Optical Microfiber Knot Resonators: Fabrication and Transmission Properties

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Abstract

In this paper, an MKR has been fabricated from an unbroken double-ended tapered microfiber. Since the guided light can be transmitted in and out of the resonator directly by integral full-size fiber ports, the proposed device has much lower insertion loss, and is more stable and robust in structure. The Q-factors of resonance exceeding 40000 are achieved at the optical communication wavelengths of 1550nm. In addition, the optical transmission properties of the fabricated MKRs have been theoretically and experimentally demonstrated.

Keywords: Microfiber knot resonator, Fabrication, Transmission properties

1. Introduction

Microfiber is a low-dimensional optical waveguide in fiber with the diameter close to or below the wavelength of light. In 2003, L. Tong and co-authors first proposed a two-step process for fabricating a low loss silica microfiber [1]: This procedure involved wrapping an optical fiber taper with the micrometric diameter around a heated sapphire tip, and drawing it into a nanowire. Since then microfibers have attracted considerable attention because they offer a number of enabling optical and mechanical properties [2-4], including large evanescent fields, strong confinement, extreme flexibility and configurability, and low-loss interconnection to other optical fibers and fiberized components. Based on these unique properties, a variety of microfiber-based components or devices, ranging from resonators[5-8], interferometers, filters and lasers to sensors, were successfully demonstrated together with many other MNF-based applications in nonlinear optics[9,10] and atom optics[11,12].

Among these groups of microfiber based applications, microfiber resonators are featured with high Q factor, compact size and simple fabrication process. Therefore, microfiber resonators have been considered the most promising microfiber functional elements [13-15]. There are three main types of microfiber resonators: the microfiber coil resonator (MCR), microfiber loop resonator (MLR), and microfiber knot resonator (MKR). MCRs are fabricated by wrapping a microfiber around a dielectric rod with lower refractive index; MLRs are fabricated by bending a microfiber on itself and keeping two sections of a microfiber together by taking advantage of surface attraction forces. Both of these resonators require precise alignment, and MLRs are also mechanically unstable unless supported in some way. MKRs are made by forming an overhand knot in a microfiber. The natural overlapping of the fiber with itself avoids the need for precise alignment to enhance the geometry stability and allow a smaller resonator diameter. However, most of the reported

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MKRs exhibit only one input-output fiberized pigtail and need to be evanescently coupled to another microfiber to provide an output because the double-ended tapered fiber is broken when knotted [16,17]. This issue seriously affects long-term reliability of MKRs and limits their practical applications.

In this paper, we fabricated an MKR made from an unbroken double-ended tapered microfiber. The whole fabrication process avoids the need for precise alignment and was much simpler. Further, the fabricated MKR has two integral fiber pigtails and is relatively stable and robust in structure. Last, we theoretically and experimentally investigated the optical transmission properties of the fabricated MKRs.

2. Fabrication of MKR

2.1 Fabrication of Microfibers

The microfiber is fabricated from a standard single mode fiber (SMF) by the flame brushing technique on a coupler fabrication rig (FSCW-4000) [18]. Figure 1 shows the schematic diagram of the fabrication set-up.

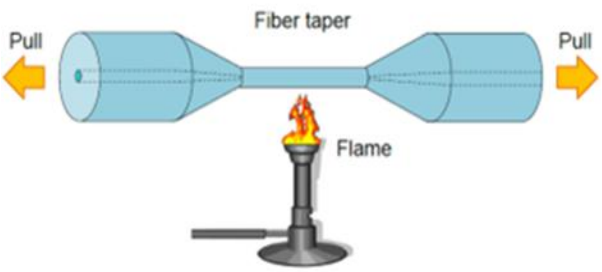

Figure 1: Schematic diagram of the flame brushing technique

First, remove the polymer protective cladding from a piece of SMF and clean it with ethanol. Then heat the bare fiber by an oxyhydrogen flames and simultaneously stretch the heated fiber by two translation stages. For the mass conservation, the diameter in the heated region will consequently decrease. And by accurately controlling the fiber stretch speed and the flame movements, the microfibers with different diameter can be finally fabricated.

Figure 2 shows the microscope image of the fabricated microfiber. The microfiber diameter is tested to be approximately 3μm. From Figure.2, we can find out that there was no visible irregularity on the physical surface of the fabricated microfiber, implying that an excellent uniformity was achieved.

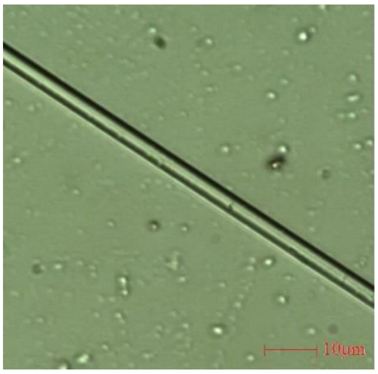

Figure 2: Microscope image of the fabricated microfiber

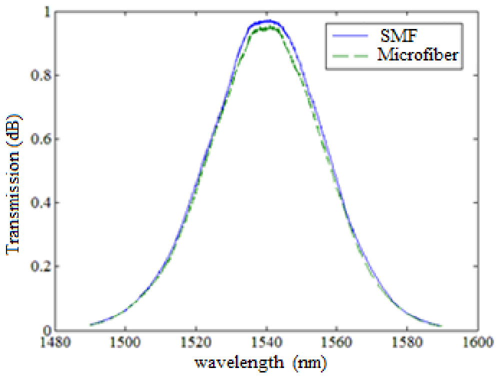

Figure 3: The optical transmission spectra of the fiber before and after being tapered.

