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Strain-induced spectral tuning of the whispering gallery modes in a cylindrical micro-resonator formed by a polymer optical fiber

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A mechanical strain assisted technique for spectral tuning of whispering gallery modes (WGM) in a cylindrical micro-resonator formed by a polymer optical fiber (POF) is investigated. WGMs in the POF-based micro-cylinder are excited by evanescent light coupling using a tapered single mode silica fiber. WGMs observed in the transmission spectrum of the silica fiber taper have a high extinction ratio of up to 19 dB and a quality factor (Q -factor) of up to 2.64×10^4 . The application of tensile axial strain ($\mu\epsilon$) in the range from 0 to 1746 $\mu\epsilon$ (0.17%) to the POF micro-resonator results in a linear shift of the WGM spectrum with a sensitivity of 0.66 pm/ $\mu\epsilon$. Under the influence of the applied strain, the WGMs undergo a blue shift and return to their initial spectral positions after the strain is decreased. The proposed strain tunable POF micro-resonator has potential applications in fiber optic sensing and tunable micro lasers. © 2017 Optical Society of America

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1. INTRODUCTION

Whispering gallery mode (WGM) micro-resonators (MRs) are attractive photonic devices due to their small mode field volume, narrow spectral linewidths, and high Q -factors [1–3]. Such MRs have found applications in numerous fields, including studies of nonlinear optical effects [4], in quantum electrodynamics [5], and for low threshold miniature scale lasers [6]. One of the most promising applications of WGM MRs is in the area of optical sensing [2,7,8], where such resonators exhibit a higher sensitivity than their macro-fiber counterparts. WGMs can be supported by a variety of resonator geometries, such as spheres [9], spheroids [10], disks [11], rings [8], and cylinders [12]. The choice of the specific resonator for a given application is typically impacted by three main considerations, such as the maximum achievable Q -factor, simplicity of fabrication, and ease of interconnection [13].

For cylindrical resonators based on a section of optical fiber, there are a number of potential advantages that make such resonators worth exploring: (1) a very simple fabrication process, since optical fibers are highly uniform in diameter, allowing large numbers of identical resonators to be fabricated and providing a high degree of repeatability; (2) optical fibers can be easily manipulated and mounted; and (3) the alignment for

optimal coupling of the excitation light into the fiber MR has on only one angular degree of freedom, as opposed to two for experiments involving microspheres [14]. As a result, the optical setup for the cylindrical fiber-based MR experiments is more straightforward.

Spectral positions of WGM resonances can be tuned by various external stimuli. Numerous reports demonstrate the tuning of WGM resonant wavelengths of spherical MRs by changing the surrounding refractive index [15], applying mechanical strain to the resonator [16], changing internal pressure [17], applying external electric field [18], etc. Self-tuning of WGM resonances has been demonstrated for a stand-alone silica microsphere by changing its temperature under the influence of the gas flow surrounding the resonator [19]. In a cylindrical MR, tuning of WGM resonances using mechanical strain was demonstrated for the first time by Huston and Eversole [20]. In this work, the morphology dependent resonance properties were studied in the elastic scattering spectra of a 1 mm long section of a 125 μm diameter single mode silica optical fiber.

Due to their relatively high elastic modules, silica WGM resonator-based sensors have limited sensitivity to strain or force. Measurement sensitivity can be improved by using

dielectric materials with smaller elastic modulus, such as polymers. For example, Ioppolo *et al.* [21–24] have demonstrated that solid, as well as hollow polymethyl-methacrylate (PMMA), microspheres have a higher strain sensitivity compared to those made of silica.

More recently, the tuning of WGM lasing modes in a polymer optical fiber (POF)-based resonator under tensile strain was reported in [25]. The experiment was carried out by the scattering of focused laser beams on a section of Rhodamine-B-doped POF. The spectral shift of WGMs excited in a photonic crystal fiber MR infiltrated with magnetic fluid under the influence of external magnetic fields is investigated in [26], and the laser assisted tuning method for WGMs in a cylindrical MR based on a magnetic-fluids infiltrated microstructured optical fiber is reported in [27].

