Strain-based tunable optical microresonator with an in-fiber rectangular air bubble

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We demonstrate a strain-based fully tunable, near-lossless, whispering-gallery-modes (WGMs) resonator made of an in-fiber rectangular air bubble (RAB), which is fabricated by splicing two segments of standard single mode fibers. Such a resonator, with a 39 µm order radius and 1 µm order wall thickness, contributes to a high quality factor exceeding 10⁶. The tuning in resonant wavelength is achieved via applying tensile strain to the resonator and the voltage-tuning rate of WGM resonance peaks is about 31.96 pm/V (strain-tuning rate ~14.12 pm/µε), and the corresponding tuning accuracy is better than 0.03 pm. Since the tensile strain applied on the resonator can reach 1000 µε, the achievable total tunable bandwidth of ~14.12 nm is more than two times of its azimuthal free spectral range.© 2018 Optical Society of America

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Optical whispering-gallery-modes (WGMs) resonators, with a combination of high quality factor (Q) and small mode volume of modes, have great potential of growth in many research and technology fields [1], such as microlasers [2-4], biosensors [5,6], chemical sensing [7], and interface for quantum communication[8,9]. A variety of resonators are currently demonstrated, covering the structures of microsphere [10], microtoroid [6], microroring[11], and mirobubble[12]. Those resonators typically confine the light in a narrow ring along its equator surface by continuous total internal reflection. While such equatorial WGMs have the advantage of a small mode volume they also exhibit a large wavelength spacing between consecutive modes [13]. Furthermore, for many of applications, matching of a resonant mode to a narrow wavelength range is required. One of the direct methods to preselect the WGM resonant wavelength is by means of the size design of the resonator. However, the fabrication limitations hinder precise control over mode peak position. Another method is to directly tune the already generated resonant mode. Therefore, various methods to tune the resonator have been reported currently, examples including applying strain [13-15], pressure [15,16], electric-field [17,18], magnetic-field [19], and bending [20].

In this letter, for the first time to the authors’ knowledge, we propose and experimentally demonstrate a novel high-Q microresonator based on an in-fiber rectangular air bubble (RAB) structure, and its WGMs resonance tuneability by applying tensile strain. Such a microresonator, with a diameter of 78 µm along its equator surface and an ultrathin wall thickness of 1 µm, is created by splicing two sections of standard single mode fibers [21]. We have successfully demonstrated the possibility of a reliable continuous tuning of WGMs in the resonator, by simply applying the tensile strain to the structure and a tunability of 31.96 pm/V is achieved, giving a tunable bandwidth of 14.12 nm. The microresonator also exhibited a superbroad tunable range, which is over two times larger than of its azimuthal free spectral range (FSR). In our experiment, the achieved quality factor of the resonator exceeds 10⁶ and the WGM is recognized as near-lossless.

As shown in Fig.1(a), an RAB, as a resonator, has a diameter (2R) of 78 µm along its equator surface and a maximum cavity length of 85 µm along the fiber axis that have been measured from optical microscope image. This RAB is fabricated by means of splicing two sections of standard single mode fiber together and tapering the splicing joint, and the detailed fabrication process is described in Ref. [21, 22]. It is noteworthy that in the whole fabrication process of the RAB, only a common fusion splicer was employed, and no additional device required like in using CO2 laser beam, pressurization or convective heating in a furnace and furnace would be involved [12, 14]. To determine the fabrication limit of the silica diaphragm thickness, the RAB was cut open at the A-point labeled on the equator surface (Fig.1(a)) by using femtosecond laser micromachining. A scanning electron microscope (SEM) image shown in inset of Fig.1(a), gives a measured wall thickness of the RAB to be about 1 µm. Such an RAB, with an ultrathin wall thickness, has excellent optical and mechanical properties. We have investigated the WGMs of the RAB microresonator by coupling WGMs through a taper fiber, as
contains a full set of resonances, which correspond to \[ \Delta \lambda \] in the inset of Fig.2, the wavelengths of WGM resonant peaks are about 1553.219, 1560.0848, 1567.0118, 1573.9976, and 1581.0428 nm, respectively. Based on Eq. (1), the calculated \( R_0 \) is about 389 pm, which agrees well with the measurement result from the optical microscope image (Fig.1(a)).

Furthermore, as shown in the inset of Fig.2, the estimated resonance Q-factor obtained by Lorentzian fitting is of \( \sim 1.23 \times 10^6 \).

As shown in Fig.1(b), the taper-fiber, with a biconical taper and a symmetrical waist, was fabricated from a conventional single-mode fiber by means of the oxyhydrogen flame direct heating method. In the experiment, the taper-fiber waist, with a diameter of \( \sim 1 \mu m \) and its near zero transmission loss character, was positioned in direct contact with the in-fiber RAB along its equator surface, as illustrated in Fig.1(b). The light can be coupled into the RAB resonator through this taper-fiber, which evanescently excites the WGMs in the RAB along its equator, and the coupling strength can be adjusted by changing the air gap between the taper-fiber and the equator surface of RAB. The WGM of RAB resonator can be measured using the set-up shown in Fig.1(c), where the input end of the taper-fiber is connected to a tunable laser source (Agilent, 81940A) via a polarization controller; and the other end is to an optical power meter (Agilent, N7744A).

