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

Author(s)
Chiba, Akito; Fujiwara, Hideki; Hotta, Jun-ichi; Takeuchi, Shigeki; Sasaki, Keiji

Citation
Applied Physics Letters, 86, 261106

Issue Date
2005-06-21

Doc URL
http://hdl.handle.net/2115/5551

Rights
Copyright © 2005 American Institute of Physics

Type
article

File Information
APL86-26.pdf
Fano resonance in a multimode tapered fiber coupled with a microspherical cavity

Akito Chiba,a) Hideki Fujiwara, Jun-ichi Hotta, Shigeki Takeuchi, and Keiji Sasaki
Research Institute for Electronic Science, Hokkaido University, N12W6, Sapporo 060-0812, Japan

(Received 11 April 2005; accepted 23 May 2005; published online 21 June 2005)

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.1,2 Anomalies occurring in diffractive grating and photonic crystal spectra have been explained by the Fano effect.3,4 Fano resonance leads to a drastic change in transmittance and reflectance over a narrow spectral range, 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 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 ωc and the free-spectral range vc (see Fig. 1), the cavity field at the position just before the coupling point is approximately given by

$$E_c = \frac{i \alpha_c v_c}{(\omega - \omega_c) + i(1 - \alpha_c t_c) v_c} \sum_j p_j E_0,$$

where \(\alpha_c\) and \(t_c\) are the round-trip factor and the transmittance in the coupling region of the microsphere, respectively. \(E_0\) is the input field introduced into the fiber waveguide and \(p_j\) (\(j = 1, 2, \ldots\)) 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

$$E_i = \sum_j (t_j E_0 + q_j E_c), \quad (2)$$

where \(t_j\) (\(j = 1, 2, \ldots\)) are the complex transmittances of the fields passing through the individual taper modes without coupling to the cavity and \(q_j\) (\(j = 1, 2, \ldots\)) 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

$$T = \frac{E_i^* E_i}{E_0^* E_0} = \left| \frac{\eta^2 (\omega - \omega_c)^2 + C_1 + C_2(\omega - \omega_c)}{(\omega - \omega_c)^2 + (1 - \alpha_c t_c)^2 v_c^2} \right|^2,$$

where \(\eta = \sum_j t_j + \alpha_c \beta_j^2 v_c^2, C_2 = 2 \alpha_c \Im(\beta p q)^* \nu_c, \) (4)

In the inset shown in Fig. 1, the cavity was scanned along the fiber axis with the position \(x\). The inset shows a micrograph of the system.

![Color online) A sketch of a multimode tapered fiber waveguide coupled with a microspherical cavity. The microsphere was scanned along the tapered fiber in the direction indicated by arrow x. The inset shows a micrograph of the system.](image)

---

a)Electronic mail: akichiba@es.hokudai.ac.jp
the 2.3 µm frequency was precisely calibrated by simultaneous measurement of two taper modes. Supposing that two taper modes are coupled with the cavity, the asymmetric line shape is periodically changed with the shifting of the coupling position, with the period being given by 2π[β₂ - β₁]⁻¹. It is noted that the coefficient C₁ containing the parameter p_q also changes with the displacement 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 µm. This permitted the propagation of not only the fundamental propagation mode (HE₁₁), but also some higher-order propagation modes. Scanning electron micrographs indicated that there was no appreciable variation (<0.1 µm) in the taper diameter over a 100 µm 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 CO₂ laser causing the fiber to melt and, due to surface tension, to form into a sphere. A sphere with a diameter of 220 µm was used. The lowest radial-order modes of such a sphere satisfy the phase matching condition for coupling with the HE₁₁, HE₂₁, TM₀₁ and TE₀₁ modes of the 2.3 µm 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 irradiated with a CO₂ laser causing the fiber to melt and, due to surface tension, to form into a sphere. A sphere with a diameter of 220 µm was used. The lowest radial-order modes of such a sphere satisfy the phase matching condition for coupling with the HE₁₁, HE₂₁, TM₀₁ and TE₀₁ modes of the 2.3 µm tapered fiber. A micrograph of the spherical microcavity attached to the multimode tapered fiber is shown in the inset of Fig. 1.

