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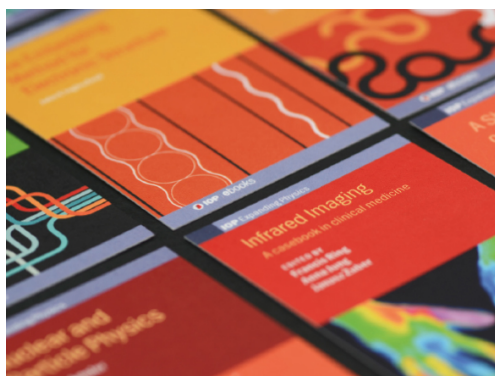
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Modal coupling strength in a fibre taper coupled silica microsphere

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Abstract

The character of the modal coupling strength β between clockwise (CW) and counterclockwise (CCW) whispering gallery modes (WGMs) represents an intrinsic property of a microsphere cavity, which is an important factor for the application of both micro-laser and cavity QED. Depending on a fibre taper coupled microsphere with quality factor larger than 10^7 , modal coupling has been observed, while reflection spectra have been captured to derive the practical modal coupling strength. Upon obtaining results the modal coupling strength is confirmed to be a constant determined only by a microcavity and modes under excitation. This measurement system and results enable ways not only to acquire the material character of a microcavity, but also to analyse microsphere-based cavity QED research.

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

Silica microsphere cavities [1] with ultra-high quality factor (Q) and relatively small mode volume have attracted growing attention in fields of highly sensitive bio-sensors [2], add-drop filters [3], low-threshold lasers [4, 5], nonlinear optical elements [6] and quantum information processing units [7]. As reported in [8], the microsphere has already been applied in research of cavity QED to realize the strong coupling between a cavity and a single quantum dot (QD). However, as distinct from microcavities which are adopted in prior strong coupling experiments [9], the microcavity basing on the whispering gallery modes (WGMs) always simultaneously exists as a pair of travelling wave modes propagating clockwise (CW) and counterclockwise (CCW) [10, 11], and they will bring about so-called modal coupling phenomena.

The clockwise mode can usually be excited by a near field coupler such as fibre taper [4] and prism [1]. Simultaneously, due to the backscattering in a microsphere [12], which arises from surface roughness, scatterers on surface, refractive index inhomogeneity and dopant in material, energy could be reflected to another travelling WGM in the counterclockwise

propagating direction. The backscattering will cause coherent coupling between CW and CCW modes, and that can be described by the factor of modal coupling strength. Above a certain coupling strength, a doublet WGM [13] from mode splitting appears in the frequency spectrum. From the information of these spectra, the fundamental property of both material and mode in a microsphere can be obtained and studied.

In the present work, the modal coupling between the CW and CCW modes in a microsphere is analysed theoretically and experimentally with the assistance of fibre taper. From the experiment results, the practical coupling strength of the modal coupling can be derived within our system. Moreover, the coupling strength would help to analyse the interaction between microcavity and QD in a strong coupling regime including the influence of the modal coupling.

In theory, for the purpose of getting a simple and clear picture, we focused on a coupling system with only one fibre mode, while the interaction between CW and CCW travelling modes was considered simultaneously (shown in figure 1(a)). Here the CW and CCW modes interact with a coupling strength β . The fibre taper serving as an in-out coupler has a coupling efficiency η to the microsphere. Therefore, the amplitude of

