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Fiber pigtailed thin wall capillary coupler for excitation of microsphere WGM resonator

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Abstract: In this paper, we demonstrate a fiber pigtailed thin wall capillary coupler for excitation of Whispering Gallery Modes (WGMs) of microsphere resonators. The coupler is made by fusion-splicing an optical fiber with a capillary tube and consequently etching the capillary wall to a thickness of a few microns. Light is coupled through the peripheral contact between inserted microsphere and the etched capillary wall. The coupling efficiency as a function of the wall thickness was studied experimentally. WGM resonance with a Q-factor of 1.14×10^4 was observed using a borosilicate glass microsphere with a diameter of 71 μm. The coupler operates in the reflection mode and provides a robust mechanical support to the microsphere resonator. It is expected that the new coupler may find broad applications in sensors, optical filters and lasers.

OCIS codes: (060.2370) Fiber optics sensors; (220.4000) Microstructure fabrication; (230.5750) Resonators.

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1. Introduction

Optical microresonators of various shapes have attracted great attention [1, 2]. These axially symmetric structures, such as spherical, circular, ring, toroid and rectangular microcavities, were successfully proven for their ability of trapping light in a micrometer scale mode volume in the form of whispering gallery modes (WGMs), resulting in periodical optical resonances in the transmission spectrum [1–3]. With high Q-factors and low transmission loss [1–4], spherical optical microresonators have attracted great interests for various applications such as optical filters, micro-lasers and sensors [4–7].

Efficiently coupling light into and out of an optical microstructure is one of the most important steps in the study and application of WGM resonators. Different methods have been investigated to excite a WGM resonator through evanescent fields, including prisms, pedestal waveguides, side-polished optical fibers, angle-polished fiber tips, and fiber tapers [1–4, 8–12]. By phase-matching the evanescent waves at the internal surface of a prism with the WGMs, light can be coupled into a microresonator [1]. Prism coupling is flexible and efficient. However, it is bulky and inconvenient in practical applications. On-chip pedestal structures have been demonstrated for efficiently and reliably coupling light into a microsphere resonator [8]. However, the pedestal waveguide has a complicated structure and requires high fabrication precision. From the application perspective, fiber pigtailed couplers are preferred because of the convenience in light source coupling and signal detection. Side-polished optical fibers [9, 10] and angle-polished fiber tips [11] have been used to excite high-Q microsphere resonators. However, these two fiber couplers have shown low coupling efficiency. The side-polished optical fiber couplers were efficient (up to 20%, defined as the ratio between the power injected into a specific mode and the power carried by the coupler) for microspheres with a large diameter (~1 mm in diameter) and much less efficient for small resonators. The angle-polished fiber tip had an efficiency of about 60%. Perhaps the most efficient fiber optic coupler is a fiber taper with a diameter less than 2 μm [12]. However, fiber tapers are fragile and sensitive to environmental perturbations.

In this paper, we report a new robust coupler for excitation of the WGMs of microsphere resonator. The coupler has a fiber pigtail for convenient connection to a light source and a photodetector (or an optical spectrum analyzer). The microsphere resonator is dropped into and in contact with the thin-wall capillary tube. Light coupling into the resonator is through the evanescent fields of the capillary wall. As a result, the coupling is not only alignment-free but also mechanically robust.

2. Thin capillary wall coupled microsphere resonator

Figure 1 shows the schematic structure of the fiber pigtailed thin wall capillary coupled microsphere resonator as well as the experiment setup to interrogate the resonator. The coupler is made by fusion-splicing a capillary tube to an optical fiber. The arc power of fusion is controlled so that a cone shape is formed at the connection of the fiber and the tube. The structure is then chemically etched to reduce the capillary wall thickness to a few microns. A microsphere can be dropped into the thin wall capillary tube from the opening. It stops at the cone shape, being in contact with the inside wall of the etched capillary tube.

To interrogate the resonator, the light from a tunable laser source (Agilent 8168F) passes through a 3dB fiber coupler, splits at the cone shape into the wall of the etched capillary, a certain portion of the evanescent wave was coupled into the microsphere to excite the WGMs. The WGMs are coupled back to the capillary wall in the opposite side. The light propagates backwards to the optical fiber through the cone shape, and can be detected by a photodetector (Agilent 8163A). By scanning the wavelength of the tunable laser source, the resonance

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spectrum is recorded. The circular periphery of the microsphere is in contact with the etched capillary wall. Therefore, multi-paths of WGMs can be excited.

