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Modified transmission spectrum induced by two-mode interference in a single silica microsphere

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Abstract

We theoretically and experimentally study the resonant transmission spectrum of light in a fibre taper coupled with a single silica microsphere cavity system, where two whispering-gallery modes (WGMs) are simultaneously excited. By changing the taper position (correspondingly, tuning the resonant frequencies of the two WGMs and modulating their coupling conditions with the fibre taper), a sharp electromagnetically-induced-transparency-like window can be observed in the transmission spectrum. This line shape origins from the taper-mediated interference between two co-existing WGMs in a single microsphere. This measurement result agrees well with the theoretical analysis.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Whispering gallery mode (WGM) optical microresonators, such as microspheres [1] and microtoroids [2], have attracted lots of attentions due to their high- Q factors and small mode volumes. The potential applications ranging from ultralow-threshold lasing, highly sensitive sensing, to cavity quantum electrodynamics have been reported (for example, see [3–6]). The transmission spectrum of these microresonators can be obtained by sweeping the resonances with tunable lasers, which couple with the resonators through an evanescently coupler. The shape of the transmission is related to the sweeping speed [7–9] and the input power [10]. In addition, the spectrum can be dramatically modified by utilizing a multi-mode waveguide [11, 12], coupling two or more microcavities [13–17] and changing the excitation conditions [18]. Fano-like and electromagnetically-induced-transparency (EIT)-like line shapes have been observed. These novel line shapes have been proposed to enhance the slope sensitivity [19, 20], improve

the optical switching [16, 21] and research on the ‘slow light’ [13, 22, 23].

In atomic systems, the EIT effect results from the destructive interference between two excitation pathways to the upper level. In a waveguide coupled microresonator system, the EIT-like effect, also called coupled resonator-induced transparency (CRIT), can be explained by the classic destructive interference [24]. It is well known that the high- Q modes in microcavities have very narrow linewidths, and their resonant frequencies strongly depend on the physical size of the microcavities. As a result, to achieve the EIT-like effect in the coupled cavity system, it is still a huge challenge to match the two modes (belong to different microcavities) in frequency. In other words, the individual frequency tuning is essentially required besides the precise fabrication.

Recently, the EIT-like resonance has been observed in a single polydimethylsiloxane-coated silica microtoroidal resonator [25] instead of a coupled cavity system. In this paper, however, we report on the EIT-like resonance lineshape in a single pure silica microsphere without coating. Here, the fibre taper is not only used for the near-field coupler, but

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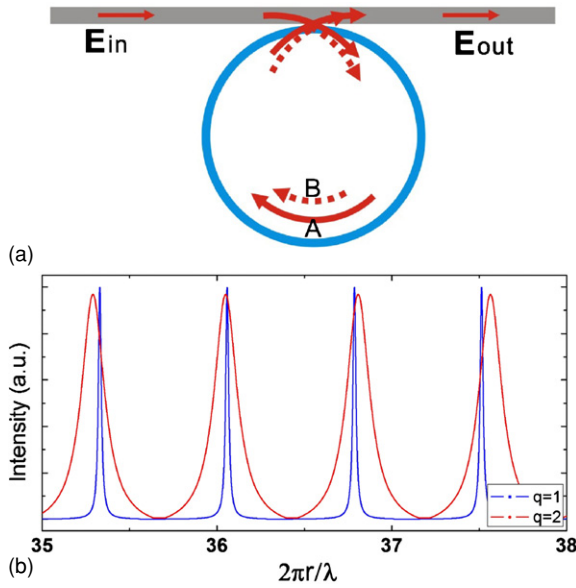


Figure 1. (a) Schematic illustration of a two-mode microcavity coupled with a waveguide. (b) Sketch of the modes distribution in a single microsphere.

also to tune the resonant wavelengths of WGMs instead of temperature tuning in [25, 26]. Two WGMs in the single microsphere, which are originally separated in frequency, can be tuned together by changing the air gap between the fibre taper and the microsphere. The indirect interaction between these two co-existing modes can create a ‘transparent window’ in the transmission spectrum. A detailed theoretical analysis allows us to uncover the basic features of interference in a waveguide and single microsphere system.

