

# Brief introduction to optical microfibers and nanofibers

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**Abstract** When its diameter goes close to or below the wavelength of the guided light, an optical microfiber/nanofiber (MNF) exhibits favorable properties such as tight optical confinement, strong near-field interaction, and excellent mechanical strength, which offers plenty of choices for combining a variety of functionalized materials ranging from semiconductors and metals to laser dyes; opens up plenty of opportunities for developing microphotonic or nanophotonic devices; and inspires new opportunities for near-field optics, nonlinear optics, and quantum optics.

**Keywords** microfiber, nanofiber, optical property

## 1 Introduction

Optical microfibers/nanofibers (MNFs) are optical fibers with diameters close to or thinner than the wavelength of guided light. A number of names have been given to these tiny fibers by different research groups or different properties of the fiber, such as “subwavelength wire/waveguide”, “optical microfiber and/or nanofiber”, “fiber taper/tapered fiber”, “photonic/optical nanowire”, “submicron-diameter fiber”, and “ultrathin fiber”. For simplicity, here we use the name “MNF”. Because of the small core diameter and large index difference between the fiber core (usually larger than 1.5) and the cladding (e.g., 1.0 for air), a number of interesting optical properties such as tight optical confinement, large evanescent fields, strong field enhancement, and large waveguide dispersions can be obtained in an MNF [1–3]; offer plenty of choices for combining a variety of functionalized materials such as rare-earth ions, laser dyes, chemical indicators, semiconductor nanowires, and quantum dots; and open up plenty of

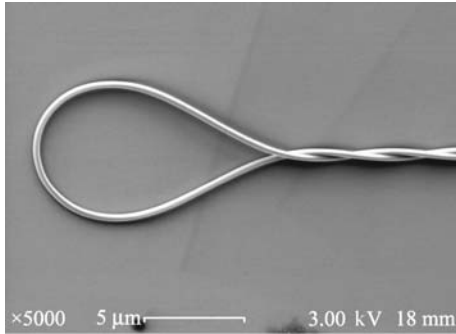
opportunities for developing microphotonic or nanophotonic components/devices ranging from interferometers, filters, and lasers to sensors.

## 2 Fabrications and optical properties

Usually, MNFs are fabricated by physically drawing viscous melts or solutions. Materials used for drawing MNFs are glass fibers [4–11], bulk glasses [12,13], or polymers [14–19]. When the starting material is melted by heating or dissolved by solvents, it is possible to obtain appropriate viscosity for MNF drawing at certain area, and high-quality MNFs with diameters down to 30 nm can be obtained with a drawing speed from several millimeters to meters per second. Compared with many other techniques that have been used for MNF or other one-dimensional nanostructure fabrication [20–24], physical drawing technique yields MNFs with unparalleled uniformities regarding sidewall smoothness and diameter uniformity. The excellent uniformity of the MNF does not only enable the low optical waveguiding loss but also bestow the MNF with high mechanical strength and flexibility. Figure 1 shows a typical scanning electron microscope (SEM) image of a twisted 360-nm-diameter silica MNF with minimum bending radius of about 3  $\mu\text{m}$ . The high uniformity and smooth sidewall of the fiber are clearly seen. The tight bend and twist do not break, indicating high mechanical strength and pliability of the MNF.

Optical waveguiding properties of MNFs can be obtained by solving Maxwell’s equations with boundary conditions in cylindrical coordination [3]. Figure 2, for example, shows diameter-dependent fractional power inside the core in an air-clad silica MNF. One may see that, when the fiber diameter and the wavelength are properly chosen, e.g., 200-nm fiber diameter with 633-nm wavelength, the fractional power guided outside the fiber core can go higher than 90%, resulting in strong evanescent fields outside the fiber core, which is very

useful for enhancement of near-field interaction between the MNF and exotic materials in the close vicinity of the fiber surface.



**Fig. 1** SEM image of a twisted 360-nm-diameter silica MNF with minimum bending radius of about  $3\ \mu\text{m}$

Benefitted from their extraordinary uniformities, taper-drawn MNFs guide light with low optical losses. Typical loss of physically drawn glass or polymer MNFs measured at the critical diameter for single-mode operation is lower than  $0.1\ \text{dB/mm}$  [4–6,17], with lowest measured loss of about  $0.001\ \text{dB/mm}$  reported in silica MNFs [6].