Figure 3 compares the optical transmission spectra of the fiber before and after being tapered. No obvious changes can be observed in the spectrum shape, from which we can obtain that the optical transmission properties of the fiber remained almost unchanged after being tapered. To measure the transmission loss of the microfiber, a broadband light source with output power of 20mW was launched into the microfiber. After being transmitted by the microfiber with waist length of 70mm, the output power was 19.7mW. Accordingly, the transmission loss of the fabricated microfiber can be estimated to be as low as 0.001dB/mm.

2.2 Fabrication of MKR

Make a large knot at the two fiberized pigtails of the fabricated microfiber. By gradually pulling the fiber ends, the knot is held between finger and thumb, and the knot length will decrease. It was important not to tug the microfiber, though it could be easily flexed without damage. When the knot length was in the order of millimeters, it could be found that the microfiber waist was straight, and the taper transitions were bent. Then fix the knot onto the translation stages so that the knot length could be further decreased by pulling the ends symmetrically by using the stages. In this case, the knot would always migrate down the transitions towards the center of the waist as required.

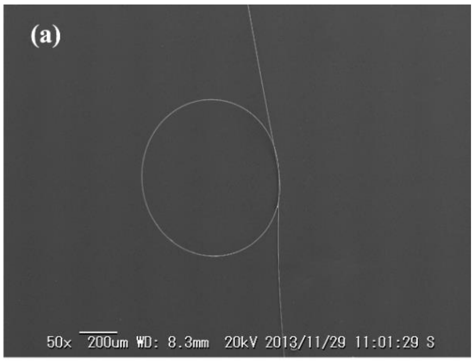

Figure 4: SEM of the fabricated MKR.

The whole fabrication process is much simpler without the need for precise alignment. Furthermore, the fabricated MKR has two integral fiber pigtails and is relatively stable and robust in structure. Figure 4 shows the scanning electron microscope (SEM) image of the fabricated MKR. The microfiber diameter and knot length are observed and tested to be approximately 3μm and 2.5 mm, respectively.

3. Optical Transmission Properties of MKR

3.1 Transmission Properties of MKR

As the fiber is tapered sufficiently small, the original fiber core may effectively disappear and large evanescence power will spread into the external material. By knotting the waist area of the tapered fiber, the evanescent mode fields in the intertwisted region will overlap, and resultantly a resonant mode coupling will occur. By combining the theory of the ring resonators and the directional couplers, the transmission equation of light propagating along the MKRs can be deduced as [14]:

$$T = \frac{1+k-\gamma_0+2\sqrt{k(1-\gamma_0)}\sin(\beta L)}{1+k+2\sqrt{k}\sin(\beta L)} \quad (1)$$

Where $\beta=2\pi n_{eff}/\lambda$ is the propagation constant of the guided mode in the microfiber, n_{eff} is the effective refractive index, and L is the length of the knot. Thus βL is the single-trip phase difference in the resonant cavity. k is the coupling coefficient which characterizes the coupling between adjacent microfiber segments, and γ_0 is the propagation loss coefficient of the microfiber.

According to Eq. (1), if k=0, then the knot is decoupled, and the MKR will be an all-pass device; its transmission behavior is similar to that of a straight microfiber. In the opposite case of strong coupling, the resonances in transmission amplitude occur only if βL is equal to the values:

$$\beta L = -\frac{\pi}{2} + 2m\pi \quad (2)$$

Which corresponds to the full transmission of electromagnetic field from one of the adjacent fiber segments to another. Then the resonances in transmission amplitude correspond to the condition:

$$\lambda_{res} = \frac{n_{eff} L}{m - \frac{1}{4}} \quad (3)$$

Where λ_{res} is the resonance wavelength, and m represents the resonance order. From Eq. (3), it is obvious that the transmission of MKRs has a periodic-notch spectrum.

3.2 Transmission Spectra of MKR

To experimentally characterize the transmission properties of the fabricated MKRs, a broadband light source (SLED1550) and an optical spectrum analyzer (YokogawaAQ6370B) were used as light source and detector, respectively. MKRs with different knot length were obtained by controlling the pulling force during fabrication. Figures 5-8 respectively show the transmission spectra of the MKRs with knot length of 1 mm, 1.8mm, 2.5mm and 6mm. A clear resonance can be observed in these figures, which agree with the theoretical analysis indicated in Eq. (1). Also, we can find out from these figures that:

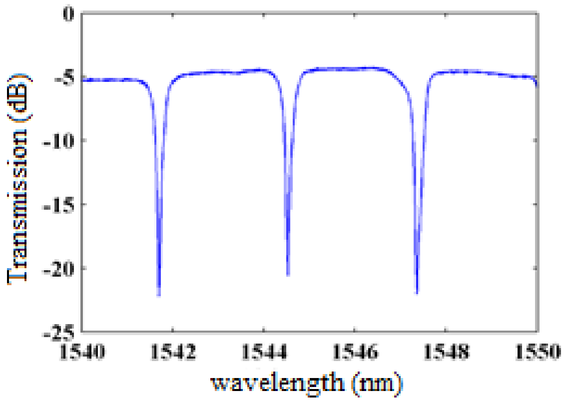

Figure 5: Transmission spectra of the MKR with knot length of 1 mm.