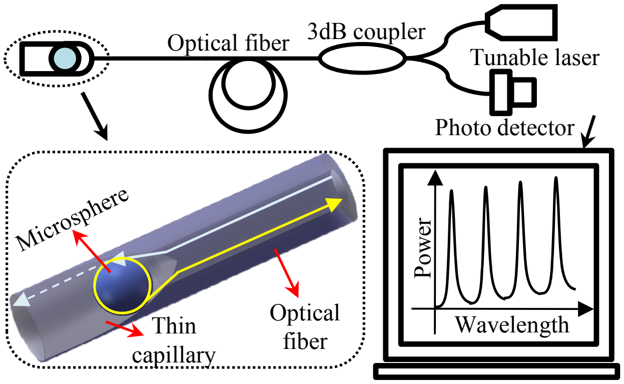

Fig. 1. Schematic of the fiber pigtailed thin wall capillary coupled whispering gallery modes microresonator and interrogation setup.

3. Fabrication of the fiber-pigtailed coupler

A flexible fused silica capillary tube (FFSCT) (Polymicro Technologies, LLC) was used to fabricate the coupler. The capillary tube has an inner diameter of 75 μm, an outer diameter of 150 μm, and a wall thickness of 37.5 μm. The FFSCT was fusion-spliced to a multimode optical fiber (Fiber Instrument Sales, INC 125/62.5). The arc power and duration of the fusion splicer (Sumitomo T-36) were adjusted to obtain a cone-shape connection between the fiber and the capillary as shown in Fig. 2(a). A microsphere was then fed into the capillary tube till it stopped at the bottom of the conical area and was stably held by the capillary wall as shown in Fig. 2(c). The microspheres used in this study were provided by MO-SCI Corporation, consisting of a distinct silica-rich and sodium borate phase with a solid morphology. The diameter of the glass microspheres ranged from 50 to 75 μm, which could be easily inserted into the capillary.

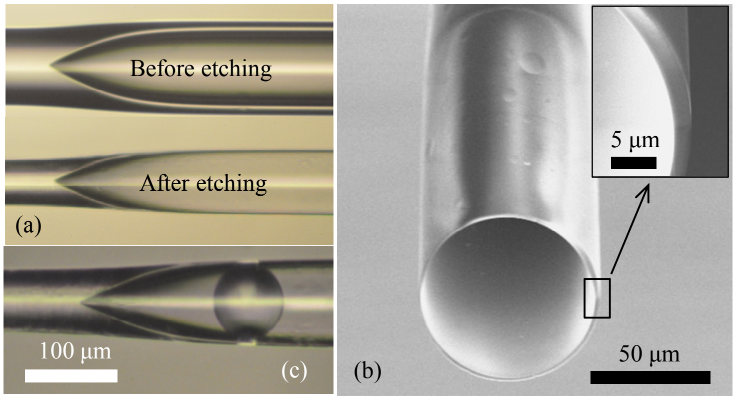

Fig. 2. Microscopic images of the fiber pigtailed thin wall capillary coupler at various fabrication steps. (a) Before and after etching, (b) SEM image of the etched capillary wall with a thickness of about 2 μm, (c) Etched capillary with a microsphere inserted.

After placement of the microsphere, the opening end of capillary cavity was sealed by fusion splicing it to a short section of optical fiber. Hydrofluoric (Acros Organics, 20%) acid was then to etch and reduce the thickness of the capillary wall. The wall thickness of the capillary was controlled during the etching process by varying etching duration. Upon

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reaching the desired wall thickness, the etched capillary can be opened by cleaving to allow the encapsulated microsphere to access the environment for sensing applications.

Figure 2 shows a set of images of the fiber pigtailed coupler during the various steps of fabrication. Figure 2(a) shows the microscopic images of the structure before and after etching. Figure 2(b) shows the scanning electron microscopy (SEM) image of the etched capillary wall with the wall thickness estimated to be about 2 μm. The final assembled WGM resonator structure is shown in Fig. 2(c), where the microsphere is held by the etched capillary wall.

4. Experiments, results and discussions

To verify the waveguide capability of the etched capillary wall, the near-field power distribution of the fiber pigtailed coupler was measured using a setup as shown in Fig. 3(a). The capillary was fusion spliced to a multimode fiber, etched to have a wall thickness of about 5 μm, and cleaved to a length of about 300 μm. A tunable laser at the wavelength of 1550 nm was connected to the multimode fiber as the source. An end-cleaved single mode fiber with a core diameter of 3 μm (Fibercore SM450) was mounted on a three dimensional translation stage and positioned at a distance of about 20 μm from the cleaved end face of the capillary. The other end of the single mode was connected to an optical power meter. Via computer control, the single mode fiber scanned through the area to map the near-field power distribution of the coupler structure.

