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High finesse microfiber knot resonators made from double-ended tapered fibers

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We fabricated optical microfiber knot resonators from thin tapered fibers (diameter down to $1\,\mu$m) linked to untapered fiber at both ends. We demonstrated a finesse of about 100, over twice as high as previously reported for microfiber resonators. Low-loss encapsulation of microfiber knot resonators in hydrophobic silica aerogel was also investigated.
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Resonators made from microfibers (optical fibers tapered down to micrometer-scale diameters) have attracted wide interest recently for their potentially high Q factor [1–11]. Their advantages over microrings, microdisks, microtoroids, and microspheres are the simple fabrication process and naturally low-loss coupling in and out of the resonator by the tapered fiber itself [2]. Applications, such as optical filters [4], optical sensing [2], microfiber lasers [5], and nonlinear resonators [6] have been investigated.

There are three main types of microfiber resonators: the microfiber coil resonator (MCR) [8–10], microfiber loop resonator (MLR) [1,2], and microfiber knot resonator (MKR) [3–7]. MCRs are made by wrapping a microfiber around a low-index rod, and MLRs are made by twisting a microfiber so that it touches itself. Both require precise alignment and MLRs are also mechanically unstable unless supported in some way [3]. 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, holds the structure in place, and allows a smaller resonator diameter. However, all reported MKRs have been formed in the freestanding end of a single-ended tapered fiber, because (it is claimed) double-ended tapered fibers break when knotted [3,4,11]. The diameter of the MKR can only be controlled by manipulating (under a microscope) the freestanding end, which then needs to be evanescently coupled to another microfiber to provide an output. These complications seriously limit the applications of MKRs.

The figure of merit most often quoted for these resonators is Q, which is the ratio of the wavelength to the full width at half-maximum (FWHM) [11]. Values of Q exceeding 100,000 have been reported [2,9]. However, of more relevance to many applications is the finesse F, which is the ratio of the free spectral range (FSR) to the FWHM and relates to losses per resonator round trip rather than per optical cycle [11,12]. High Q can be obtained for modest F simply by lengthening the cavity (and reducing the FSR) [9,12]. The highest finesses of reported MCRs, MLRs, and MKRs are around 20, 42, and 28, respectively [10,2,4]. A higher F would increase the ratio of minimum to maximum measurable changes in a sensor and the resonant enhancement of optical power in the cavity.

In this Letter, we demonstrate the first (to our knowledge) MKR made from a double-ended tapered fiber, so that light can be coupled in and out of the resonator directly via integral full-size fiber ports. We attained a finesse of 104, over twice as high as previously reported. We have also successfully encapsulated the resonator in silica aerogel, a low-loss encapsulant that is refractively like air.

SMF-28 fiber was fixed in the linear stages of our taper rig, and the two loose fiber ends were knotted [see Fig. 1(a)]. Transmission was monitored using an LED source and an optical spectrum analyzer (OSA) with a resolution of 0.02 nm. The fiber was tapered by a flame-brushing method to a microfiber of the desired diameter, which for our experiments was between 1 and $4\,\mu$m. The loss after tapering was always less than 0.05 dB. The tapered fiber was carefully removed from the stages, the knot held between finger and thumb, and the loop diameter decreased gradually by pulling the fiber ends. It was important not to tug the microfiber, though it could readily be flexed without damage. When the diameter was ~4 cm [see Fig. 1(b)], we found that the microfiber waist was straight and the taper transitions were bent. Then we held the knot between the stages so that the

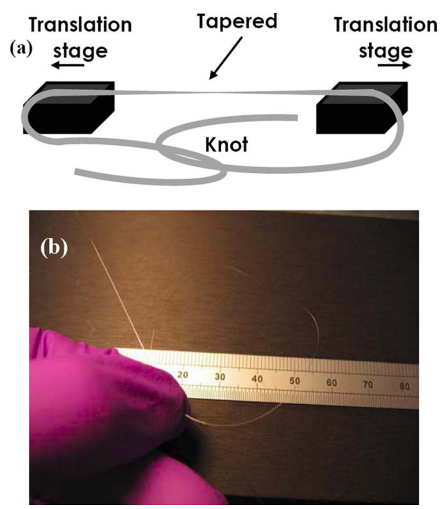

Fig. 1. (Color online) (a) Schematic of the setup before the knot was pulled tight. (b) Photo of a large loop with the knot held by finger and thumb. The 10 mm long microfiber section of $1\,\mu$m diameter is in the middle of the loop.

