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Fano resonance in a multimode tapered fiber coupled with a microspherical cavity

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Fano resonance in a tapered optical fiber in contact with a high-Q microsphere is demonstrated. Multimode waves propagating in a 2.3 μm diameter taper were coupled with a single whispering gallery mode of a 220 μm sphere, and their coherent interaction resulted in Fano resonance. The asymmetric line shapes of the transmission spectra changed periodically with scanning of the coupling position along the taper. The observed 24 μm period was due to modal dispersion in the tapered fiber. © 2005 American Institute of Physics. [DOI: 10.1063/1.1951049]

Fano resonance, originating in the interference between a discrete energy state and a continuum of states, is observed as a characteristically asymmetric line shape in transmission and reflection spectra.3,4 Anomalies occurring in diffractive grating and photonic crystal spectra have been explained by the Fano effect.5,6 Fano resonance leads to a drastic change in transmittance and reflectance over a narrow spectral range, giving a polymer microring resonator fabricated by nanoimprinting.9 In this waveguide/cavity coupling system, Fano resonance can be induced in a single-mode waveguide coupled with a microcavity.8 This has been demonstrated experimentally using a polymer microring resonator fabricated by nanoimprinting.9 In this waveguide/cavity coupling system, two partially reflecting elements are placed in the waveguide to control the phase difference between the resonant field and the transmitted wave, which is indispensable for the formation of the asymmetric line shape.

In this letter, we report that Fano resonance can be induced in a multimode tapered fiber waveguide coupled with a high-Q microspherical cavity without the use of any additional elements, such as reflectors and delay optics. The tapered optical fiber, fabricated by heating and stretching a standard single-mode fiber, is a highly efficient coupling element for a microspherical resonator.10,11 By adjusting the taper diameter, the number of modes propagating in a tapered fiber can be restricted and the coupling modes of the tapered fiber and the microsphere can be selected.12,13

When the multimode waves in the taper are coupled to the microsphere with the resonant angular frequency ωr and the free-spectral range νc (see Fig. 1), the cavity field at the position just before the coupling point is approximately given by

\[ E_c = \frac{iα_cν_c}{(ω - ω_r) + i(1 - α_c)t_cν_c} \sum_j p_j E_0, \]

where αc and tc are the round-trip factor and the transmittance in the coupling region of the microsphere, respectively. E0 is the input field introduced into the fiber waveguide and \( p_j \) (j = 1, 2, ...) are the coupling coefficients from the input field to the microsphere through the individual taper modes, that include the phase components depending on the propagation length. The output field from the fiber waveguide is expressed as

\[ E_i = \sum_j (t_jE_0 + q_jE_c), \]

\[ T = \left| \frac{E_i}{E_0} \right|^2 = \frac{\left| t + \frac{1}{2}v_c \right|^2}{\left| v_c \right|^2 + \left| 1 - \alpha_c \frac{t_c}{v_c} \right|^2}, \]

\[ C_1 = \left| 1 - \alpha_c \frac{t_c}{v_c} \right|, \]

where \( t_j \) (j = 1, 2, ...) are the complex transmittances of the fields passing through the individual taper modes without coupling to the cavity and \( q_j \) (j = 1, 2, ...) are the complex coupling coefficients from the cavity to the output field through the multimodes. From Eqs. (1) and (2), the intensity transmittance is given by

\[ C_2 = 2\alpha_c \text{Im}(\overline{q}) \text{Im}(\overline{q})^*, \]

where \( \overline{q} = \sum_j q_j \) and \( \text{Im}(\overline{q})^* \) denotes a complex conjugate. The first and second terms in the numerator of Eq. (3) represent a symmetric Lorentzian dip of the whispering gallery mode, while the last term exhibits an asymmetric line shape. In the case of a single-mode tapered fiber, the asymmetric component does not appear (\( C_2 = 0 \)), while the interaction among the multiple taper modes gives \( C_2 \neq 0 \), which induces the Fano resonance.

When the coupling position is shifted by the distance x along the fiber axis, \( t_j \) is not changed but \( p_j \) and \( q_j \) are phase shifted as \( \text{Im}(\overline{q})^* \left| x = \sum_j \left| q_j \right|^2 \text{Im}(\overline{q})^* \right| \exp\left( -i(\beta_k - \beta) x \right) \), where

![Image](https://example.com/image.png)
The 2.3 m frequency was precisely calibrated by simultaneous measure-
ments scanned over a range of 18 GHz around a wavelength of
the propagation of not only the fundamental propagation
modes, but also some higher-order propagation
modes. Supposing that two taper modes are coupled with the
fiber, the asymmetric line shape is periodically changed
with the shifting of the coupling position, with the period
being given by $2\pi/|\beta_1 - \beta_2|$. It is noted that the coefficient
$C_1$ containing the parameter $\beta q$ also changes with the dis-
placement $x$.

A tapered fiber was prepared from a fused-silica single-
mode optical fiber. After stripping the polymer coating, the
fiber was heated using a ceramic heater and stretched into a
fine thread with a waist diameter of 2.3 $\mu$m. This permitted
the propagation of not only the fundamental propagation
mode (HE$_{11}$), but also some higher-order propagation
modes.