2. Theory

The EIT-like effect has been theoretically and experimentally in the system of two or more interacting microresonators [13–16, 24]. Necessary conditions for the CRIT are as follows: (1) the modes possess closely resonant frequencies, and (2) they are coupled together. Similarly, to observe the EIT-like effect in a single microcavity, the system must also satisfy these two conditions. Here, we first provide some discussions about the feasibility of the EIT-like effect in a single microsphere coupled with an optical waveguide system, as shown in figure 1(a).

On one hand, the WGMs in a microsphere with different radial mode order (q) have various field distributions. For example, the field of the first-order (fundamental) mode is closer to the boundary than the second-order mode. Therefore, the effective refractive index (n_{eff}) for the first- and second-order modes is different. In other words, their free space ranges (FSR) are different. As shown in figure 1(b), the FSR of mode ($q = 2$) is slightly larger than the mode ($q = 1$) in the same band. Obviously, the second-order modes approach to first-order modes and separate again with increasing the dimensionless parameter $2\pi r/\lambda$. Hence, with a certain wavelength band and a microsphere size, we can always find two modes whose resonant wavelengths are close or even overlapped

On the other hand, the presence of the fibre taper also alters the resonant wavelengths of the WGMs, as studied in experiments [26–28] and numerical simulations [29]. The near field effect is easy to be understood as the fibre taper influences the effective refractive index outside the microsphere. According to the coupled-mode theory, the perturbation of frequency can be described by $\Delta\omega \propto \int |E|^2 dv$ [31], where E is the normalized electrical field of the WGM, and the integration is taken over the volume of the fibre taper. The field outside the microsphere decays exponentially with the distance to the boundary, so changing the position of the fibre taper with a translation stage could give rise to the resonant wavelength shift. It is well known that the fundamental modes ($q = 1$) have stronger coupling than the second-order modes ($q = 2$), so that the influence of the fibre taper to the fundamental modes is larger. This allows us to tune the resonance shift between the two modes in a single microcavity by a fibre taper. For instance, as shown in figure 1(b), the modes $\text{TE}_{47,1}$ ($2\pi r/\lambda = 36.786$) and $\text{TE}_{42,2}$ ($2\pi r/\lambda = 36.807$), which are slightly detuned, can be shifted on-resonance with this method.

In a barely single microsphere, two WGMs with different azimuthal numbers are orthogonal. Therefore, they have no interaction. However, with the introduction of a fibre taper, these modes are perturbed so that they are no longer orthogonal. As shown in figure 1(a), we consider two independent WGMs A and B. In an intuitive image, light in mode A (B) could couple with the fibre taper, and part of light could couple back to the microsphere. In other words, the fibre taper introduces indirect coupling between modes A and B. This situation is much similar to the three-waveguide direct coupler in plane [32], which is different from the traditional fibre taper coupled with a single mode in the microsphere [31]. Through the analysis of the propagation matrix, the three-mode coupling could be described by coupled differential equations in space which is approximately reduced to the input–output relation:

$$\begin{cases} \begin{pmatrix} C_A \\ C_B \\ C_F \end{pmatrix}_{\text{out}} = \begin{pmatrix} 1 & -\eta_{AB} & i\eta_A \\ -\eta_{AB}^* & 1 & i\eta_B \\ i\eta_A^* & i\eta_B^* & 1 \end{pmatrix} \begin{pmatrix} C_A \\ C_B \\ C_F \end{pmatrix}_{\text{in}}, \end{cases} \quad (1)$$

where $C_{A(B)}$ is the A(B)th cavity mode with resonant frequency $\omega_{A(B)}$; C_F is the mode in the taper fibre; η_A , η_B , η_{AB} are the coupling coefficients of A-taper, B-taper, A–B coupling, respectively. These coupling coefficients are independent of each other and could be adjusted by changing the taper position. Taking into account the resonant relationship of A and B, the coupled mode equations can be expressed in time as

$$\begin{cases} \frac{dC_A(\omega)}{dt} = (-\kappa_{0A} - \kappa_{1A} + i\Delta\omega_A)C_A(\omega) \\ \quad - gC_B(\omega) + \frac{i\eta_A}{\tau}E_{\text{in}}(\omega), \\ \frac{dC_B(\omega)}{dt} = (-\kappa_{0B} - \kappa_{1B} + i\Delta\omega_B)C_B(\omega) \\ \quad - g^*C_A(\omega) + \frac{i\eta_B}{\tau}E_{\text{in}}(\omega), \end{cases} \quad (2)$$

where $\Delta\omega_{A(B)} = \omega - \omega_{A(B)}$ denotes the detuning of the input carrier from the resonant frequency; τ is the cavity round-trip time; $\kappa_{0A(B)}$ is the intracavity decay rate and $\kappa_{1A(B)} =$