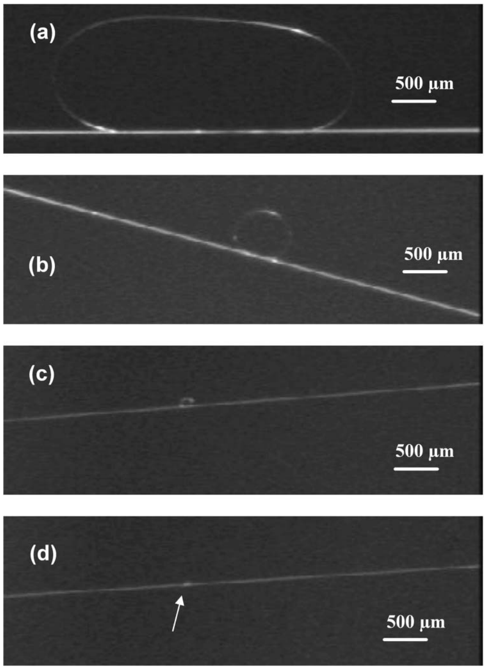

Fig. 2. Micrographs of MKRs with fiber diameters and resonator diameters of (a) 2 μm (not circular), (b) 1 μm, and ~570 μm, (c) 1 μm and ~128 μm, and (d) 1 μm and 46 μm (from the measured FSR).

diameter of the loop could be further decreased by pulling the ends symmetrically using the stages. We found that the loop always migrated down the transitions toward the center of the waist, as required. The whole process took less than 10 min and produced high quality MKRs by just controlling the stages and observing the corresponding transmission spectra, even without a microscope. It was simpler than any previously reported fabrication process for microfiber resonators, yielding a stable and relatively robust device.

Figures 2 and 3 and Table 1 show different-diameter MKRs with their corresponding transmission spectra and key parameters, MKR (a) being that of Fig. 2(a), etc. MKR (a) had an extinction ratio of 13 dB but its low-finesse response was more like that of a simple interferometer. The FSRs of the MKRs (b) and (c) were 1.16 and 5.41 nm, matching the measured resonator diameters of 570 and 128 μm, respectively. Their Q was high and their finesse, as high as 104, exceeded previously reported values. This is a consequence of our fabrication process, with low microfiber attenuation (close to 0.001 dB/mm) and controllable coupling. Indeed the FWHM of (b) was below our OSA's resolution and was measured with a narrow-linewidth tunable external-cavity diode laser.

An advantage of MKRs over other microfiber resonators is the possibility of much smaller diameters and larger FSRs. The 14 nm FSR of MKR (d) corresponded to a diameter of 46 μm, though this could not be measured directly in the low-resolution micrograph.

To achieve long-term stability, microfiber resonators have been embedded in low-index polymers, such as Teflon [7–9]. Recently we demonstrated the advantages of embedding microfibers in hydrophobic aerogel, which has a refractive index of ~1.05 and behaves optically like "solid air" [13]. The MKR of Fig. 4 was embedded in aero-