### 3 Potentials and applications

So far, a variety of MNF-based components or devices, ranging from optical couplers [12,18,25], resonators [4,26–36], interferometers [7,37], filters [38–40], and lasers [41–44] to sensors [17,45–58], were demonstrated or proposed, together with many other MNF-based applications including nonlinear optics [6,59–68], atom optics [69–77], and photon-momentum-induced effect [78]. Here, we briefly introduce some typical applications of MNF-based photonic components/devices.

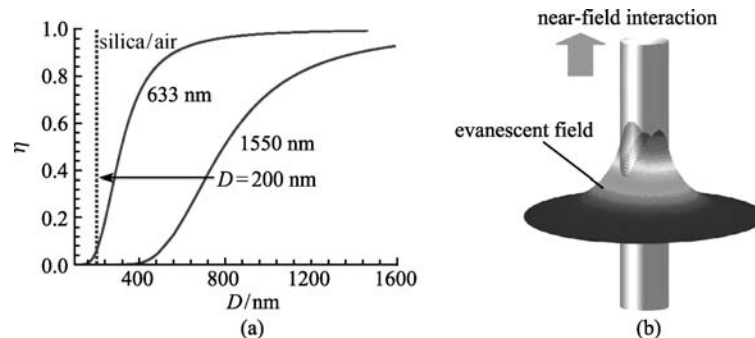
One of the simplest components is MNF-based optical

coupler. The high fractional evanescent fields outside the MNF makes it possible to form an optical coupler by simply put two MNFs in close contact [4,12,18,25]. Due to the strong near-field interaction, light exchange in these MNFs can be realized within a very short interaction length. For example, in two closely contacted 350-nm-diameter silica MNFs, optical power of a 633-nm-wavelength guided light can be transferred from one MNF to the other within a transfer length of less than  $3\ \mu\text{m}$  [25]. Optical coupling between different MNFs have also been investigated theoretically [79] and experimentally [12]. For example, Fig. 3 shows a micro-coupler assembled using two tellurite glass MNFs with diameters of 350 and 450 nm, respectively. The high-index tellurite MNFs ( $n = 2.05$ ) are supported on a low-index  $\text{MgF}_2$  crystal ( $n = 1.39$ ). The transfer length for 3-dB splitting of 633-nm-wavelength light is around  $3\ \mu\text{m}$  with low excessive loss [12].

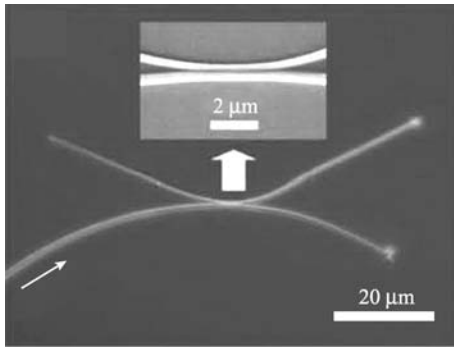
When two MNF-based micro-couplers are connected in cascade, a microscale Mach-Zehnder interferometer (MZI) is obtained. Shown in Fig. 4 is a typical MZI assembled from two 480-nm-diameter tellurite MNFs. With a whole size around  $50\ \mu\text{m}$ , clear interference fringes are observed with extinction ratio of about 10 dB [37].

Relying on strong near-field coupling, tying a MNF into a loop or knot is proven an efficient approach to micro-ring resonators. Figure 5, for example, shows a micro-knot tied with a  $1.1\text{-}\mu\text{m}$ -diameter silica MNF. The knot can be tightened to a diameter below  $50\ \mu\text{m}$  while maintaining a  $Q$  factor larger than 2000 [38]. Much higher  $Q$  factors (e.g., 105) have been reported in MNF-based ring resonators [29].

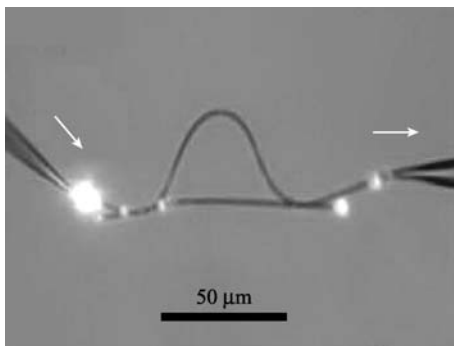
Based on micro-ring resonators, several functional components or devices, including filters, sensors, and lasers, have been reported [38,42,43,50,52,54,55,58]. Figure 6 shows a passive component assembled with a MNF knot and a drop MNF [38]. The  $200\text{-}\mu\text{m}$ -diameter knot, assembled with a  $2.7\text{-}\mu\text{m}$ -diameter silica MNF, shows a  $Q$  factor of about 13000 and a finesse of 14.6 with



