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Raman lasing and Fano lineshapes in a packaged fiber-coupled whispering-gallery-mode microresonator

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ABSTRACT

We report Raman lasing and the optical analog of electromagnetically-induced-transparency (EIT) in a whispering-gallery-mode (WGM) microtoroid resonator embedded in a low refractive index polymer matrix together with a tapered fiber coupler. The microtoroid resonator supports both single mode and multimode Raman lasing with low power thresholds. Observations of Fano and EIT-like phenomena in a packaged microresonator will enable high resolution sensors and can be used in networks where slow-light effect is needed. These results will open up new possibilities for portable, robust, and stable WGM microlasers and resonator-based sensors for applications in various environments.

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1. Introduction

Whispering gallery mode (WGM) resonators have received increasing interest in many fields of contemporary photonics, such as optical sensing [1–5], nonlinear [6–9] and quantum optics [10,11], lasing [12–16], optomechanics [17–19], and fundamental studies [20–23], owing to their high quality factors and highly confined fields (i.e., micro-scale mode volume). Traditionally, prisms, angle-polished fibers, and tapered fibers have been used for coupling light in and out of WGM microresonators. With advances in fabrication technologies, monolithic fabrication of resonators and their coupling waveguides has also been demonstrated [24]. More recently, there have been reports of coupling free-space light into the resonator by breaking the circular symmetry of WGM resonators via intentionally induced deformations [25,26] or scatterers [27]. Among these various coupling schemes, tapered fibers have been demonstrated to be ideal couplers because of their high coupling efficiency and their ability to achieve critical coupling at which transmission drops to zero [28]. Despite their ideality, there are still issues to be solved to utilize tapered fiber couplers in practical and in-field applications, because (1) achieving and maintaining good coupling requires the use of expensive nanopositioning systems for the resonators, (2) fiber tapers are fragile and thus

need careful handling when the system is moved out of the laboratory, (3) maintaining long term stability of coupling is difficult (i.e., air flow, mechanical perturbations, etc. will alter the coupling conditions) and requires additional electronics and equipment, and (4) in an uncontrolled environment, contaminants may fall on the coupler, inducing additional losses or changing the coupling condition. In some environments, keeping the resonators clean and free from contaminants is also difficult. Packaging the resonators with their tapered-fiber couplers by using a low refractive index polymer has been demonstrated as a possible solution for the problems listed above [29].

Spot packaging, where the tapered fiber and the resonator are attached to each other at a single spot either by thermally-fusing them together [30] or by gluing the fiber to the resonator using a low-index optical glue [29], has been demonstrated for microspheres [31]. Although this provides a stable coupling, it does not protect the coupler and the resonator from contaminants. In parallel to this, full packaging, where the resonator and the tapered fiber are embedded together in a low-index polymer matrix, has been demonstrated for microspheres [29] and microtoroids [32]. Many applications can benefit from such a packaged resonator system, such as portable WGM microlasers, temperature sensors [33], humidity sensors, and filters for communication networks. The sensing system for packaged WGM resonators can also be made compact, about the size of a cell phone [34]. It is also worth noting that a packaged resonator can have more features than what can be

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achieved by the resonator itself. For example, by packaging a high-quality resonator in a polymer, we can utilize the resonator as a transducer to process changes in the polymer, thus developing a class of sensors relying on the specific response of the materials selected to encapsulate the resonator.

In this paper, we demonstrate Raman lasing and all-optical analog of EIT and Fano resonances in a silica microtoroid resonator which is embedded in a low-index polymer matrix together with its coupling tapered-fiber. In these fully packaged systems, we have observed quality factors as high as 2×10^7 , which is limited by the absorption loss, and achieved different coupling conditions, including critical coupling.