Theoretical analysis has shown that at a 780 nm wavelength, the fundamental HE₁₁ mode and the HE₂₁, TM₀₁, and TE₀₁ modes of the microsphere/tapered-fiber-waveguide system were in resonance, with the -5% dip and the side peaks varies sinusoidally with a period of 230 MHz, respectively, exhibit the same change in shape as the dips described above, in spite of the difference in their widths and depths. It was confirmed that the spectral shapes did not change on increasing and decreasing the laser power. This indicates that, in the present experiment, thermal nonlinear effects caused by the introduction of the laser were negligibly small.

The coupling-position dependence of the resonant spectra was measured at different coupling positions, x = (a) 0 µm, (b) 6 µm, (c) 12 µm, and (d) 18 µm. 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 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 corresponding to a Q value of 2.4 × 10⁶. Characteristically asymmetric Fano resonance line shapes were clearly observed in Figs. 2(b) and 2(d). One shoulder of the dip comprises a steep slope including an overshoot, while the other shoulder has a moderate slope followed by a long tail. The dip in Fig. 2(c) is symmetric and much deeper than that of Fig. 2(a). The width of the left-side shoulders, which are defined as the frequency width required for a change in transmission from 90% to 10% of the dip depth, are (a) 320 MHz, (b) 130 MHz, (c) 290 MHz and (d) 550 MHz. The two small dips at 3.8 and 4.0 GHz, which possess Q values of 4.1 × 10⁶ and 1.0 × 10⁷, respectively, exhibit the same change in shape as the dips described above, in spite of the difference in their widths and depths. It was confirmed that the spectral shapes did not change on increasing and decreasing the laser power. This indicates that, in the present experiment, thermal nonlinear effects caused by the introduction of the laser were negligibly small.

The coupling-position dependence of the resonant spectra was measured at every 1 µm displacement within a scan range of 45 µm. The shapes of the spectra gradually 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 μm. The data were highly reproducible on backward scanning.

Theoretical analysis has shown that, at a 780 nm wavelength, the fundamental HE₁₁ mode and the HE₂₁, TM₀₁, and TE₀₁ modes of the microsphere were in resonance, with the -5% dip and the side peaks varies sinusoidally with a period of 230 MHz, respectively, exhibit the same change in shape as the dips described above, in spite of the difference in their widths and depths. It was confirmed that the spectral shapes did not change on increasing and decreasing the laser power. This indicates that, in the present experiment, thermal nonlinear effects caused by the introduction of the laser were negligibly small.

Theoretical analysis has shown that, at a 780 nm wavelength, the fundamental HE₁₁ mode and the HE₂₁, TM₀₁, and TE₀₁ modes of the microsphere were in resonance, with the -5% dip and the side peaks varies sinusoidally with a period of 230 MHz, respectively, exhibit the same change in shape as the dips described above, in spite of the difference in their widths and depths. It was confirmed that the spectral shapes did not change on increasing and decreasing the laser power. This indicates that, in the present experiment, thermal nonlinear effects caused by the introduction of the laser were negligibly small.

Theoretical analysis has shown that, at a 780 nm wavelength, the fundamental HE₁₁ mode and the HE₂₁, TM₀₁, and TE₀₁ modes of the microsphere were in resonance, with the -5% dip and the side peaks varies sinusoidally with a period of 230 MHz, respectively, exhibit the same change in shape as the dips described above, in spite of the difference in their widths and depths. It was confirmed that the spectral shapes did not change on increasing and decreasing the laser power. This indicates that, in the present experiment, thermal nonlinear effects caused by the introduction of the laser were negligibly small.
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. Dependent 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.

The authors would like to express sincere thanks to Professor H. F. Hofmann for useful discussions and to Professor K. Hakuta and Professor M. Kozuma for their advice regarding the experimental setup. This work was partially supported by the program “R&D support scheme for funding selected IT proposals” of the Ministry of Public Management, Home Affairs, Posts, and Telecommunications and was also supported in part by Grants-in-aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS) (13450024 and 15206007).

References