This paper presents the findings of a comprehensive investigation of mechanical strain tuning of WGMs for a POF-based cylindrical MR. Cross coupling takes place between the evanescent fields of the guided modes from a tapered single mode silica optical fiber in close physical contact with a micro-cylinder with an outer diameter of 490 μm . The transmission spectrum of the silica taper coupled to the POF MR shows very high extinction ratio dips, corresponding to the WGM eigenmodes. Spectral tuning of the WGM dips is investigated under the influence of increasing and decreasing axial tensile strain that is applied to the POF micro-cylinder. The influence of the input light polarization on the WGM's tuning is also studied by carrying out the experiments for different input light polarization states.

The proposed POF cylindrical MR possesses several desirable features, such as highly sensitive strain assisted tunability, high linear strain dependence, and ease of fabrication, which make it a good candidate for applications in optical fiber sensing and tunable micro-fiber lasing.

2. EXPERIMENTAL ARRANGEMENTS

The experimental setup for studies of the influence of strain on the WGMs excited in the cylindrical MR is schematically shown in Fig. 1. The cylindrical MR was formed by a section of a $490 \pm 5 \mu\text{m}$ (outer diameter) graded index POF (GIPOF 50, Thorlabs). The evanescent light coupling to the micro-cylinder was achieved by a full fiber taper placed in close

contact with the POF micro-cylinder [28]. The optical fiber tapering is undertaken using the micro heater brushing technique [29]. The fabricated fiber taper has a waist diameter of circa 1.3 μm . The input end of the fiber taper was connected to a super luminescent diode (SLD) (Thorlabs) with a wavelength range of 1500–1600 nm. Light from the SLD was passed through a three-paddle manual polarization controller, and the output of the fiber taper was connected to the optical spectrum analyzer (OSA) (86142B, Agilent).

As illustrated in Fig. 1, in order to apply the strain to the resonator, one end of the POF micro-cylinder was immobilized with a fiber holder, and the other end was attached to the micro translation stage with a resolution of 10 μm . The length between the two fixed points is considered as the sensing length. Here, the sensing length of the POF MR was set to 63 mm for ease of mounting. The strain is applied to the POF micro-cylinder by moving the translation stage with a step size of 10 μm [corresponding to an applied tensile strain step of 159 $\mu\epsilon$ (0.016%)] in a direction away from the fixed end.

During each experiment, the polarization state of the input light was controlled by the three-paddle polarization controller (FPC030, Thorlabs). For investigation of the effect of the input light polarization on the WGM's tuning properties, we compare our results for three different linear polarization states, as described later in this paper. During each measurement of the shift of the WGM spectrum with respect to the applied strain, the input polarization state was fixed. All of the measurements were carried out at a constant laboratory temperature (20°C).

A. Effect of Strain on the WGM Resonance Wavelength

Figure 2(a) shows the WGM spectrum of the unstrained POF micro-cylinder with a diameter of 490 μm . Three WGM resonance dips are observed within the selected 3.6-nm-wide wavelength band. The full widths at half-maxima (FWHMs) of the observed resonance dips are measured, and their Q -factors are calculated using the equation $Q = \lambda/\Delta\lambda$, where λ is the resonance wavelength, and $\Delta\lambda$ is the corresponding FWHM. All of the Q -factors of the resonance dips in the selected range are approximately equal to 2×10^4 . For example, Fig. 2(b) shows the Lorentz fit of a selected resonance dip (p1). The dip has the central wavelength at 1500.71 nm, and its FWHM and the corresponding Q -factor are 0.072 nm and 2.09×10^4 , respectively. The extinction ratios of all three of the resonant dips are larger than 18 dB. The average free spectral range associated with the resonant pattern in the specified wavelength range is 1.07 nm.

We experimentally investigated the strain tuning of the POF-based MR using the experimental setup schematically illustrated in Fig. 1. Figure 3 shows the evolution of the WGM spectrum of the POF MR as the axial strain is increased from zero to 1746 $\mu\epsilon$ and then decreased back to zero. As the axial strain increases, the resonant dips exhibit a linear blue shift. When the applied tensile strain is decreased back to zero, the resonance dips linearly red shift back to their initial positions, which indicates a good reversibility of the proposed WGM tuning approach.