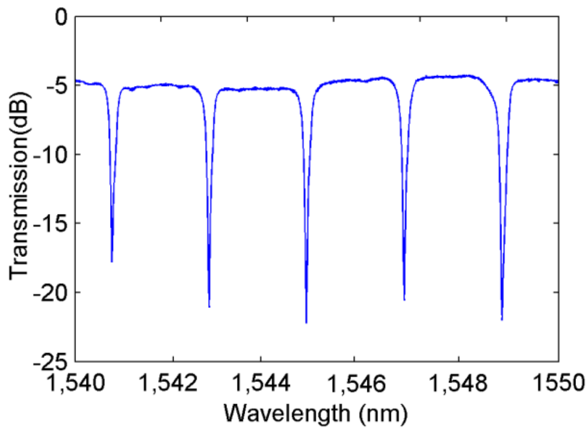

Figure 6: Transmission spectra of the MKR with knot length of 1.8 mm

1). FSRs decrease with increasing of the knot length of MKRs

The free spectrum range (FSR) is the wavelength period of the resonance peaks in the MKR transmission spectra. As shown in Figures 5-8, when the knot length of the MKRs are 1mm, 1.8mm, 2.5mm and 6mm, the corresponding FSRs are 2.92nm, 2.05nm, 1.3nm and 0.51nm, respectively. By contrasting these data, we can observe that the FSRs in the transmission spectra decrease with increasing of the knot length of MKRs. This is attributed to variations of the round-trip optical path length in the resonant cavity along with the knot length.

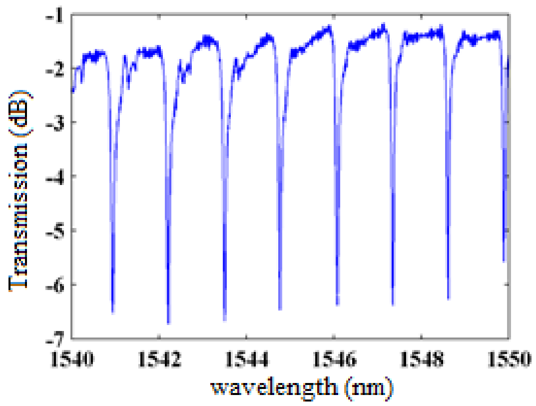

Figure 7: Transmission spectra of the MKR with knot length of 2.5 mm.

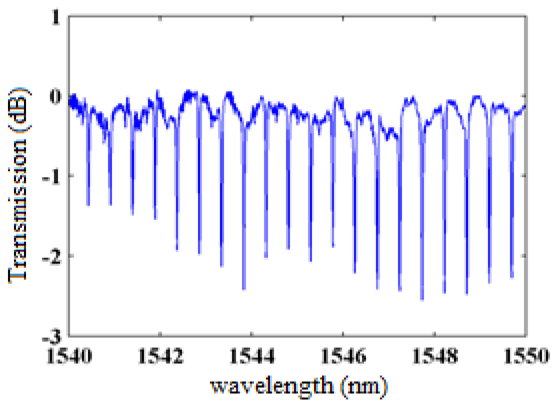

Figure 8: Transmission spectra of the MKR with knot length of 6 mm.

2). Q factors increase with increasing of the knot length of MKRs

The Q factors of a resonator in its resonance spectra is defined as the ratio of the resonance wavelength λ to the full width at half-maximum (FWHM) of this wavelength Δλ: Q =λ/Δλ[20]. As shown in Figures 5-8, when the knot length of the MKRs are 1mm, 1.8mm, 2.5mm and 6mm, the corresponding FWHM are 0.15nm, 0.108nm, 0.07nm and 0.038nm, respectively. Accordingly, the corresponding Q factors can be calculated to be 10333, 14351, 22142 and 40789. By contrasting these data, we can find that as the knot length of MKRs increase, the Q factors of its resonance spectra increase. Therefore, longer knot length is beneficial to construct MKRs with higher Q factor.

4. Conclusion

In this paper, we fabricated an MKR made from an unbroken double-ended tapered microfiber. Excellent resonant responses with Q-factors of about 40000 are obtained. Compared with the present reported microfiber based resonators, the device has much lower insertion loss, and is more stable and robust in structure. Furthermore, the optical transmission properties of the fabricated MKRs have been theoretically and experimentally demonstrated. The results hold great promises for the potential application in MKR based sensors, lasers and nonlinear components.

Acknowledgement

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