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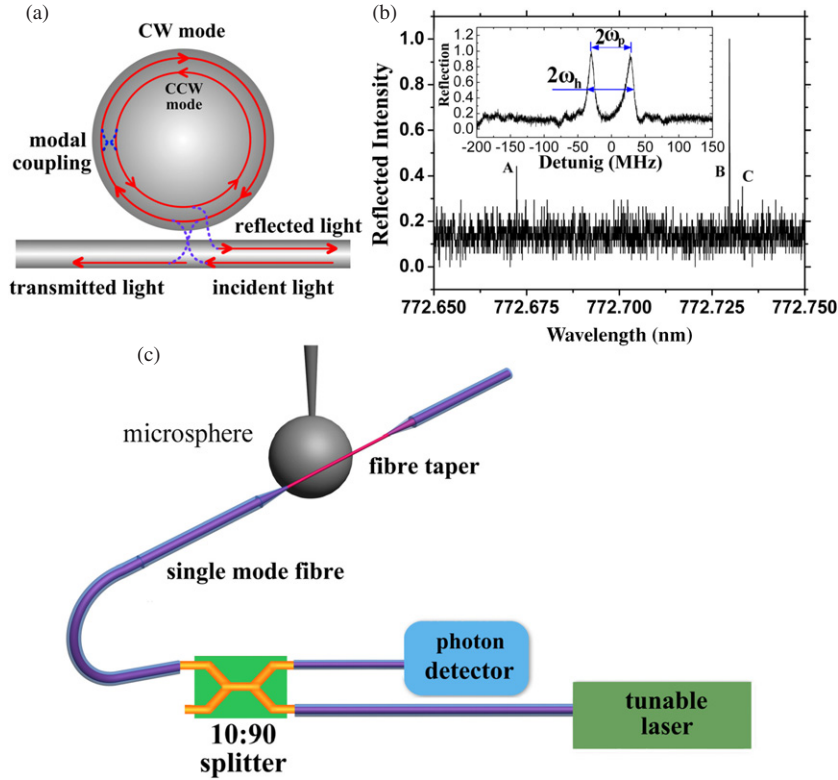


Figure 1. Experiment setup of a microsphere–taper coupling system and a typical reflection spectrum. (a) Description of coupling between CW and CCW modes in a microsphere. (b) Three WGMs are scanned in this range, each of which has a Q -factor larger than 10^7 . The inset image describes the detail of mode B. The mode splits into two peaks with a frequency deviation of $2\omega_p$. The FWHM of the double peaks is labelled as $2\omega_h$. (c) Diagram of experiment, utilizing an optic fibre beam splitter in order to capture the backscattering signal.

coupled modes can be presented as

$$\begin{aligned} \frac{d}{dt} \begin{bmatrix} E_{cw} \\ E_{ccw} \end{bmatrix} &= \begin{bmatrix} -(i\Delta\omega + \kappa) & i\beta \\ i\beta & -(i\Delta\omega + \kappa) \end{bmatrix} \\ &\times \begin{bmatrix} E_{cw} \\ E_{ccw} \end{bmatrix} + \begin{bmatrix} i\frac{\eta}{\tau} E_{in} \\ 0 \end{bmatrix} \end{aligned} \quad (1)$$

where $\Delta\omega$ is the new carrier frequency detuning from the original degenerated frequency [12–14], when the mode splitting occurs. The cavity decay rate κ is defined as $\kappa = \kappa_0 + \kappa_1$, where $\kappa_0 = \omega/2Q_0$ associates the resonant frequency with an intrinsic quality factor of the microsphere. And if the photon has a travelling time τ taken to be a circulation of the cavity, the fibre taper will have a coupling strength $\kappa_1 = -\ln(\sqrt{1 - |\eta|^2})/\tau$ [15] with the microsphere.

Equation (1) gives the travelling wave form of the modal coupling. In a stable system, the original travelling wave modes in the microsphere would generate two standing wave fields, as the energy expression of

$$\begin{aligned} E^+ &= E_{cw} + E_{ccw} = i\frac{\eta}{\tau} E_{in} / (i\Delta\omega + i\beta + \kappa) \quad \text{and} \\ E^- &= E_{cw} - E_{ccw} = i\frac{\eta}{\tau} E_{in} / (i\Delta\omega - i\beta + \kappa). \end{aligned} \quad (2)$$

