# Polymer Micro or Nanofibers for Optical Device Applications

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**ABSTRACT:** Silica taper incorporated polymer micro or nanofibers have been fabricated by direct drawing. This method could provide stable and high-optical-coupling efficiency. The as-fabricated polymethyl methacrylate (PMMA) fibers not only show low-optical losses, but also offer good flexibility, making them promising elements for sharp-bending waveguides and ring resonators. A low-loss microcoupler has been assembled with two 860-nm-diameter PMMA fibers and a polymeric knot resonator with a loaded *Q*-factor of about 3000 has been assembled using a 3-μm-diameter PMMA microfiber. Thermostability of the PMMA fibers has also been investigated. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 1080–1084, 2008

**Key words:** polymethyl methacrylate; micro or nanofiber; direct drawing; optical device

## INTRODUCTION

Recent works have shown that taper-drawn silica nanowires,[1–4] directly drawn glass nanowires[5,6] and chemically grown nanoribbons and/or nanowires[7–10] are promising components for subwavelength waveguiding and nanophotonic devices. Compared with the inorganic counterparts, polymer optical waveguide devices may play a key role in several rapidly developing areas of broadband communications because of their lightweight, chemical specificities, low cost, mechanical flexibility, tunable properties, easier processibility, and integration.[11] Polymer-based optical devices have been achieved by standard semiconductor processing technology, molding process, soft lithography, etc.[11,12] Examples of chemical synthesis,[13] electrochemical synthesis,[14] nanolithography,[15] electrospinning,[16–21] and mechanical drawing[22,23] have been used to prepare polymer nanowires or nanofibers. By incorporating electrical, optical, and magnetic nanoparticles into these nanostructures, multifunctionalized composite polymer nanofibers have been synthesized.[19–21]

Previous reports suggest the possibility of achieving optical elements based on polymer micro or nanofibers.[20,23,24] There is a need to study the waveguiding properties of the polymer micro or nanofibers and to build up optical devices with them. Herein, we demonstrated a method to direct drawing silica taper incorporated polymer micro or nanofibers from the solution to improve the coupling efficiency between the silica fiber and the polymer micro or nanofiber. Optical waveguiding properties were investigated, and photonic devices such as a 3-dB coupler and a microfiber knot resonator were assembled.

## EXPERIMENTAL

### Materials

Polymethyl methacrylate (PMMA, Alfa Aesar, MW = 350,000) is selected as the polymer waveguiding material in the experiments. PMMA is one of the conventional optical polymers because of its high mechanical strength, good dimensional stability, good weather resistance, and natural transparent above deep ultraviolet.

### Formation of PMMA micro or nanofibers by direct drawing

In the experiments, PMMA is dissolved in chloroform to prepare the polymer solution. Steeper silica taper made from single-mode optical fiber is used to draw PMMA fiber from the mixture solution, which has been manufactured by heating and drawing

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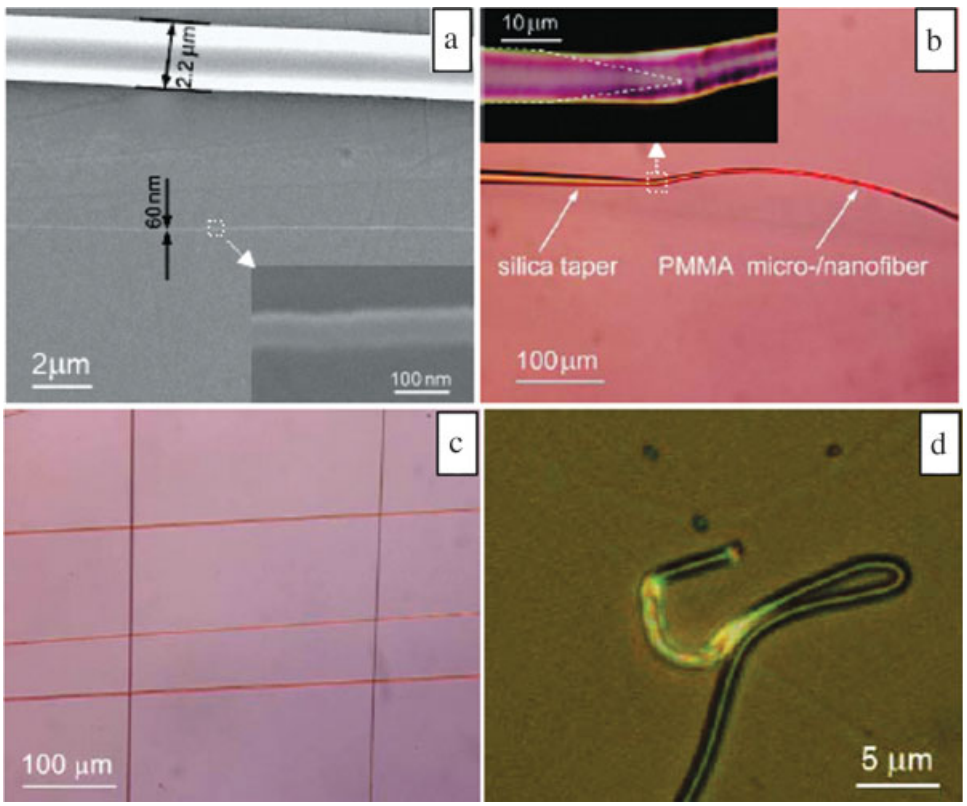