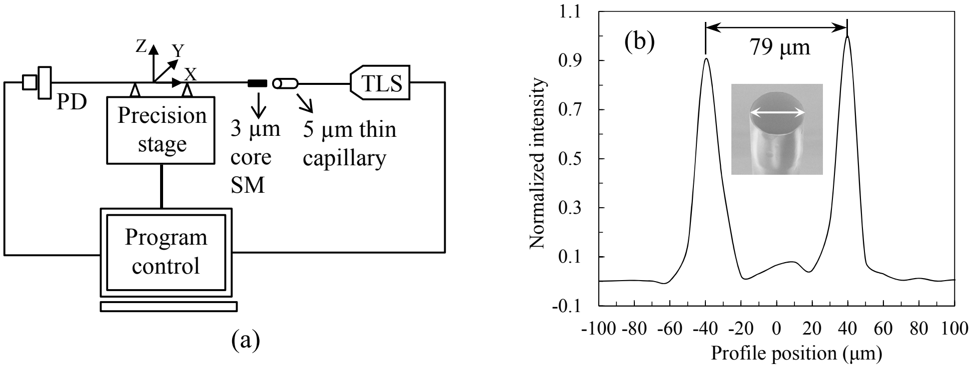


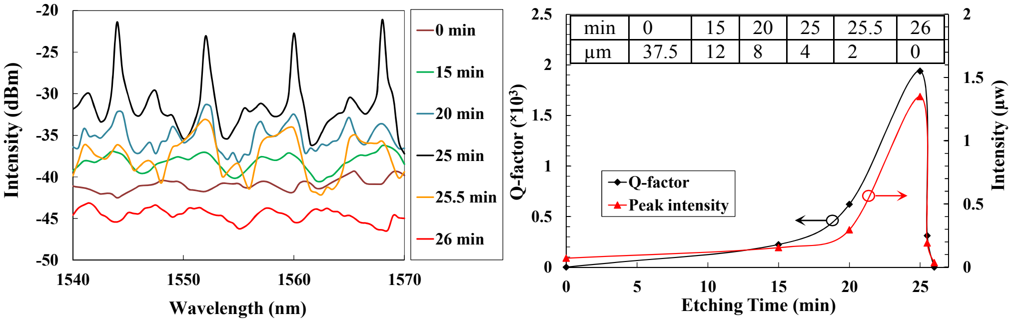
Fig. 3. Measurement of the near-field power distribution of the fiber pigtailed thin wall capillary waveguide. (a) Schematic of the near-field power distribution measurement system, (b) Line-scan power distribution profile.

Figure 3(b) shows the measured line-scan power distribution profile across the center of the capillary tube as shown in the inserted SEM image. The distance between the two power intensity peaks was measured to be 79 μm, which agreed well with the dimension of the thin capillary. The power distribution measurement indicated qualitatively that majority of power was guided through the capillary wall.

The effect of wall thickness on WGM excitation has also been investigated experimentally. The glass microsphere used in the experiments had a diameter of 68 μm. During the etching process, the structure was pulled out from the etching liquid every minute, cleaned and dried. The wall thickness was then measured using a measuring optical microscope (Nikon MC-203) and the reflection spectrum of the resonator structure was recorded using the setup shown in Fig. 1.

Figure 4(a) shows the recorded reflection spectrum of the resonator at the etching times of 0, 15, 20, 25, 25.5 and 26 minutes, respectively. The wall thicknesses at these time intervals, estimated based on the assumption of a constant etching rate, were 37.5, 12, 8, 4, 2 and <1 μm, respectively. At the etching time of 15 minutes, the spectra started showing periodical coupling and the average intensity increased by 3 dB compared to the original structure before etching. At the etching time of 20 minutes, the periodical spectra were observable. At the etching time of 25 minutes, the coupling strength reached its peak value and the resonance became obviously periodic. At the etching time of 26 minutes, the resonance disappeared and the average reflection intensity also dropped significantly, indicating that the capillary tube was etched through.

Figure 4(b) shows the calculated Q-factor and peak intensity of the resonance as a function of etching time, where both the Q-factor and peak intensity increased drastically when the wall thickness decreased to a few microns after 20 minutes of etching. However, when the etching time passed 25 minutes, both the Q-factor and peak intensity dropped. In addition, the periodical spectra began to diminish. The experiment clearly showed the under coupling, critical coupling and over coupling when the wall thickness changed as the etching process progressed.



(a) (b)

Fig. 4. Progress of coupling as a function of etching time. (a) Reflection resonance spectrum at various etching times, (b) Resonance Q-factor and peak intensity as a function of etching time. Inset table, the wall thickness estimated based on etching time.

Figure 5 shows another reflection spectrum of a fiber pigtailed thin wall capillary coupled microsphere resonator with a diameter of 71 μm in air. The wall thickness was determined to be about 5 μm based on the SEM image. The spectrum shows a clear pattern of periodic resonant peaks. In addition to the strongest set, other set of resonance peaks are also identifiable. As shown in Fig. 5, the Q-factor of the dominant resonance, at the resonant wavelength of 1535.114 nm, has a full width at half maximum (FWHM) of 0.134 nm. The Q-factor was calculated to be 1.14×10^4 and the free spectrum range (FSR) was 7.25 nm.