2. Fabrication

We fabricated silica microtoroid resonators with major diameters around $80 \mu\text{m}$ in this study [35]. In our system, we also designed a reflowed side wall next to each microtoroid [36]. The side walls provide a support for the fiber taper waveguide to rest on so that the fiber does not experience a significant change in its position during the injection and curing of the low-index polymer (MY Polymers Ltd., MY-133 MC). We fabricated the tapered fiber using a heat-and-pull method. A tunable laser was coupled into and out of the resonator via this fiber taper. The wavelength of the laser was scanned linearly to obtain the transmission spectrum for characterization of the resonances. We characterized the resonances using two different tunable lasers, one of which was in the 780 nm band and the other in the 980 nm band. After the resonances were characterized and the proper coupling condition was obtained, we started the packaging process, which is outlined schematically in Fig. 1. In our previous work on microtoroid packaging, we used a UV curable low-index polymer (MY Polymers Ltd., MY-132 A). However, we experienced two major problems. First, the curing process was so fast that the time varying tension and

stress made it hard to maintain the initial coupling condition and did not allow for enough time to tune the coupling condition. Second, the curing process required the polymer to be isolated from oxygen, so the packaging had to be done either in a nitrogen box or between two glass slides. After the curing process, it was difficult to separate the packaged chip from the glass slides. In this work, instead of the UV curable polymer, we used a moisture curable polymer (a low-loss polymer with a refractive index of 1.33) which needed a longer time (~ 30 min for complete curing), enabling us to monitor and continuously tune the fiber-resonator coupling during the process. During the first fifteen minutes of the curing process, the coupling is still tunable. We kept the system operated under the critical coupling condition till we finish this step. We waited for another fifteen minutes to finish the first curing process as shown in Fig. 1b. Subsequently, more polymers were dropped to cover the whole glass substrate to complete the fabrication, which needs another thirty minutes as shown in Fig. 1c. Following this fabrication procedure, we can achieve a packaged high-Q microresonator. In Fig. 1e, we show a typical transmission spectrum obtained for a packaged resonator at critical coupling condition. The resonance had a quality factor of 10^6 .

3. Results and discussion

3.1. Raman lasing

Raman gain in silica microresonators has been used for WGM Raman lasing as well as loss compensation to improve the quality factor. WGM Raman microlasers are very promising for extending the wavelength of existing laser sources. Their use so far has been limited due to the portability issues outlined above. Obtaining Raman gain and Raman laser in a packaged fiber-coupled silica microtoroid will expand the use of these microlasers beyond the laboratory and will certainly benefit many applications. Using a