Before considering the wavelength tuning in more detail, it is useful to analyze the expected tuning effect of strain. For this,

Fig. 1. Schematic diagram of the experimental setup for studies of the tunability of WGMs in the POF resonator under the influence of applied strain.

Fig. 2. (a) WGM's spectrum generated by the POF MR, (b) Lorentzian fittings of the spectral dips p1. The dip has the central wavelength at 1500.71 nm, and its FWHM and the corresponding Q-factor are 0.072 nm and 2.09×10^4 , respectively.

Fig. 3. Evolution of the tapered fiber transmission spectrum under the influence of the increasing axial strain, followed by the strain decrease back to the unstrained position. For illustrative purposes, each consecutive spectrum is plotted with an artificial offset of 30 dB compared to the prior spectrum. The arrows indicate the resonant wavelength shift direction.

a simple model to predict the tuning of the WGM resonances was developed based on the two primary assumptions as follows: the first one is the fact that the MR diameter can be related to the value of the applied axial tensile strain. The second assumption is that there is a measurable change in the refractive index brought about by the different mechanical stress and strain components within the resonator material. Taken together, the fractional change in the wavelength of the WGMs is [21–25,30–32]

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta D}{D} + \frac{\Delta n}{n}, \quad (1)$$

where $\Delta D/D$ is the fractional change in the MR diameter (D) due to the deformation of the micro-cavity, and $\Delta n/n$ is the fractional change in the refractive index (n) due to the induced stress. The transverse deformation ($\Delta D/D$) of the micro-cavity can be related to the axially applied tensile strain ($\Delta L/L$) by the Poisson ratio (σ). The Poisson ratio is the ratio of the lateral contraction strain ($\Delta D/D$) to the axial tensile strain ($\Delta L/L$):

$$\sigma = \frac{\Delta D/D}{\Delta L/L}, \quad \frac{\Delta D}{D} = \sigma \frac{\Delta L}{L}. \quad (2)$$

Changes in the fiber dimensions result in changes in the material density with the corresponding induced changes in its refractive index (Δn). Thus, changes in the refractive index can be expressed as

$$\Delta n = n P_{\text{eff}} \frac{\Delta L}{L}, \quad (3)$$

where P_{eff} is the effective strain–optic coefficient [25,32]. Subsequently, the WGM resonance wavelength shift can be expressed as

$$\frac{\Delta\lambda}{\lambda} = - \left(\sigma \frac{\Delta L}{L} + P_{\text{eff}} \frac{\Delta L}{L} \right). \quad (4)$$

Here, the negative sign shows that the axial tensile strain applied to the POF MR will result in a blue shift of the WGM resonance. The Poisson ratio and the effective strain–optic coefficient of PMMA are 0.35–0.45 and 0.099 (± 0.0009), respectively, [20,25,32,33]. By assuming the Poisson's ratio (σ) of the POF is 0.35, the theoretical calculation based on Eq. (4) shows that the sensitivity of the WGM resonance wavelength shift with respect to the increasing and decreasing tensile strain is 0.68 pm/ $\mu\epsilon$.

Figures 4(a) and 4(b) correspond to the resonance dips p2 and p3, respectively (as depicted in Fig. 1). Here, the black dots are the measured data, and the solid red line is the linear fit. It is clear that all of the resonance dips move toward the shorter wavelengths in a linear fashion with a good sensitivity to the applied axial tensile strain. For each 10 μm axial elongation [corresponding to a tensile strain of 159 $\mu\epsilon$ (0.016%)], it is found that the WGMs shift by 0.11 nm on average. Here, the second dip of the WGM spectrum, p2, shifts from 1501.77 to 1500.605 nm, and the third dip, p3, shifts from 1502.84 to 1501.66 nm in response to a 110 μm elongation [corresponding to the applied strain of 1746 $\mu\epsilon$ (0.17%)]. Linear fitting of the wavelength response data indicates that the linear regression coefficient is greater than 0.99 for both p2 and p3 dips. It could also be seen that the tuning sensitivities

Fig. 4. Wavelength shift of the selected WGM resonances as a function of increasing axial strain: (a) dip p2 and (b) dip p3 (as depicted in Fig. 2). The measured wavelength shift (scatter data) is linearly fitted (solid line). Linear fitting of the wavelength response data indicates that the linear regression coefficient is greater than 0.99 for both p2 and p3 dips. The slopes of the linear dependencies are $-0.64 \text{ pm}/\mu\epsilon$ for p2 and $-0.66 \text{ pm}/\mu\epsilon$ for p3, respectively.