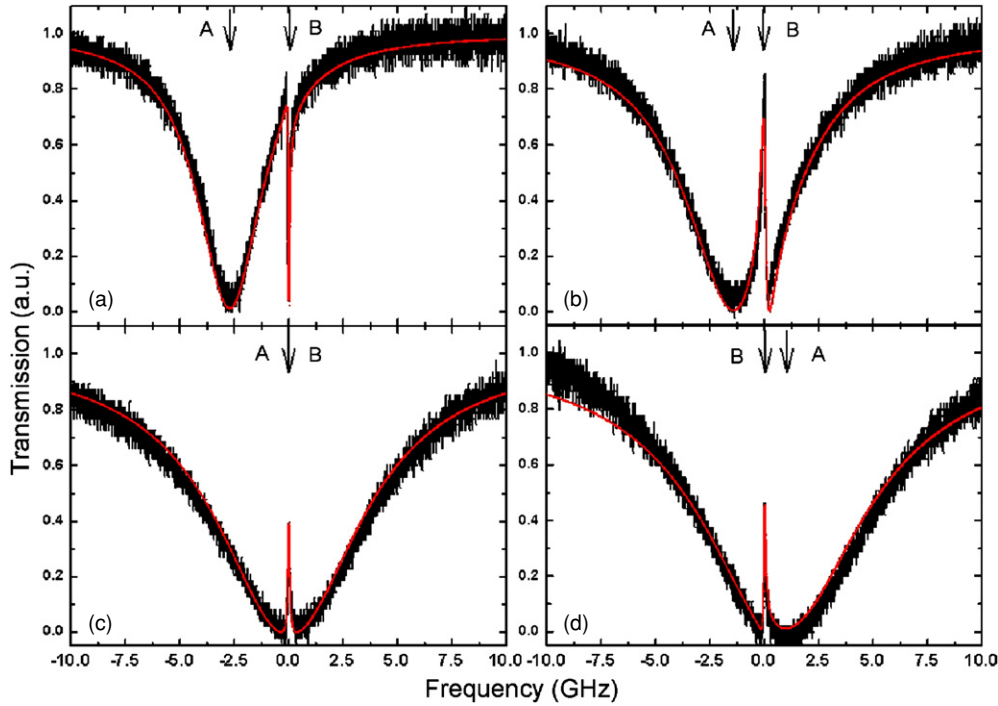


Figure 2. Experimental transmission spectrum (black lines) and theoretical calculation (red lines) obtained using equation (4). The fitting parameters are set as $(\kappa_{0A(B)}, \kappa_{1A(B)}, g)$ (a) $2\pi \times (1.4(0.02), 0.8(0.014), 0.17)$ GHz, (b) $2\pi \times (1.9(0.02), 1.2(0.015), 0.28)$ GHz, (c) $2\pi \times (2.0(0.02), 2.0(0.016), 0.27)$ GHz, (d) $2\pi \times (2.0(0.02), 2.4(0.016), 0.29)$ GHz.

$|\eta^2_{A(B)}|/(2\tau)$ is the external cavity decay rate; E_{in} and E_{out} describe the input and output fields, respectively. $g = \eta_{AB}/\tau$ is the effective coupling strength between modes A and B. Here, the equations show that the resonant modes could be simultaneously excited and coupled with each other in the single microresonator. The light input from the fibre taper would interfere between the two optical pathways and finally induce the EIT-like phenomenon.