Scanning electron micrographs indicated that there was
no appreciable variation (<0.1 $\mu$m) in the taper diam-
eter over a 100 $\mu$m length. A microsphere having a stem was
also fabricated from a single-mode fiber as follows. The tip
of a fiber from which the coating had been stripped was
irradiated with a CO$_2$ laser causing the fiber to melt and, due
to surface tension, to form into a sphere. A sphere with a
diameter of 220 $\mu$m was used. The lowest radial-order
modes of such a sphere satisfy the phase matching condition
for coupling with the HE$_{11}$, HE$_{21}$, TM$_{01}$ and TE$_{01}$ modes of
the 2.3 $\mu$m tapered fiber.

A micrograph of the spherical microcavity attached to the multimode tapered fiber is shown in the inset of Fig. 1.

A tunable external-cavity laser diode with a linewidth of
300 kHz was coupled to the tapered fiber waveguide and the
output light at the other end of the fiber was detected using a
photodiode. The output intensity from the fiber when not
coupled to the microsphere was 50 $\mu$W. The laser frequency
was scanned over a range of 18 GHz around a wavelength of
780 nm in order to observe the transmission spectra. The
frequency was precisely calibrated by simultaneous measure-
ment of rubidium vapor D$_2$ lines as well as by means of a Fabry–Perot etalon (free spectral range = 2.5 GHz). The $5s^2S_{1/2}(F=3)\rightarrow 5p^2P_{3/2}$ transition peak of $^{85}$Rb was set to the origin of frequency detuning. In order to control the relative position of the sphere and the tapered fiber in three dimen-
sions, the microsphere was mounted on a piezoelectric stage.

The microsphere was kept in contact with the taper waist and
the contact point was scanned along the tapered fiber. The
microsphere/tapered-fiber-waveguide system was placed in a
chamber which was filled with dry air (humidity < 1.0%) to
reduce water adsorption that may cause adhesion forces at
the surfaces. The chamber was kept at a stable temperature,
which is necessary to avoid any resonant frequency shift in
the microspherical cavity.

Figure 2 shows typical transmission spectra of the multimode tapered fiber/microsphere coupling system. These spectra were measured at different coupling positions, $x = (a)0$ $\mu$m, (b) 6 $\mu$m, (c) 12 $\mu$m, and (d) 18 $\mu$m. The spectral intensity was normalized using the signal at off-resonant frequency. The spectra exhibit an intense resonance at a detuning frequency of 4.7 GHz, as well as two small dips at 3.8 GHz and 4.0 GHz. The shapes of the resonant dips are de-
dependent on the coupling position. The dip at 4.7 GHz in Fig.
2(a) has a symmetric line shape with a linewidth of 160 MHz
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Theoretical analysis has shown that, at a 780 nm wave-
length, the fundamental HE$_{11}$ mode and the HE$_{21}$, TM$_{01}$, and
TE$_{01}$ modes of such a sphere satisfy the phase matching condition
for coupling with the HE$_{11}$, HE$_{21}$, TM$_{01}$ and TE$_{01}$ modes of
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The coupling-position dependence of the resonant spec-
tra is shown as a three-dimensional plot in Fig. 3. Transmis-
sion spectra were measured at every 1 $\mu$m displacement
within a scan range of 45 $\mu$m. The shapes of the spectra gradu-
ally change over the scan range. Clearly, the three-
dimensional plot shows a periodicity in the change in the
spectra with respect to the displacement. The intensity at the
dip and the side peaks varies sinusoidally with a period of
24 $\mu$m. The data were highly reproducible on backward
scanning.
TE\(_{01}\) modes of the 2.3 \(\mu m\) tapered fiber possess propagation constants of \(1.154 \times 10^7\) m\(^{-1}\), \(1.129 \times 10^7\) m\(^{-1}\), \(1.127 \times 10^7\) m\(^{-1}\), and \(1.131 \times 10^7\) m\(^{-1}\), respectively. For the mode pairs HE\(_{11}\)/HE\(_{21}\), HE\(_{11}\)/TM\(_{01}\) and HE\(_{11}\)/TE\(_{01}\), the calculated periods \(2\pi|\beta_j - \beta_k|^{-1}\) are 24.5 \(\mu m\), 23.1 \(\mu m\), and 27.1 \(\mu m\), respectively. Since a single whispering gallery resonance is either a TM or TE mode, coupling from both TM\(_{01}\) and TE\(_{01}\) taper modes into a single cavity mode of the microsphere cannot occur simultaneously. The experimental results show the period to be 24 \(\mu m\), falling between 23.1 and 24.5 \(\mu m\). This suggests that the dip observed in Fig. 3 can be ascribed to the TM microspherical resonance mode coupled with the HE\(_{11}\), HE\(_{21}\) and TM\(_{01}\) taper modes but not coupled with the TE\(_{01}\) wave. Furthermore, this suggests that the period is determined by the amplitude ratio between the HE\(_{21}\) and TM\(_{01}\) mode waves which are coupled to the cavity. The details of this analysis, which is based on the theory developed for multiple-input-output cavity systems,\(^{15}\) will be presented elsewhere.

In conclusion, Fano resonance in a multimode taper waveguide coupled with a microspherical cavity has been demonstrated. Depending on the coupling position, the asymmetric line shape of the transmission spectrum was observed to change. This phenomenon is due to the modal dispersion in the tapered fiber and the multimode coupling between the taper and the microsphere. The steep transmission change originating from the high quality factor of a microsphere can be further enhanced by the Fano effect. In comparison to the single-mode-waveguide/cavity system using partially reflecting elements,\(^{8,9}\) the present system has the advantages of simplicity of device fabrication and controllability of the Fano resonance line shapes.

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