**Figure 1** Geometric characterization of PMMA micro or nanofibers. (a) FE-SEM image of a PMMA microfiber and a PMMA nanofiber. (b) Optical microscope image of the connection region of the PMMA fiber and the incorporated silica taper on a $MgF_2$ crystal, 633-nm-wavelength He–Ne laser is launched into the single mode fiber for easier monitoring; the inset image is a close-up image of the connection region, the contour of silica taper is marked by dashed line. (c) Optical microscope image of a PMMA fiber array. (d) Optical microscope image of a sharp bend with a minimum bending radius of about 1.4 μm. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

technology. To get good mechanical strength, the drawing speed is fast ($\sim$ 1 m/s) to get a steep silica taper. Then, the silica taper is dipped into PMMA/chloroform solution and taken out upwardly. If the solution viscosity is appropriate, a silica taper incorporated PMMA micro or nanofiber can be drawn from the solution with a drawing speed of about 0.1 m/s. During the drawing process, 633-nm-wavelength He–Ne laser is launched into the single mode fiber for easier monitoring. The diameter of the as-drawn PMMA fiber can be roughly controlled by controlling the concentration of PMMA. Starting from the connection region, the diameter of the PMMA fiber decreases slowly and reduces to micrometers or submicrometer about 2–10 mm away from the connection region.

### Optical investigation of PMMA micro or nanofibers

Evanescent-coupling method is used to pick up the light from the polymer fiber to a single mode fiber for optical investigation. To measure the optical loss of the PMMA fiber, we cut the fiber in steps using a scanning tunnel microscopy (STM) tip and determine the loss by measuring the length-dependent transmittivity. The as-fabricated microfiber is tied to a knot under an optical microscope to assemble ring resonator using a micromanipulation process described elsewhere.[4]

## RESULTS AND DISCUSSION

We found that PMMA micro or nanofibers were fabricable when the weight percentage of PMMA in the solution was between 25 and 40, and the diameter of PMMA fibers increases as the weight percentage of PMMA increases. PMMA fibers with diameters ranged from several micrometers to sub-100-nm and lengths up to 10s of centimeters have been drawn by this method. Figure 1(a) shows a field emission scanning electron microscopy (FE-SEM, Siron, FEI) image of a PMMA microfiber and a PMMA nanofiber. The uniform diameter and defect-free surface of the fibers are clearly seen, which made them ideal for photonic applications. Figure 1(b) shows the connection region of the PMMA fiber and the incorporated silica taper on a $MgF_2$ crystal. It can be seen from