We are interested in the steady-state regime of the system, corresponding to $dC_A/dt = dC_B/dt = 0$. Thus, the internal cavity modes can be expressed as

$$\begin{cases} C_A(\omega) = -\frac{(i\eta_A X_B - ig\eta_B)/\tau}{X_A X_B - g^2}, \\ C_B(\omega) = -\frac{(i\eta_B X_A - ig^*\eta_A)/\tau}{X_A X_B - g^2}, \end{cases} \quad (3)$$

where $X_{A(B)} = -\kappa_{0A(B)} - \kappa_{1A(B)} + i\Delta\omega_{A(B)}$. Considering the coupling between the taper and the microsphere that gives rise to standard cavity input-output formalism $E_{out} = E_{in} + i\eta_A C_A + i\eta_B C_B$, we obtain the normalized output field:

$$E_{out}(\omega) = 1 + 2\frac{\kappa_{1A} X_B + \kappa_{1B} X_A + 2\text{Re}(g)\sqrt{\kappa_{1A}\kappa_{1B}}}{X_A X_B - |g|^2}. \quad (4)$$

This is a general description for propagation of light through a single-cavity, waveguide system. With this formula, we can get the output intensity and the phase.

3. Experimental results

From the discussion above, by choosing proper cavity size and changing the position of the fibre taper, an EIT-like

phenomenon in a single microsphere can be created. In our experiment, a tunable, single frequency, narrow linewidth (<300 kHz) external-cavity laser in the 780 nm band is used to analyse the transmission. The microsphere with the diameter about $14 \mu\text{m}$ is fabricated by using a focused CO_2 laser beam. A tapered fibre with a waist diameter of $\sim 1 \mu\text{m}$ is fabricated by pulling a single mode fibre at 780 nm wavelength and placed next to the microsphere to evanescently couple light in and out of the microsphere. The output light is finally detected by a 125 MHz low-noise photo detector, which is connected to a digital oscilloscope to measure the transmission spectra. The coupling strength between the tapered fibre and the microsphere can be adjusted by changing the air gap between them, which is controlled by translation stages, with a step resolution of 20 nm.

The transmission spectra are found to be modified by adjusting the fibre taper position. Figures 2(a)–(d) display four typical experimental transmission spectra (black) with different detunings $\Delta\omega_{AB}/2\pi = (-2.7, -1.35, 0, 0.8)$ GHz, respectively. The theoretical fittings (red) using equation (4) are also shown correspondingly. It is easily to find that the experimental results have a good agreement with the theoretical model. In detail, the linewidth of mode A ($Q_0 \sim 2 \times 10^5$) is broader than that of mode B ($Q_0 \sim 10^7$), which indicates that mode A is a high-order mode. In our experiment, mode A is operated from under-coupling to over-coupling regime in figures 2(a)–(d), while mode B is in the under-coupling regime. When the frequencies of modes A and B are tuned to be overlapped (figure 2(c)), the transmission will create a ‘transparent window’ in the spectrum. The different line shapes, which are induced by the interference between the

co-exciting WGMs in a single microcavity, strongly depend on the coupling strength, intrinsic loss, external loss and resonant frequency of the microresonator, i.e. the parameters g , $\kappa_{0A(B)}$, $\kappa_{1A(B)}$, $\omega_{A(B)}$. In addition, we note that the fitting parameters, especially $\kappa_{0A(B)}$, are changed with the different detuning. It originates from the small thermal distortion when scanning the excitation wavelength, and weak direct coupling among the normal modes induced by backscattering.

4. Conclusion

In summary, the EIT-like effect is observed in a single silica microsphere with the fibre taper tuning at room temperature. This lineshape is derived from the taper-mediated interference between two co-existing WGMs in a single microsphere. The sharp transparency peak can be used in biochemical sensing to improve the sensitivity. And it also holds potential applications in modulating the light transmission, for instance, fast light and tunable narrow-band filter in classical and quantum information processing. In our experiment, the fibre taper tuning provides a simple and available method to get the controllable frequency instead of the complicated tuning methods. In other words, this coupled system can induce the stable EIT-like effect, which is immune to the perturbation from the surrounding, for example, temperature drifts. Therefore, the demonstration of optical transparency provides an easy way to achieve integrated photonic devices for applications requiring the EIT effect.