Fig. 5. Wavelength shifts of the selected WGM resonances as a function of decreasing axial strain: (a) dip p2 and (b) dip p3. The measured wavelength shift (scatter data) is linearly fitted (solid line). Linear fitting of the wavelength response data indicates that the linear regression coefficient is greater than 0.99 for both p2 and p3 dips. The slopes of the linear dependencies are $0.63 \text{ pm}/\mu\epsilon$ for p2 and $0.64 \text{ pm}/\mu\epsilon$ for p3, respectively.

of these WGMs are equal to 0.64 and $0.66 \text{ pm}/\mu\epsilon$ for p2 and p3 dips, respectively, which is in close agreement with the theoretically calculated sensitivity of $0.68 \text{ pm}/\mu\epsilon$.

The wavelength tuning of the WGM of the POF MR by applying axial tensile strain is also found to be reversible. Figure 5 shows the return of the shifted spectra to their initial positions with the decrease of the applied axial tensile strain.

Figures 5(a) and 5(b) illustrate the wavelength shift corresponding to the decrease of the applied axial tensile strain for the WGM resonant dips p2 and p3, respectively. Here, the black dots are the experimentally measured data, and the solid red line is the linear fit. Here, the linear regression coefficient is greater than 0.99 for both p2 and p3 dips. The negative values of the X axis illustrate the gradual decrease of the applied axial tensile strain from its maximum value to the initial unstrained state. It is clear that all of the resonance dips move toward the longer wavelengths (initial position) in a linear fashion. For each $10 \mu\text{m}$ translation [corresponding to the decrease in the applied strain by $159 \mu\epsilon$ (0.016%)] in the axial direction, it is found that the WGMs experience an average red shift of 0.11 nm . That means that the spectral shifts of the WGMs are

similar in both cases with the increase and decrease of the applied axial tensile strain. Here, the second dip of the WGM spectrum, p2, shifts from 1500.60 to 1501.76 nm , and the third dip, p3, shifts from 1501.66 to 1502.81 nm over the range of strains from the maximum value of $1746 \mu\epsilon$ (0.17%) to zero. The strain sensitivity of dip p2 is $0.63 \text{ pm}/\mu\epsilon$ and that of p3 is $0.64 \text{ pm}/\mu\epsilon$, both are in close agreement with the theoretical slope of $0.68 \text{ pm}/\mu\epsilon$.

Detailed studies of the hysteresis of the WGM's tuning with the applied strain and the outcomes are presented in Fig. 6. Figures 6(a) and 6(b) show the WGM's resonance wavelengths of p2 and p3 during the full measurement cycle, including the increase in the applied axial tensile strain and its subsequent complete decrease. Here, the black arrows indicate the direction of the WGM's shift during the increase of the applied axial tensile strain, and the red arrows show the direction of the spectral shifts during the strain decrease. The inset graphs in Figs. 6(a) and 6(b) illustrate the differences in the WGM dip wavelengths corresponding to the same strain values applied axially during the strain increase [$\lambda(\text{S.I.})$] and strain decrease [$\lambda(\text{S.D.})$] cycles. The maximum dip wavelength difference between the increase

Fig. 6. Selected WGM resonances during the strain increase (blue) and strain decrease (red) cycles: (a) dip p2 and (b) dip p3. Inset figures show the discrepancies in WGM wavelengths during the increase and decrease cycles.

and decrease cycles of the applied axial strain is estimated as 90 pm.

Such small discrepancies between the WGM wavelengths when increasing and decreasing the strain could be explained by the nonuniform deformations experienced by the POF micro-cylinder during elastic deformation [25].

B. Polarization Effects

In order to investigate the impact of the input light polarization and to demonstrate the repeatability of the results presented in the previous section, we carried out the experiments above for different input light polarizations.