It reveals that if the loss in the microsphere is low enough, the coupled CW and CCW modes comprise a pair of standing wave modes with different frequencies upon which the mode

splitting occurs. Considering equation (1) and $E_r = i\eta E_{ccw}$ [14], the reflection rate is

$$R = \left| \frac{E_r}{E_{in}} \right|^2 = \left| \frac{2\kappa_1\beta}{(\kappa_0 + \kappa_1 + i\Delta\omega)^2 + \beta^2} \right|^2. \quad (3)$$

This expression for R reveals that the coupling strength (β) is closely related to the quality factor. In the experimental part of this work, the light at the 770 nm wavelength band was coupled into the microsphere, and the absorption from surface-attached water vapour is almost negligible on the quality factor of a microsphere in this band compared to some inferred band, e.g., of 1550 nm [5, 16]. Therefore, in our experiment Q_0 was almost constant. Figure 1(b) is a typical reflected spectrum of WGMs in a microsphere taken from the photon detector. Three groups of modes with individual intensity were swept in the range, all of which kept a quality factor larger than 10^7 . When mode B was examined in detail, the double-peak structure was observed easily (inset of figure 1(b)).

For a practical mode splitting spectrum of reflected light as shown in figure 1(b), the two peaks correspond to the standing wave modes coming from the modal coupling as the explanation of equation (2). As shown in the reflection spectrum, it is apparent that the split double-peak provides a frequency detuning $2\omega_p = \pm 2\sqrt{(\beta^2 - \kappa^2)}$ deriving from equation (3); in addition, the full width at half maximum of the

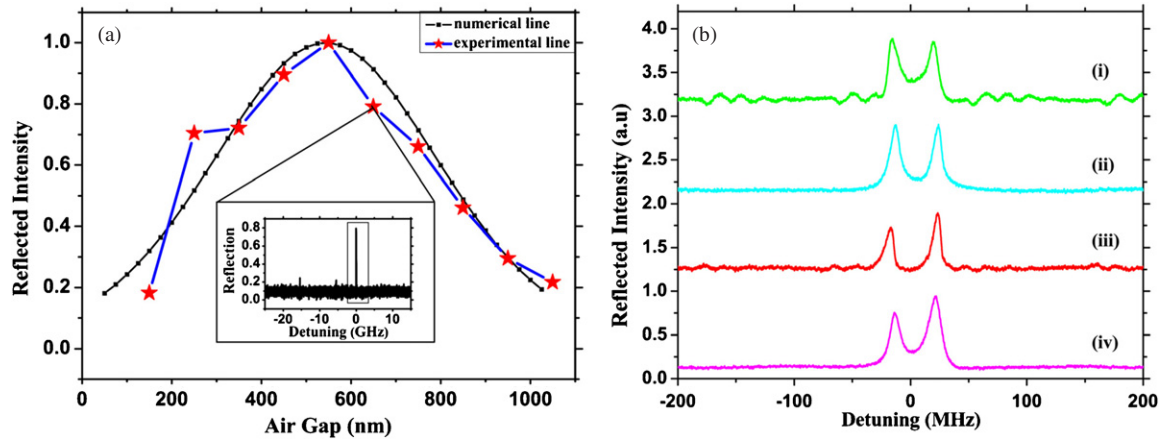


Figure 2. (a) Normalized reflection of a fibre taper coupled microsphere versus the air gap between the microsphere and the fibre taper. The sphere is $50\ \mu\text{m}$ in diameter. The inset of (a) shows the reflected intensity of the focused mode. (b) The detail of the mode splitting with variation of fibre taper coupling, and the splitting modes keep the Q -factor about 2×10^7 . Four spectra disposed vertically for clarity, besides the mode splitting, are 35.42 MHz, 37.34 MHz, 40.54 MHz, 35.55 MHz from (i) to (iv), respectively. The asymmetric double peaks are revealed clearly in (iii) and (iv).

whole double-peak is $2\omega_h = 2\sqrt{(\omega_p^2 - \beta\kappa)}$. Consequently β satisfies

$$\beta^2 = \frac{1}{2}(\sqrt{\omega_p^4 + 4(\omega_h^2 - \omega_p^2)^2} + \omega_p^2), \quad (4)$$

and all the parameters in equation (4) can be accessed from the mode splitting spectrum directly. Beyond that, each κ_1 will generate a new group of ω_p and ω_h like presentations in the equations, so that it will be applied as a basic tool in the experimental process. Utilizing this consequence, it would be a precise and direct method to derive the coupling strength in different kinds of WGM microcavities.