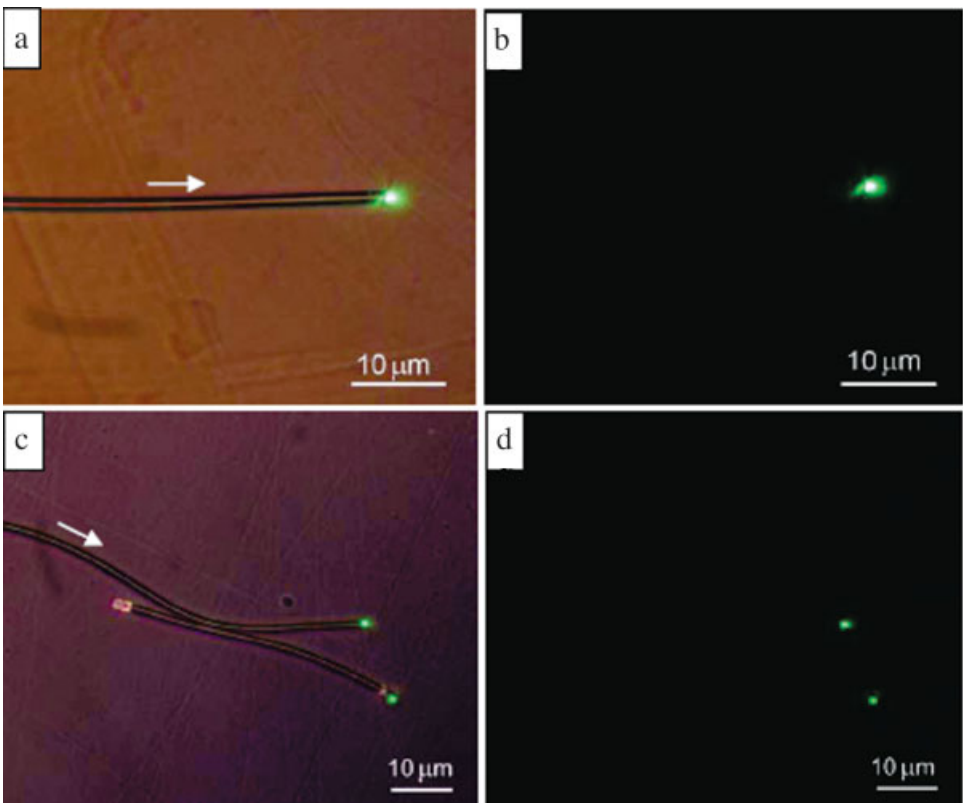


**Figure 2** Optical investigation of PMMA micro or nanofibers, the white arrows in (a) and (c) indicate the direction of light propagation. (a,b) Optical microscope images (with and without external illumination) of 532-nm-wavelength light guided by a 500-nm-diameter PMMA fiber placed on a $MgF_2$ crystal. (c,d) Optical microscope images (with and without external illumination) of an optical coupler assembled using two PMMA fibers (about 860 nm in diameter) on the surface of a $MgF_2$ crystal. The coupler splits the 532-nm-wavelength light equally. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

the inset image that an abruptly tapering end of the silica fiber was surrounded by PMMA. For photonic applications, coupling light in and out of a micro or nanofiber is an essential step. As shown in Figure 1(b), no obvious coupling loss is observed around the connection region between the single-mode silica fiber and the PMMA fiber. Meanwhile, the coupling is very stable. Additionally, the interfaces of PMMA/inorganic material may offer nanoconfined effects for other possibilities such as nonlinear optics.[25]

For PMMA fibers that are connected to single-mode silica fibers and freestanding in the air, they are easy to be manipulated into arrays or spatial geometries such as knots. An array of PMMA fibers is demonstrated in Figure 1(c) by manipulating the fibers using a STM tip. It is noted that the polymer fibers are very flexible, so that they can be manipulated into very sharp bend. As shown in Figure 1(d), a 680-nm-diameter PMMA fiber is bent with a minimum bending radius of about 1.4 μm, indicating the possibility for using them in photonic devices that require sharp bends.

Figure 2(a,b) shows the optical microscope images of a $MgF_2$-crystal-supported 500-nm-diameter PMMA fiber guiding 532-nm-wavelength light. No scattering is observed along the whole length of the fiber in spite of the strong guided intensity, indicating the low optical loss and no substrate-induced loss of the fiber. Measured loss of an 800-nm-diameter PMMA fiber at 532-nm-wavelength is about 0.2 dB/mm.

Figure 2(c,d) shows the optical microscope images of an optical coupler assembled using two 860-nm-diameter PMMA fibers, which is supported by a $MgF_2$ crystal with a refractive index of 1.38. As shown in Figure 2(c,d), the fiber assembly works as a 3-dB coupler (50 of 50 splitter in this case) with virtually no excess loss (no scattering is observed around the coupling area).

