes of two microresonators are unequal. For comparison purposes, we present transmission spectrum for the same system with two resonators of the same size ($a_1 = a_2 = 10$ μm) in Fig. 4**a**, showing three CRIT peaks. When the diameter of the second resonator is changed as $a_2 = 1$ μm, the second resonator is off-resonance at the first and third resonant wavelengths of the first resonator, and on-resonance at the second resonant wavelength. Thus, the sharp asymmetric Fano resonances which result from interference between the optical resonance mode in the upper arm and the continuing propagating mode in the lower arm, appear on the left-hand side and the right-side of the spectrum, as shown in Fig. 4**a**. The phase differences between the two modes are opposite in these two regions of the spectrum, hence two Fano resonances are inverted. On the other hand, the destructive interference between two resonant modes in the middle of the spectrum gives CRIT. When the diameter of the second resonator is changed to $a_2 = 5$ μm, the Fano resonances turn to symmetric CRIA dips which result from constructive interference between two optical pathways, as shown in Fig. 4**c**. These symmetric or asymmetric line shapes are due to symmetric or asymmetric phase differences between two modes at the shorter and longer wavelength sides of the resonance of the first resonator, as shown in Figs. 4**b** and 4**d**.

4. Conclusions

We have investigated interference effect between propagating modes in two arms of a Mach–Zehnder interferometer in which two microresonators were side coupled to both of its arms. The analysis showed that asymmetric Fano resonance, CRIT and CRIA which arise from interference between a resonance mode and a continuing propagating mode with asymmetric phase difference, destructive interference between two overcoupled resonance modes, and constructive interference between an overcoupled resonance mode and an undercoupled mode or a continuing propagating mode with symmetric phase differences, can be created. These effects may offer a better understanding of the analogous effects in atomic medium and also make optical resonators a potential device for utilizing these effects.

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