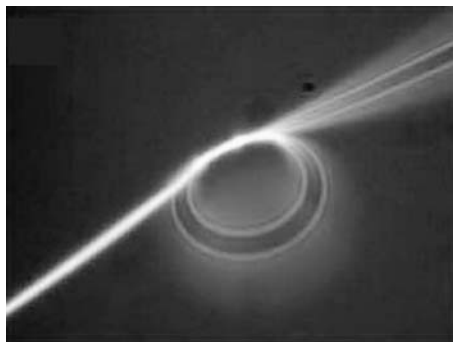
**Fig. 2** (a) Diameter-dependent fractional power inside core ( $\eta$ ) in an air-clad silica MNF with wavelengths of 633 and 1550 nm, respectively; (b) schematic diagram of typical evanescent fields outside an air-clad 200-nm-diameter silica MNF operated at 633-nm wavelength (refractive indices of silica are 1.46 and 1.44 for 633- and 1550-nm light, respectively)



**Fig. 3** Optical microscope image of a micro-coupler assembled using two tellurite glass MNFs with diameters of 350 and 450 nm, respectively (Tellurite MNFs ( $n = 2.05$ ) are supported on a low-index  $\text{MgF}_2$  crystal ( $n = 1.39$ )) (Adapted from Ref. [12])



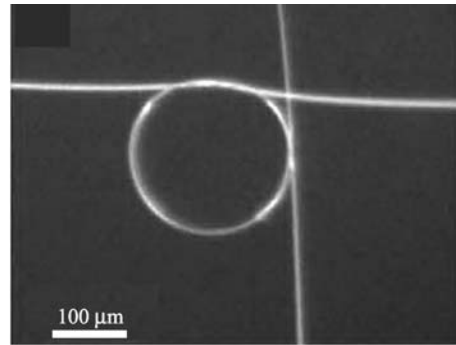
**Fig. 4** Optical microscope image of an MZI assembled from two 480-nm-diameter tellurite MNFs on an  $\text{MgF}_2$  substrate (Adapted from Ref. [37])



**Fig. 5** Optical microscope image of a 50- $\mu\text{m}$ -diameter micro-knot tied with a 1.1- $\mu\text{m}$ -diameter silica MNF

a free spectral range (FSR) of 1.8 nm. With wavelength tunable light input centered at 1550 nm, the MNF assembly operates well as an add-drop filter [38].

The micro-ring resonator can be readily developed into an active device when the MNF is functionalized with active medium. For example, dope the MNF with rare-earth ions to achieve an active micro-ring cavity for lasing activity. As shown in Fig. 7, a 2-mm-diameter knot assembled using a 3.8- $\mu\text{m}$ -diameter Er: Yb-codoped

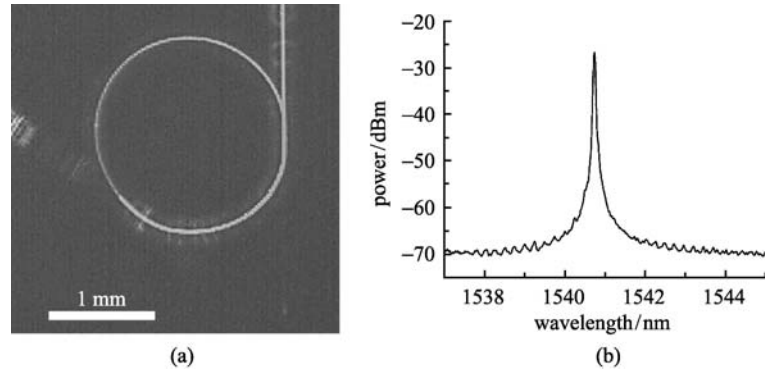


**Fig. 6** Optical microscope image of an add-drop filter assembled with an MNF micro-knot and a drop MNF (Adapted from Ref. [38])

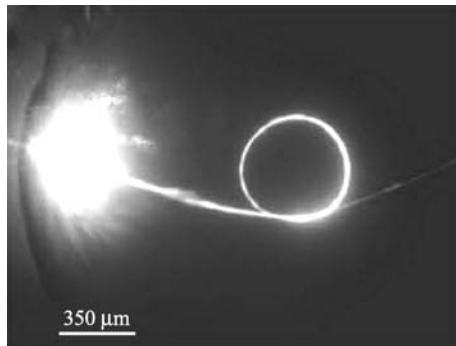
phosphate glass MNF serves as both active medium and resonating cavity for lasing [42]. When the cavity is pumped by a 975-nm-wavelength continuous wave light, single-longitudinal-mode laser with threshold of about 5 mW and output power up to 8  $\mu\text{W}$  is obtained.