Optical resonators are essential optical devices finding wide applications in optical processing, sensing, and active devices. As fabrication technologies mature, microring resonators have garnered significant interest in the recent years, because they may open new avenues toward compact-integrated optical devices such as filters and delay elements. As indicated in Figure 1(d), the PMMA fiber has very good flexibility, so that it can be readily assembled

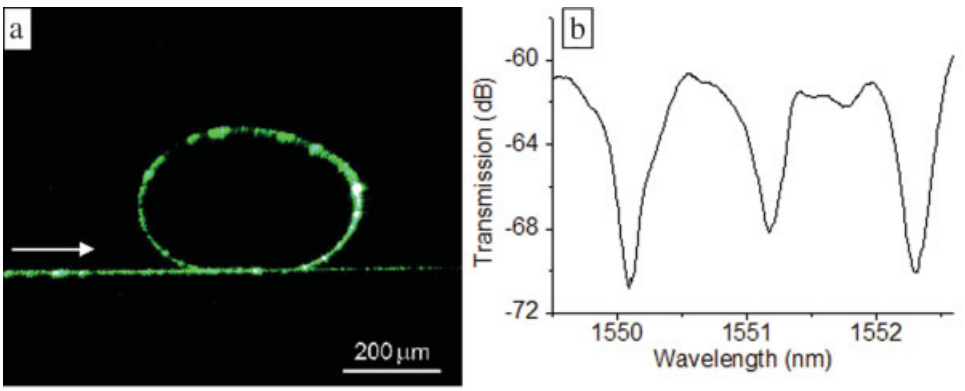


**Figure 3** (a) Optical microscope image of 532-nm-wavelength light traveling through a PMMA microfiber knot, the white arrow indicates the direction of light propagation. (b) Transmission spectra of a 450-μm-diameter microfiber knot resonator. The knot resonator is assembled with a 3-μm-diameter microfiber. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

into rings with small diameters. Figure 3(b), for example, shows typical transmission spectra of a 450-μm-diameter PMMA microfiber knot resonator assembled with a 3-μm-diameter PMMA microfiber. The resonance is clearly seen with a free spectral range of about 1.1 nm. Measured extinction ratio of the knot resonator is about 10 dB with a loaded *Q*-factor of about 3000 and a finesse of 2.2. The loaded *Q*-factor of PMMA resonator is comparable to those reported in integrated polymeric microring resonators at 1.55 μm wavelength.[26–28]

In addition, we have also tested the thermostability of the PMMA fibers fabricated in this work. As shown in Figure 4, we heat the fiber from 20 to 72°C in steps, while monitoring the morphology and optical transmittance of the fiber under an optical microscope. No obvious change on the morphology and light propagation is observed until 42°C. When the temperature exceeds 45°C, the fiber shows slight distortion and becomes twisting when the temperature rises to 72°C. However, the light propagating along the fiber maintains well within the whole range.

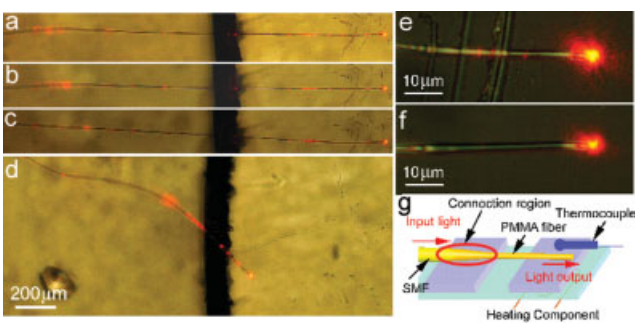


**Figure 4** Thermostability test of the PMMA fibers. Optical microscope images of the fiber in testing temperature of (a) 20, (b) 42, (c) 45, and (d) 72°C, respectively. (e,f) Close-up image of the output end of the fiber at 20 and 72°C, respectively. (g) Schematic diagram of the experimental setup for the test. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

## CONCLUSIONS

In conclusion, we have demonstrated the direct drawing of silica taper-incorporated polymer micro or nanofibers from the solution. The coupling efficiency between the polymer fiber and single mode silica fiber is high and stable. The as-fabricated fibers not only show low optical losses, but also offer good flexibility. A low-loss optical coupler assembled using two 860-nm-diameter PMMA fibers works as a 3-dB coupler and a polymeric knot resonator assembled using a 3-μm-diameter PMMA microfiber has a loaded *Q*-factor of about 3000. Results demonstrated in this work indicate that polymer micro or nanofibers are promising elements for optical device applications.

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