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References

- [1] Gorodetsky M L, Savchenkov A A and Ilchenko V S 1996 *Opt. Lett.* **21** 453–5
- [2] Armani D K, Kippenberg T J, Spillane S M and Vahala K J 2003 *Nature* **421** 925–8
- [3] Yang L, Carmon T, Min B, Spillane S M and Vahala K J 2005 *Appl. Phys. Lett.* **86** 091114–6
- [4] Armani A M, Kulkarni R P, Fraser S E, Flagan R C and Vahala K J 2007 *Science* **317** 783–7
- [5] Park Y S, Cook A and Wang H 2006 *Nano Lett.* **6** 2075–9
- [6] Srinivasan K and Painter O 2007 *Nature* **450** 862–5
- [7] Schmidt C, Chipouline A, Pertsch T, TÄunermann A, Egorov O, Lederer F and Deych L 2008 *Opt. Exp.* **16** 6285–301
- [8] He L, Xiao Y F, Zhu J G, Ozdemir S K and Yang L 2009 *Opt. Exp.* **17** 9571–81
- [9] Dong C H, Zou C L, Cui J M, Yang Y, Han Z F and Guo G C 2009 *Chin. Opt. Lett.* **7** 299–301
- [10] Rokhsari H, Spillane S M and Vahala K J 2004 *Appl. Phys. Lett.* **85** 3029–31
- [11] Chiba A, Fujiwara H, Hotta J, Takeuchi S and Sasaki K 2005 *Appl. Phys. Lett.* **86** 261106
- [12] Ruege A C and Reano R M 2009 *Opt. Express* **17** 4295–305
- [13] Totsuka K, Kobayashi N and Tomita M 2007 *Phys. Rev. Lett.* **98** 213904
- [14] Notomi M, Kuramochi E and Tanabe T 2008 *Nature Photonics* **2** 741–7
- [15] Xiao Y F, Zou X B, Jiang W, Chen Y L and Guo G C 2007 *Phys. Rev A* **75** 063833
- [16] Mingaleev S F, Miroshnichenko A E and Kivshar Y S 2008 *Opt. Exp.* **16** 11647–59
- [17] Liang W, Yang L, Poon J K S, Huang Y, Vahala K J and Yariv A 2006 *Opt. Lett.* **31** 510–2
- [18] Galli M, Portalupi S L, Belotti M, Andreani L C, O’Faolain L and Krauss T F 2009 *Appl. Phys. Lett.* **94** 071101
- [19] Chao C Y and Guo L J 2003 *Appl. Phys. Lett.* **83** 1527–9
- [20] Xiao Y F, Gaddam V and Yang L 2008 *Opt. Exp.* **16** 12538–43
- [21] Mario L Y, Darmawan S and Chin M K 2006 *Opt. Exp.* **14** 12770–81
- [22] Yanik M F, Suh W, Wang Z and Fan S 2004 *Phys. Rev. Lett.* **93** 233903
- [23] Xu Q, Shakya J and Lipson M 2006 *Opt. Exp.* **14** 6463–8
- [24] Smith D, Chang H, Fuller K A, Rosenberger A T and Boyd R W 2004 Coupled-resonator-induced transparency *Phys. Rev. A* **69** 063804
- [25] Xiao Y F, He L, Zhu J G and Yang L 2009 *Appl. Phys. Lett.* **94** 231115
- [26] Tomita M, Totsuka K, Hanamura R and Matsumoto T 2009 *J. Opt. Soc. Am. B* **26** 813–8
- [27] Dubreuil N, Knight J C, Leventhal D K, Sandoghdar V, Hare J and Lefere V 1995 *Opt. Lett.* **20** 813–5
- [28] Larsson M, Dinyari K N and Wang H 2009 *Nano Lett.* **9** 1447–50
- [29] Guo Z, Quan H and Pau S 2006 *J. Phys. D: Appl. Phys.* **39** 5133–6
- [30] Popović M A, Manolatu C and Watts M R 2006 *Opt. Exp.* **14** 1208–22
- [31] Gorodetsky M L and Ilchenko V S 1999 *J. Opt. Soc. Am. B* **16** 147–54
- [32] Paspalakis E 2006 *Opt. Commun.* **258** 30–4