Referring to the theoretical scheme, we have surveyed microspheres following the experimental scheme as shown in figure 1(c). The microsphere was fabricated by preparing a tipped optical fibre taper using a CO_2 laser, and then reheating the tip to achieve a spherical shape with the help of surface tension. Considering that we have used a bare microsphere to survey in a clean room, the backscattered light is generated mainly from surface roughness, material defects and refractive index inhomogeneity in the experiment. As a near field coupler is needed here, the fibre taper is made by hydrogen flame heating and pulling a standard single mode fibre [4]; at the same time, the diameter of the taper's waist was approximately $1\ \mu\text{m}$ in order to reach phase matching.

A tunable laser ranging from 764 nm to 781 nm was used as a light source (50 GHz precise scanning and linewidth smaller than 300 kHz) to excite and scan the resonant WGMs via the fibre taper. In practice, the microsphere was placed on a 3D piezoelectric transition (PZT) stage with a positioning accuracy of 10 nm, so that the air gap between the fibre taper and the microsphere could be controlled precisely. For receiving the backscattering light, a fibre optic beam splitter (splitting ratio of 10:90) was adopted in the system. During the experimental procedure, the fibre taper effectively coupled light into and out of the microsphere. When the backward light in the microsphere transmitted through the fibre, the photon

detector could capture the signal; afterwards an oscilloscope recorded the reflected spectra.

Using a fibre taper as the coupler to detect WGMs without splitting has already been stated elsewhere [17], and it is known that the coupling condition of a microsphere–taper system could be modified by continuously adjusting the air gap between the fibre taper and the microsphere [18]. In our experiment, we observed that WGMs involving modal coupling caused splitting by monitoring the reflected light. Figure 2(a) demonstrates the normalized reflection intensity of a mode varying with the air gap between a fibre taper and a microsphere in the experiment. The numerical simulation result established on a given coupling strength is also shown in figure 2(a) for comparison with the measured data. During variation of the microsphere–taper coupling, the spectra of modal coupling have been captured later on. As exhibited in figure 2(b), the four spectra were captured in the course of moving a fibre taper. In the exploration of each mode, all of them provided a quality factor of about 2×10^7 . The pattern of mode splitting was modified by the selected modes; beyond that, the asymmetry presented in this group of modes is shown explicitly in (iii) and (iv), since the split peaks give notable disparity in width and height. The behaviour of the asymmetrical peaks originates from the environment difference between the two standing waves. Because the field distributions of the two standing waves have spacing in the microsphere, they could be located in a dissimilar environment which would lead to a difference in loss for the two modes. As a result, the quality factor would not be equal. Depending on that, the two modes also may bring a diverse phase-matching condition for the fibre taper coupling [14], which would also vary the collecting efficiencies of the fibre taper for these two standing modes.

For a certain pair of CW and CCW modes, the coupling strength between them is constant unless the environment changes or the mode hops. As stated before, the variant mode splitting spectra of the fixed modal coupling strength