As shown previously in Fig. 1, the polarization of the light at the input end of the fiber taper is controlled by the three-paddle polarization controller (FPC030, Thorlabs). The working principle of FPC030 is based on the stress-induced birefringence within single mode fiber (SMF 28) created through the bending and twisting of the fiber.

The quarter wave plate in the polarization controller transforms the input polarization state into a linear polarization state. The linearly polarized light can then be rotated to a desired angle with respect to the initial state using the middle half-wave plate paddle of the polarization controller. The twisting regions of the fiber due to rotating the paddle by an angle “ τ ” will rotate the polarization by an angle

Fig. 7. WGM resonant spectra from the POF MR with different input light polarizations.

$$\theta = \alpha\tau, \quad (5)$$

where $\alpha = -n^2 p_{44}$ [34]. Here, p_{44} is the elasto-optic coefficient of the fiber, and n is the refractive index of the core. The elasto-optic coefficient of fused silica is given by $p_{44} = \frac{p_{11} - p_{12}}{2}$, where the numerical values of p_{11} and p_{12} , respectively, are given by 0.121 and 0.270 [35].

For the experiments, the input polarization state was set as follows: the three paddles had initial vertical positions, and then the middle half-wave fiber paddle was rotated through its full travel range, while the other two quarter wave fiber paddles remained in their starting vertical positions. The strain tunability experiments using POF MR were repeated for three more linearly polarized input states by rotating by a 0°, 45°, and 90° angle of the central half-wave plate of the polarization controller from its initial vertical position. The corresponding rotation of polarization from the initial position is calculated by Eq. (5) as 0°, 7.22°, and 14.44°, respectively.

For comparison, Fig. 7 shows the WGM resonance spectra excited by a 490 μm diameter POF MR with the 0°, 7.22°, and 14.44° angles of the input light polarization. The Q -factors of the resonance dips are of the same order of magnitude in each of the cases ($\sim 10^4$). The maximum extinction ratio of the resonances reaches up to 19 dB. The average free spectral range of the resonances is 1.07 nm. With the changes in the input light polarization, the WGM spectra show small differences in the dip amplitudes and shapes, but no significant influence was observed on the tunability of the WGM's spectrum.

Strain sensitivity during the increasing and decreasing cycles of the axial tensile strain shows small differences arising from polarization state changes, possibly because of the nonuniform deformation experienced by the strained POF MR. Figures 8(a)–8(c) show the selected WGM resonance wavelengths during the increasing and decreasing cycles of the axial tensile strain for different input polarization orientations.

Figure 8(d) shows the corresponding strain sensitivity of the POF MR undergoing increasing and decreasing strain cycles.

Fig. 8. Selected WGM resonances during the strain increase (black) and strain decrease (red) cycles with different input light polarization. Here, linearly polarized input light is rotated by angle (a) 0°, (b) 7.22°, and (c) 14.44°, respectively. (d) Sensitivity of the increase and decrease cycles of the axial tensile strain.

3. CONCLUSION

In conclusion, we investigated the effect of mechanical strain tuning of the WGM resonances excited in a POF cylindricalMR. The light was evanescently coupled into the micro-cylinder from a standard single mode silica optical fiber taper fabricated by the micro heater brushing technique. WGMs observed in the fiber taper's transmission spectrum had a high extinction ratio of up to 19 dB and a Q -factor of up to 2×10^4 . We experimentally demonstrated that the spectral positions of the WGM resonances shift linearly during the increase and decrease of the axial tensile strain applied to the micro-cylinder in the range of strains from 0 to 1746 $\mu\epsilon$ (0.17%). The WGMs move toward shorter wavelengths with the increase of the applied strain and return to their initial positions when the strain is decreased. Tuning of the WGMs is observed independently of the input light polarization. The WGM's resonance strain sensitivity reaches 0.66 pm/μ ϵ . Strain sensitivity during increasing and decreasing cycles of axial tensile strain shows small differences, possibly due to non-uniform deformation experienced by the strained POF MR. The proposed POF-based strain tunable MR possesses several desirable features, such as ease of fabrication and modification of the resonator surface for potential applications in fiber optic sensing and tunable micro lasing.

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