Light coupling from the capillary wall into the microsphere is similar to the case of using tapered fiber as the coupler whose propagation constant matches that of the WGMs. The wall thickness used in our experiment was about 5 μm, which was larger than the typical diameter of commonly used fiber tapers. We expect that the lowest radial mode number (n = 1) WGM was preferentially excited [12]. The group index n_g of the lowest radial mode number WGM can be estimated using the following equation [1, 13]:

$$n_g = \frac{\lambda_1 \times \lambda_2}{2\pi R \times FSR} \tag{1}$$

where λ_1 and λ_2 correspond to the adjacent resonance peak wavelengths and R is the microsphere radius. Using the data shown in Fig. 5, the effective group index was calculated to be 1.496, which was close to the index (1.47-1.51) of the microsphere material (borosilicate glass) [14], suggesting that the fundamental mode (n = 1, $l = |m|$) was excited. The corresponding mode order numbers are provided in Fig. 5.

When an optical fiber taper is used to excite a microsphere resonator, light coupling is mainly in single orbital plane. The etched capillary wall coupler described here can couple light into a microsphere in many orbital planes along the circular peripheral contact between the microsphere and the capillary wall. Because the microsphere usually has an imperfect sphericity, multiple set of resonance peaks are expected, as seen in Fig. 5.

The Q-factor of the capillary wall coupled microresonator observed in our experiments was lower than that excited by a fiber taper. The low Q-factor may be attributed to several reasons. First, the fundamental modes excited in different orbital planes may have slightly different optical paths. As a result, the actual FWHM might be broadened. Second, the solid microspheres used in the experiments were made of borosilicate glass which has higher optical loss compared with the fused silica microspheres. Third, the microsphere was in contact with the capillary wall. As result, the coupling was not at the highest efficiency position where the excitation waveguide should be placed at a slight distance (about 300 nm) from the resonator [15]. The contribution mechanisms of these and other possible reasons deserve a detailed study and will be the subject of further research.

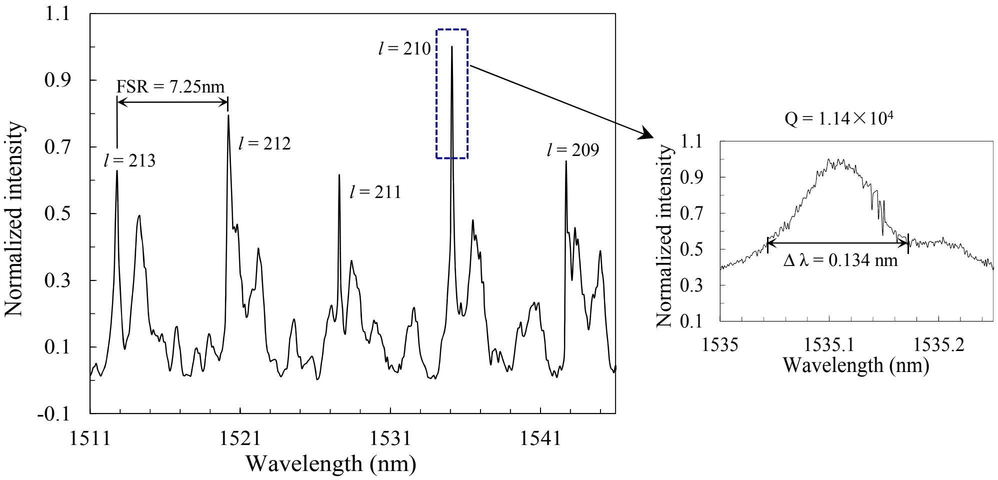


Fig. 5. Reflection spectrum of the thin wall capillary coupled microsphere resonator in air, with mode identification numbers. Inset: Zoom-in spectrum of the resonance peak.

On the other hand, the thin wall capillary contact-type coupler provides a robust support for the microsphere resonator. The microresonator and the coupler are well-integrated and mechanically stable.

5. Conclusion

In summary, we have demonstrated a fiber pigtailed thin wall capillary structure for excitation of WGM microsphere resonators. Light coupling is through the circular peripheral contact between the microsphere and the supporting capillary wall. By etching the capillary wall to a thickness of a few microns and using a borosilicate glass microsphere as the resonator, periodical resonance spectrum was observed with a Q-factor of 1.14×10^4. The coupling conditions as a function of the wall thickness have been experimentally studied showing the under coupling, critical coupling and over coupling as the wall thickness reduced. The coupler operates in the reflection mode and provides a robust mechanical support to the microsphere resonator. It is expected that the new coupler may find broad applications in WGM resonator based sensors, optical filters and lasers.

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