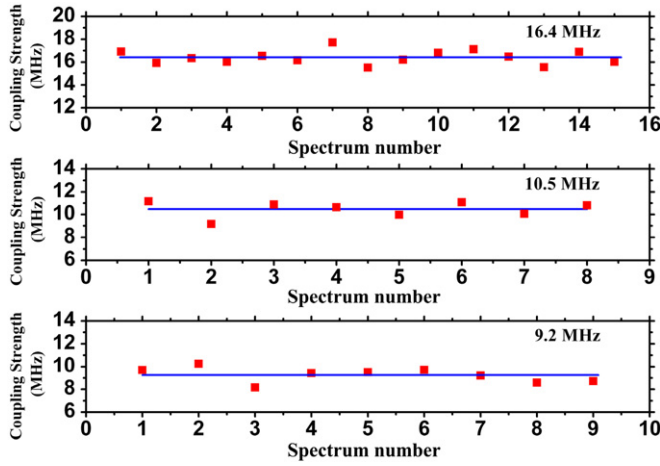


Figure 3. Value of coupling strength (β); the microspheres in the experiment are typically $30\ \mu\text{m}$ in diameter. (a) Fifteen data points, which are calculated from backscattering spectra, are used for fitting. The horizontal axis represents the spectrum from which the coupling strength is calculated. The result of β is 16.4 MHz with the standard error of 0.15. (b) and (c) are from another microsphere, but with different modes. (b) Eight data points for fitting. β is 10.5 MHz and the standard error is 0.24. (c) Even in the same microsphere, as the excited mode has changed, the coupling strength shifted simultaneously. For this mode, β is 9.2 MHz with nine data points for fitting, and the standard error is 0.20.

can be achieved by modifying the coupling of a microsphere–taper system in the experiment, generally following the method depicted in figure 2(a).

Therefore coupling strength was derived following the approaches of collecting the reflected spectra and fitting the constant. ω_p and ω_h were read directly depending on experimental spectra, and then they were applied in equation (4) to calculate β . Diverse groups of ω_p and ω_h were adopted in linear fitting for β at the definite mode. Figure 3 shows the measured values of β in the silica microsphere. Figure 3(a) demonstrates a value of 16.4 MHz for the coupling strength β between CW and CCW modes. There are 15 spectra which are collected and used in fitting, while the standard error is 0.15. The microsphere is almost $30\ \mu\text{m}$ in diameter together with the measured quality factor over 10^7 . For another microsphere (figures 3(b) and (c)) approximately $30\ \mu\text{m}$ in diameter, β is measured to be 10.5 MHz and 9.2 MHz towards two groups of modal coupling. The standard errors in fitting from two groups of coupling strength are 0.24 and 0.20, respectively. It is evident that in a different microsphere, the coupling strength between the CW and CCW modes changes remarkably directly by virtue of disparity resulting from the fabricating process. Even if the two microspheres have the same material and a similar shape, the internal character of some micro domain is enough to make distinct scattering and coupling in the cavity. This mainly results from refractive index uniformity in a microsphere and the surface roughness status here; they cannot be identical under the fabricating process for every microsphere. On the other hand, in a certain microsphere the change of WGMs can still be reflected in the modal coupling strength for the same microsphere, such as is shown in figures 3(b) and (c). The two excited modes for (b)

and (c) correspond to the respective wavelength at 772.90 nm and 778.49 nm; nevertheless their coupling strength retains a comparatively close value in one microsphere in contrast to 16.4 MHz from the first microcavity.

The motivation for obtaining the modal coupling strength is to utilize it in the study of cavity QED with strong coupling. In recent years, strong coupling has attracted great attention for its potential application in quantum information processing units. Other than the F-P-type cavity and photonic crystal microcavity, the WGM-based microsphere can easily be fabricated and relatively simply controlled, and the cavity decay rate κ can be adjusted by air gap tuning conveniently. However, the microsphere exhibits modal coupling induced splitting; the distribution of splitting depends on the modal coupling strength, and sometimes it will remodel the form of strong coupling in the frequency domain. In order to obtain a clear picture, we consider a CdSe quantum dot [19] on a microsphere with a diameter of $30\ \mu\text{m}$ and quality factor 2×10^7 such as has been produced in the experiment. Here the cavity–QD coupling strength g_0 is 1.5 GHz, the dephasing rate γ of the QD is 326 MHz at about 10 K [20] and κ is 12 MHz. In addition, the modal coupling strength has been measured to be 16.4 MHz in our experiment. Comparing the parameters including the modal coupling strength, the system stands as $g_0 > \gamma > (\kappa, \beta)$, which will reveal vacuum Rabi splitting with normal splitting with 4.24 GHz (equal to $2\sqrt{2}g_0$) [9]. Here β is approximate to κ . The simulation for the quantum master equation may present a triple peak structure in the optical spectrum. Since the modal coupling will lead the QD to be coupled with neither standing mode in the cavity fully, the uncoupled parts of both modes are unchanged and contribute the third peak, contrasting with the standard J.C. modal [9].