Benefitted from the near-field coupling, the MNF can be also activated by coupling functional materials outside the fiber. For example, when an undoped silica MNF is immersed in a dye solution, the dye molecules in the close vicinity of the fiber surface can be evanescently coupled with the MNF, making it work as a dye-doped active MNF. Therefore, an undoped silica MNF knot embedded in a laser dye solution may work as a microscale dye laser. This has been experimentally verified [43], as shown in Fig. 8, in which a composite micro-ring laser is formed by immersing a MNF knot (assembled with a 3.9- $\mu\text{m}$ -diameter silica MNF) in a rhodamine 6 G dye solution. When the 350- $\mu\text{m}$ -diameter knot is pumped by 532-nm-wavelength pulses, lasing oscillation occurs inside the evanescently coupled closed-ring microcavity. Laser emission around 570 and 580 nm wavelengths is observed with a threshold of about 9.2  $\mu\text{J}/\text{pulse}$  [43]. Using the similar approach, solid-state semiconductor nanomaterials have also been successfully integrated with undoped MNFs for light emission devices. Recently, functionalized MNF micro-rings with surface-coupled ZnO nanowires have been operated as hybrid MNF-ZnO-nanowire lasers [80], exhibiting low lasing threshold and high compatibility with outer fiber system.

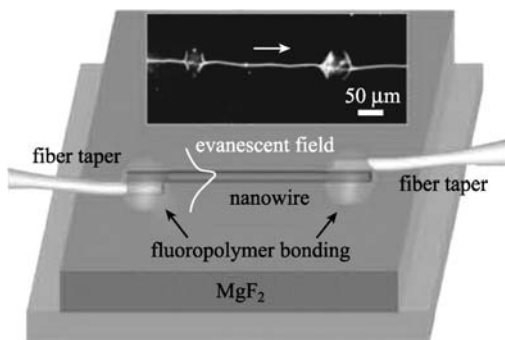
Low-loss optical MNFs are also favorable for optical sensing. The low dimension, tight optical confinement, high fractional evanescent fields, and engineerable transmission (functionalized by, e.g., sensitive dopants or coatings) of the MNF make it possible to realized micro/nanoscale fiber-optic sensors with small footprint, fast response, high sensitivity, and/or low detection limit. Figure 9, for example, shows a polymer MNF sensor for humidity detection [17]. The sensitive element used here is a polyacrylamide (PAM) MNF that, when exposed to moisture, decreases its refractive index by absorbing water molecules. The reduced index leads to increased leakage of



**Fig. 7** Micro-knot laser assembled using a 3.8- $\mu\text{m}$ -diameter Er:Yb-codoped phosphate glass MNF. (a) Optical microscope image of 2-mm-diameter knot under pumping; (b) laser output around 1540-nm wavelength (Adapted from Ref. [42])



**Fig. 8** Optical microscope image of a composite micro-ring laser formed by immersing a MNF micro-knot into a rhodamine 6 G dye solution (Adapted from Ref. [43])



**Fig. 9** Schematic diagram of PAM MNF sensor for humidity detection (PAM MNF is supported on a low-index  $\text{MgF}_2$  crystal and coupled to outer fibers by fiber tapers; inset shows optical microscope image of an  $\text{MgF}_2$ -supported 410-nm-diameter PAM MNF with a 532-nm-wavelength light launched from left side; white arrow indicates the direction of light propagation) (Adapted from Ref. [17])

guided light into the low-index substrate ( $\text{MgF}_2$  crystal), resulting in humidity-dependent leakage of the MNF. By measuring the output intensity of the MNF, relative

humidity of the environment is obtained with a response time of 30 ms, over 100 times faster than in conventional humidity sensors.

Besides the microphotonic components/devices introduced above, many other applications of optical MNFs, including nonlinear optical effects [6,11,59–65], atom manipulations [69–77], and instant response to momentum change of light guided through [78], as well as some new designs of microphotonic components [81–84], have been reported recently, making the MNF research an exciting frontier of fiber-optic technology.

## 4 Conclusion

MNFs fabricated by physical drawing process exhibit excellent uniformities for low-loss optical waveguiding. With wavelength- or subwavelength-scale diameters, optical MNFs provide interesting properties such as tight optical confinement, large evanescent fields, strong field enhancement, and large waveguide dispersions, making them promising building blocks or platforms for both device applications and fundamental research.

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