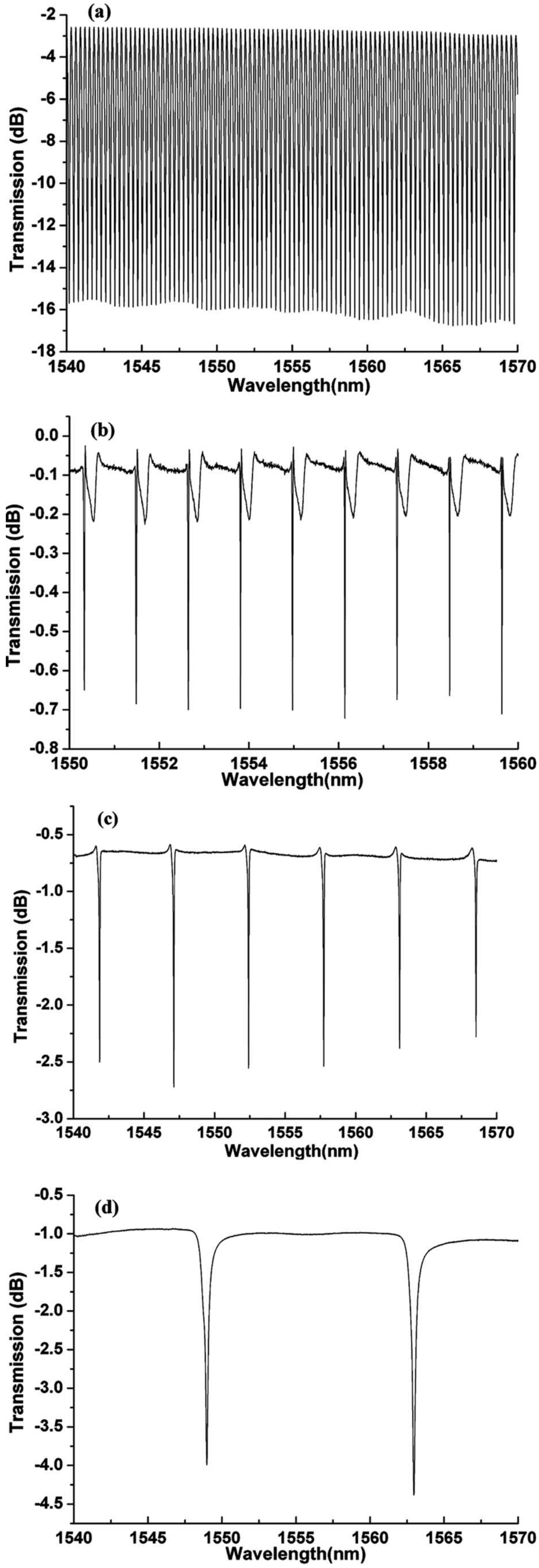

Fig. 3. Transmission spectra of the MKRs in Fig. 2. The two families of resonances in (b) appear to be due to polarization splitting as discussed in [2].

Table 1. Key Parameters of the MKRs of Figs. 2(a)–2(d) and 4

MKR	Loss (dB)	FSR (nm)	FWHM (nm)	Q	Finesse
(a)	2.6	0.31	0.16	9720	2
(b)	0.1	1.16	0.016	97260	73
(c)	0.6	5.41	0.052	30060	104
(d)	1.0	13.99	0.264	5870	53
Figure 4	0.75	0.504	0.162	9420	3.1

gel using the procedure of [13]. The off-resonance loss of the encapsulated MKR was 0.75 dB, much lower than has been achieved with other encapsulants. Q and F (Table 1) were, however, worse than those of the resonators in air. We believe it is because the knot was disturbed when sol was poured over the resonator, and could perhaps be mitigated by adjusting the knot after immersion but before the gel has formed. If so, then with greater care it should not be necessary to sacrifice finesse to achieve stability. Finally, aerogel minimizes the weakening of light confinement and change of dispersion caused by encapsulation in higher index polymers, which may be undesirable for nonlinear applications.

In conclusion, we have made MKRs from unbroken double-ended tapered fibers, with two integral fiber ports. The measured finesse exceeds 100, over two times larger than the best previously reported for microfiber resonators. We have also embedded MKRs in hydrophobic aerogel, with much lower loss than has been achieved with other encapsulants.

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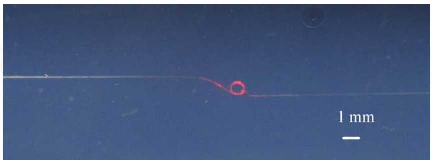

Fig. 4. (Color online) MKR with fiber diameter $4\,\mu$m and resonator diameter 1 mm embedded in hydrophobic aerogel. The MKR carries red laser light from left to right.

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