In summary, we have demonstrated a practically measured modal coupling strength which is induced from the backscattering in a bare microsphere. Due to the existence of scattering in microspheres, the modal coupling strength is an intrinsic parameter that is unchanged whenever the external coupler modifies the coupling condition. The work provides an efficient method to analyse the modal coupling in a WGM-based microcavity. And depending on the measurements of the modal coupling strength, the actual parameter is provided to help estimating phenomena for cavity QED in a strong coupling regime between a WGM microcavity and a QD. Furthermore, the material character of the microcavity such as attenuation ratio could also be inspected by this method with a precise and sensitive outcome in future.

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References

- [1] Gorodetsky M L, Savchenkov A A and Ilchenko V S 1996 *Opt. Lett.* **21** 453–5
- [2] Armani A M, Kulkarni R P, Fraser S E, Flagan R C and Vahala K J 2007 *Science* **317** 783–6
- [3] Yilmaz Y O, Demir A, Kurt A and Serpengüzel A 2005 *IEEE Photonics Technol. Lett.* **17** 1662–4
- [4] Yang L and Vahala K J 2003 *Opt. Lett.* **28** 592–4
- [5] Dong C-H, Xiao Y-F, Han Z-F, Guo G-C, Jiang X-S, Tong L-M, Gu C and Ming H 2008 *IEEE Photonics Technol. Lett.* **20** 342–4
- [6] Min B, Kippenberg T J and Vahala K J 2003 *Opt. Lett.* **28** 1507–9
- [7] Xiao Y-F, Lin X-M, Gao J, Han Z-F and Guo G-C 2004 *Phys. Rev. A* **70** 042314
- [8] Le Thomas N, Woggon U, Schöps O, Artemyev M V, Kazes M and Banin U 2006 *Nano Lett.* **6** 557–61
- [9] Yoshie T, Scherer A, Hendrickson J, Khitrova G, Gibbs H M, Rupper G, Ell C, Shchekin O B and Deppe D G 2004 *Nature* **432** 200–3
- [10] Gorodetsky M L and Ilchenko V S 1992 *Laser Phys.* **2** 1004–9
- [11] Swindal J C, Leach D H, Chang R K and Young K 1993 *Opt. Lett.* **18** 191–3
- [12] Humphrey M J, Dale E, Rosenberger A T and Bandy D K 2007 *Opt. Commun.* **27** 124–31
- [13] Kippenberg T J, Spillane S M and Vahala K J 2002 *Opt. Lett.* **27** 1669–1671
- [14] Gorodetsky M L, Pryamikov A D and Ilchenko V S 2000 *J. Opt. Soc. Am. B* **17** 1051–7
- [15] Gorodetsky M L and Ilchenko V S 1999 *J. Opt. Soc. Am. B* **16** 147–54
- [16] Vernooy D W, Ilchenko V S, Mabuchi H, Streed E W and Kimble H J 1998 *Opt. Lett.* **23** 247–9
- [17] Cai M, Painter C and Vahala K J 2000 *Phys. Rev. Lett.* **85** 74–7
- [18] Zou C-L, Yang Y, Dong C-H, Xiao Y-F, Wu X-W, Han Z-F and Guo G-C 2008 *J. Opt. Soc. Am. B* **25** 1895–8
- [19] Aichele T, Zwiller V and Benson O 2004 *New J. Phys.* **6** 90
- [20] Palinginis P, Wang H, Goupalov S V, Citrin D S, Dobrowolska M and Furdyna J K 2004 *Phys. Rev. B* **70** 073302