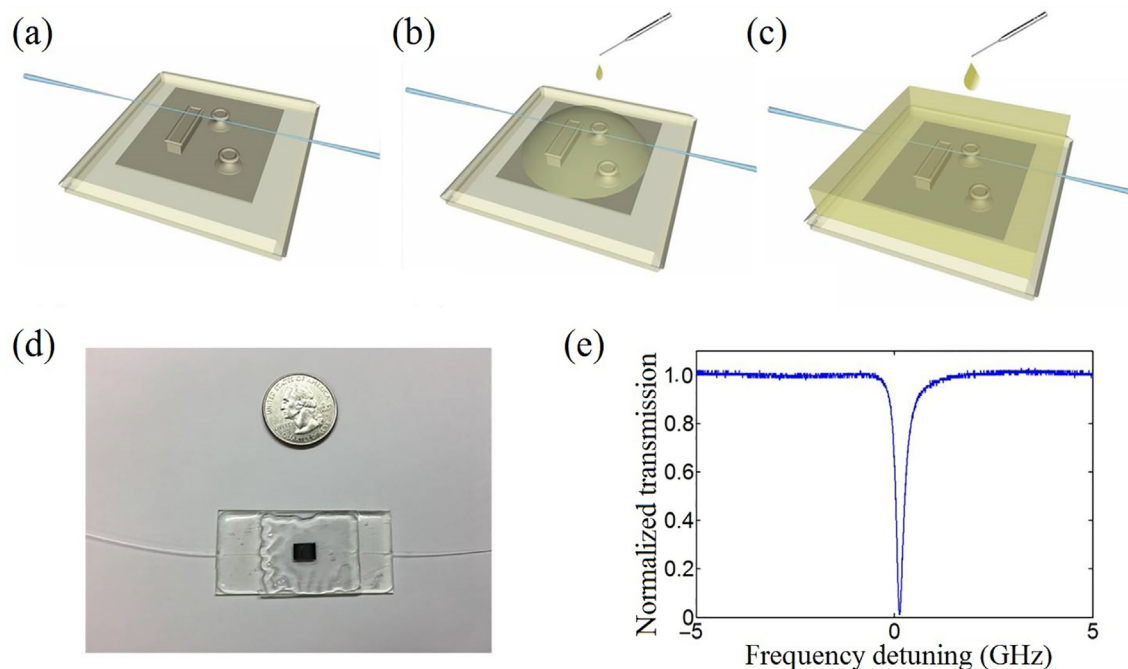


Fig. 1. (Color online) Packaging a fiber-coupled microtoroid resonator with a low index polymer. (a) The desired coupling condition was first established in air with the help of the reflowed side wall. (b) Polymer was dropped onto the chip in small droplets while the transmission was continuously monitored. Any change in the coupling condition was thus detected, and coupling was accordingly optimized. The process continued until a stable transmission and coupling was maintained during the curing process. (c) More polymers were added to complete the packaging process and cover the tapered portions of the fiber completely. (d) An image of the completely cured packaged fiber-coupled resonator. (e) A typical transmission spectrum obtained from one of the packages, depicting critical coupling and a quality factor of 10^6 .

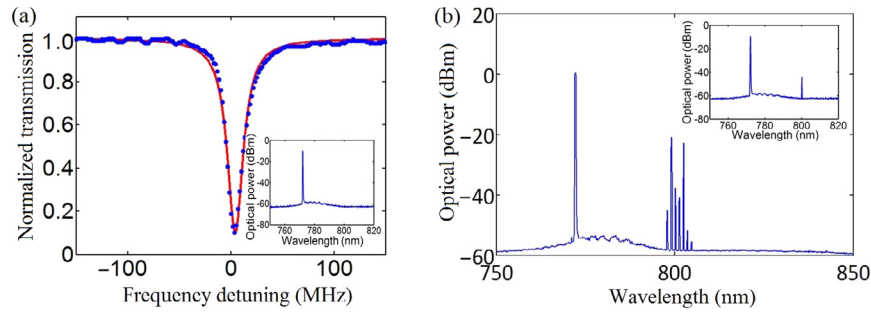


Fig. 2. (Color online) Raman lasing in a packaged WGM silica microresonator. (a) Transmission spectrum of a packaged microresonator showing a resonance mode with $Q \sim 2 \times 10^7$ in the pump wavelength band of 780 nm. Inset shows an optical spectrum of pump laser below threshold. (b) Optical spectra of single mode Raman lasing (inset) and multimode lasing. The pump is located at 770 nm and the Raman emission is located around 800 nm band.