As shown in Fig.2, the equatorial WGMs of the RAB resonator were measured by the optical power meter with a resolution of 0.6 pm covering the wavelength range from 1550 to 1585 nm. While such equatorial WGMs have a small mode volume, they also exhibit a large azimuthal FSR between consecutive modes, and the measured azimuthal FSR is about 6.9 nm around the wavelength of 1556 nm. Here, the azimuthal FSR could be expressed as [14]

\[
\Delta \lambda_{FSR}^{azimuthal} = \frac{\lambda^2}{(2\pi n_{eff} R_0)} \tag{1}
\]

where, \( \lambda \) is the resonant wavelength, \( n_{eff} \) is the effective index of the silica, and \( R_0 \) is the radius of the rectangular air bubble along the equator surface. As shown in Fig.2, the wavelengths of WGM resonant peaks are about 1553.219, 1560.0848, 1567.0118, 1573.9976, and 1581.0428 nm, respectively. Based on Eq. (1), the calculated \( R_0 \) is about 389 pm, which agrees well with the measurement result from the optical microscope image (Fig.1(a)).

In addition, it also can be seen that the transmission spectrum of the RAB resonator is near-lossless as the measured loss is only about -0.03 dB, which owing to the factor of a very smooth inner and outer surface of the RAB ensuring better confinement of the light in a narrow ring along the equator surface by continuous total internal reflection. Note, the positive dips occurred under 0-dB level are due to the measurement error caused by the power meter, thus not real signal.

According to Eq.(1), it can be seen that any FSR interval of length \( \Delta \lambda_{FSR}^{azimuthal} \) contains a full set of resonances, which correspond to WGMs under different quantum numbers. For this reason, a resonator can be regarded as fully tunable if its tuning wavelength range exceeds the FSR, i.e. \( \Delta \lambda_{FSR}^{azimuthal} \) [14]. Thus, a resonance, corresponding to any transversal WGM distribution of a fully tunable resonator, can be shifted to any predetermined wavelength. To evaluate this tunable function, an experiment was set up to apply tensile strain to the RAB resonator for tuning the resonance wavelength of WGMs, as shown in Fig.3(a). To apply the tensile strain to the resonator, one end of the RAB was glued on a fixed stage, and another end was fixed to a piezoelectric transducer (PZT) controlled stage. In order to measure the actual applied strain to the RAB, a broadband light source (BBS), a 3-dB fiber coupler, and an optical spectrum analyzer (OSA) with a resolution 0.01nm were employed to directly monitor the cavity length variation (i.e. applied tensile strains) of the RAB in real time, as shown in Fig.3(b).
Fig. 4. (a) Applied PZT voltage to resonator and the calculated voltage-tuning rate of about 31.96 pm/V. (b) Spectrum evolution of the resonator based on RAB with PZT voltage increases from 0 to 27.5 V.

Fig. 5. (a) Strain response and (b) spectral evolution of the RAB FPI under manual stretching. (c) Spectral evolution of RAB FPI under PZT applied voltage from 0 to 27.5 V. (d) The correlation between the input voltage and strain sensitivity of the PZT. According to the measured results in Fig. 5(a), the strain sensitivity of the RAB FPI is calculated to be 28.56 pm/μ µC, corresponding to a linear fitting with a correlation factor of R² = 0.99992. Fig. 5(b) and (c) show the spectral evolution of the RAB FPI under manual and PZT (0 to 27.5 V) stretching, respectively. From Fig. 5(a) and (c), we can build a correlation between the applied voltage and tensile strain, as plotted in Fig. 5(d). Thus, we can see the applied PZT voltage from 0 to 27.5 V corresponds to the tensile strain from 0 to 60.9 μ µC. From Fig. 5(d), we can obtain a strain-tuning WGM rate to be about 14.12 pm/μ C. Although the tuning range is limited by the extension length of the PZT, according to the measured results in Fig. 5(a), the available stretching range of 1000 μ µC will allow a total WGM tunable range of ~14.12 nm for the RAB resonator, which is ten times more than its azimuthal FSR of 6.9 nm. The tunability figure of merit of this RAB WGM is about Δλ/ΔV FSR ≈ 2.05.

Fig. 6. (a1) Three-dimensional stress distribution contours and (a2) the stress distribution contours along the Y direction. The deformation vector field of RAB along (b1) the transverse section and (c1) the longitudinal section. The corresponding deformation of the RAB under 1 μ µC strain for (b2) the transverse section (Y-axis), (c2) longitudinal section (Y-axis) and (c3) longitudinal section (Z-axis), respectively.

In order to investigate the strain-based tunability of the WGM resonator, the structural deformation and stress distribution of the RAB under strain were calculated by establishing simulation models utilizing commercial software of finite element analysis. Fig. 6 (a1) illustrates the three dimensional stress distribution contour of the resonator, which is mirror model.
among the following equations:

\[ \Delta L \approx \frac{L}{\lambda} \Delta \lambda \]

where \( \Delta \lambda \) is the change in the wavelength and \( L \) is the effective length of the resonator. The measured values of \( \Delta L \) are shown in Fig. 7 (right axis). Furthermore, the measured center wavelength \( \lambda_0 \) is calculated by \( \lambda_0 = \lambda - \Delta \lambda \), where \( \Delta \lambda \) is the wavelength shift due to the change in strain. From the measured values, we can see that the maximum wavelength shift is observed when the strain reaches about 35 µm. This result agrees with the theoretical calculations and demonstrates the capability of the RAB resonator for strain sensing applications.

**References**