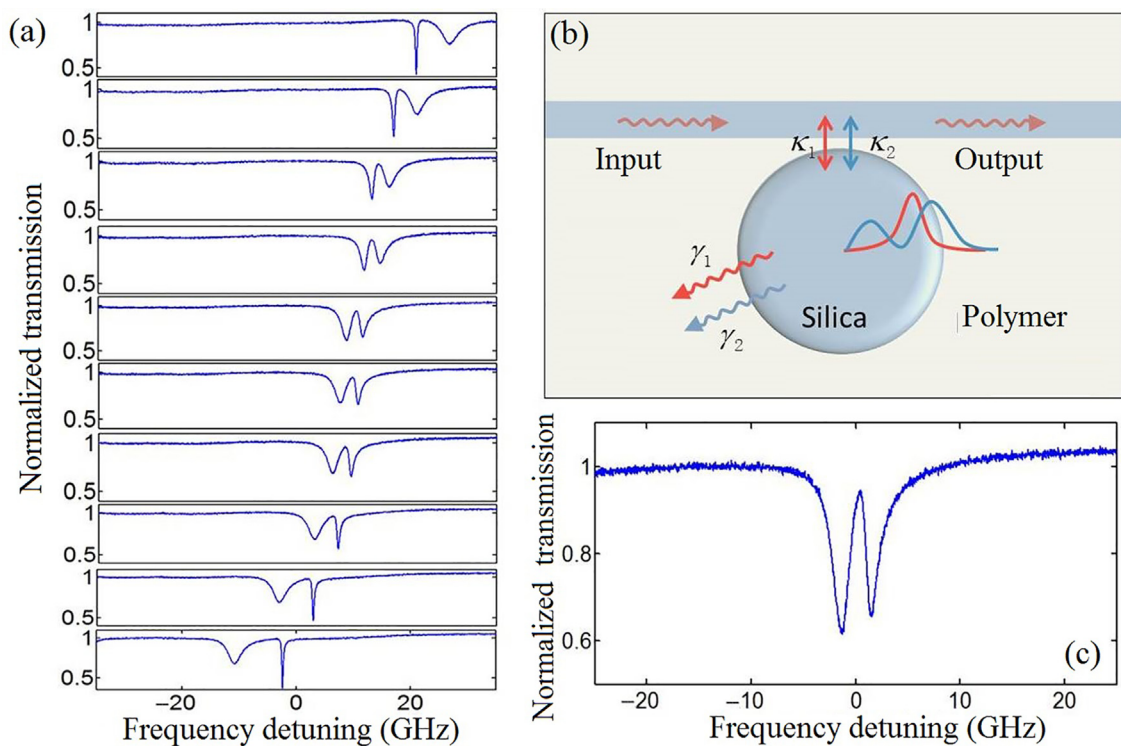


Fig. 3. (Color online) Fano and EIT-like lineshapes in a packaged microtoroid resonator. (a) Evolution of the transmission spectra obtained in experiments with changes in temperature. As the temperature increases, the high- Q mode which is initially 8.5 GHz blue-detuned from the low- Q mode becomes 5.5 GHz red-detuned. Temperature increases from the bottom spectrum to the top spectrum. (b) Schematic illustration of the distribution of the fields of the low- and high- Q modes in the packaged resonator. The modes with decay rates of γ_1 and γ_2 are coupled to the fiber-taper waveguide with different coupling coefficients denoted by κ_1 and κ_2 . Note that the low- Q mode has a higher field distribution in the polymer. (c) Typical EIT-like spectrum obtained in the experiments.

packaged silica microresonator whose transmission spectrum in the pump band of 780 nm is shown in Fig. 2a, we obtained Raman lasing around 820 nm, with the pump mode Q factor of 2×10^7 . By adjusting the pump power, we could obtain both single- and multimode lasing operations as shown in Fig. 2b, respectively. The lasing threshold is about 430 μ W.

3.2. Electromagnetically induced transparency (EIT) and Fano lineshapes

Electromagnetically induced transparency (EIT) and Fano lineshapes have various applications, such as ultraslow light propagation and light storage as well as highly sensitive sensors. All-optical analogs of EIT and Fano lineshapes have been demonstrated in various WGM optical microresonators by coupling two optical modes

with the same resonance frequency but significantly different quality factors [37–39]. In the packaged resonator, we identified two closely located WGMs, one with low $Q \sim 10^5$ and the other with high $Q \sim 10^6$ (see Fig. 3a). We used them to demonstrate EIT in a packaged WGM resonator, which can maintain a long-term stable coupling condition. The high- Q mode was a low order mode, whereas the low- Q mode was a high order mode, which has a larger portion of the light field in the polymer (Fig. 3b). When the temperature of the packaged system was increased 5 $^{\circ}$ C using a thermo-electric cooler [40], we observed that both of the modes experienced blue shift. However, the low- Q mode shifted faster than the high- Q mode, due to the large negative thermo-optic coefficient of the polymer, in which a substantial portion of the light field of the low- Q mode resides. The shift in high- Q mode was slower because it was predominantly located in the silica (positive

thermo-optic coefficient), with only a small portion of the field inside the polymer (negative thermo-optic coefficient). This difference in the thermal response of these two modes helped us to vary the detuning between them. The spectrally overlapped modes are then coupled to each other via the fiber taper coupler, resulting in the observation of Fano and EIT-like lineshapes, depending on the frequency detuning between the modes.

4. Conclusion

In conclusion, we have developed an effective way to embed high-Q microresonators in a low-index polymer together with their tapered fiber couplers. We also demonstrated critical coupling condition achieved in the packaged system. Both single-mode and multi-mode Raman lasing from a packaged silica microtoroid resonator have been observed. By making use of different thermal responses of two resonant modes due to their difference in the field distributions in a packaged microtoroid, we demonstrated Fano and EIT-like lineshapes. Our work offers a feasible way to provide stability, robustness, and portability to WGM microresonators and will pave the way to move fiber-coupled WGM microresonators from the laboratory to the field for a variety of applications, such as sensing and slow light for communication.

Conflict of interest

The authors declare that they have no conflict of interest.

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