Fabrication of polymer microfiber through direct drawing and splicing of silica microfiber via vapor spray and flame treatment

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1. INTRODUCTION

Microfibers have gained tremendous interest in recent years as promising components for subwavelength waveguide and nanophotonics devices. They have been drawn and demonstrated by flame-heated silica fiber [1] and bulk glasses [2] method. The method provides an easy and cheap photonic wires manufacturing technique, when constant temperature distribution is required in the drawing region. Subsequently, flame-brushing technique was proposed to fabricate silica microfibers [3, 4], which can be used to assemble a variety of functional structures, such as resonators [5], interferometers [6, 7], filters [8], sensors [9, 10], and lasers [11]. To maintain the functional shape or geometry of the assembled structures, several approaches have been reported including van der Waals attraction [7, 12, 13], substrate-supported friction [14, 15], laser-heated fusion splicing [16, 17], and splicing via polymer nanowires [18]. Although the van der Waals attraction and substrate-supported friction are easy to realize, they are sensitive to environmental disturbance and impossible to sustain in liquid. Laser-heated fusion splicing offers much greater robustness; however it is limited to glass microfibers and requires a complicated experimental system. For splicing via polymer nanowires, amount of polymers is quite critical and it has to be well-controlled in order to reduce the splicing loss, and the polymers are sensitive to higher temperature and hard to sustain in solvent.

Polymer optical microfibers may play a key role in several rapidly developing areas for broadband communications and also for sensing purposes because of their chemical specificities, low cost, mechanical flexibility, tunable properties, and ease of processing and integration [19]. To date, polymer-based microfibers or nanowires have been achieved by various techniques such as chemical synthesis [20], nano-lithography [21], electro-spinning [22], and mechanical drawing [23]. Chemical synthesis and nano-lithography are quite complicated and require expensive facilities. Electro-spinning is only for microfiber mat fabrication and unfortunately it is not suitable for a single microfiber structure. The simplest and most effective method is based on mechanical drawing where the microfiber is normally drawn from solvated liquid polymer. In this technique, the main concerns are on the nature of solvent and concentration of polymers. Typical polymer solvents are volatile organic compounds.

In this paper, we demonstrate an eco-friendly and simple drawing method of fabricating polymer microfibers. This drawing method is somewhat similar to dissolved polymer drawing [23] but requires no solvent and polymer state is manipulated through temperature control. Polymethylmethacrylate (PMMA) polymer used in this work has many interesting properties such as lower loss at visible light and high refractive index, which provides a good optical confinement. In a rubber-like
state, PMMA poses a weak restoring force and will deform significantly under stress [24] and thus microfiber can be easily fabricated by a direct drawing technique. Microfibers have wide applications for sensing purposes such as micro-ring, micro-knot, and microfiber loop, and in this work we apply it for splicing purposes. The fabricated polymer microfiber is then used in splicing silica microfiber using solvent vapor technique in conjunction with flame treatment. We also use the same technique to fabricate ring resonator by coiling a tapered fiber. The first step of this technique is similar to the previous work of Tong [18] with the use of solvent vapor technique to splice the fiber. However, the splicing technique proposed in this work is followed up with a flame treatment to solve the scattering problem like using polymer nanowire to splice. The solvent vapor technique demonstrated in this work is a temporary technique to adhere the fiber and will be removed after the flame, which is able to eliminate problems of residual polymer microfiber due to serious scattering loss or weak splicing. In comparison with other splicing techniques such as using CO2 laser, the proposed splicing technique is much simpler as no laser or other expensive equipment is required in the process. Besides, no bent segment that occurs in CO2 laser splicing [25] was noticed in this splicing method such that scattering loss due to abrupt change of the fiber can be avoided. This technique can be used in a harsh environment as in high-temperature or solvent environment. The splicing technique proposed in this paper provides a permanent joint and can be applied to construct a permanent connection for almost all kinds of microfiber structures.

### 2. EXPERIMENTAL METHOD

Using direct drawing technique, polymer microfibers with diameter of 1.5 μm and length 3 mm were fabricated by one-step process as described in Fig. 1. PMMA is selected as the polymer waveguide material in this work because of its high mechanical strength, good dimensional stability, good temperature resistance, and natural transparency above deep ultraviolet wavelengths. A hotplate is used to melt PMMA and keep temperature constant during the fiber drawing. For this polymer, it is important to maintain desirable viscosity level, which means temperature of heating plate should be controlled within the temperature range between glass transition temperature and melting temperature of polymer. As the glass transition temperature \(T_g\) of PMMA ranges from 85°C to 165°C, heating plate temperature was kept around 115°C during the fiber drawing. First, a silica fiber with diameter about 125 μm is assembled and its tip is immersed into the molten PMMA. Then the fiber tip is retracted from the molten polymer with a speed of 0.1–1 ms\(^{-1}\), leaving a PMMA microfiber extending between the molten PMMA and the tip. The extended PMMA microfiber is quickly quenched in air and finally, a bare PMMA microfiber is formed. The microfiber diameter can be controlled by the speed of pulling and viscosity of polymer (which depends on the hotplate temperature). Microfibers produced by this technique are uniform in diameter over long length with good flexibility. The highest difference of individual microfiber diameter, discussed in a subsequent section, is 1 μm over 350 μm length. The uniformity could be improved by pulling the fiber over a constant speed in an automated way.

The splicing process is schematically shown in Fig. 2 using micromanipulation under an optical microscope by two-step processes. Figures 2(a) and 2(b) show the first step of solvent vapor spray to the attached microfiber and the second step of flame brushing treatment, respectively. First, two bisected silica microfibers are temporarily attached at the end through electrostatic force. Next, a piece of polymer microfiber with a diameter slightly smaller than the silica microfiber is obtained from direct drawing process of molten PMMA as discussed previously. The polymer microfiber is tailored to a certain length and transferred to the coupling area of the microfibers via micromanipulation.

![Fig. 1. Schematic illustration of polymer microfiber fabrication using direct drawing method from molten PMMA: (a) cylindrical silica fiber is approaching the molten PMMA; (b) fiber tip is immersed into the molten PMMA; (c) fiber conglomerated PMMA is being drawn out; (d) PMMA microfiber is formed.](image)

![Fig. 2. Schematic diagram of the splicing process of silica microfibers using two-step process: (a) solvent vapor spray; (b) flame treatment; (c) silica microfiber is then spliced together and PMMA microfiber is removed after two-step process.](image)
These microfibers stick together due to electrostatic and van de Waals forces. Then, a solvent vapor is conducted to the splicing area through a capillary tube until the polymer microfiber is completely dissolved and re-solidified to adhere the two microfibers as shown in Fig. 2(a). The purpose of applying solvent (acetone) vapor is to connect both silica microfiber/nanofiber together temporarily through the process and strengthen the structure for the next step. Subsequently, a flame treatment is carried out on the splicing part to remove the polymer microfiber and globule formed on the fiber, which caused scattering loss in signal, and to fuse both microfibers together [Fig. 2(b)]. The two microfibers are now adhered together and tested in water and solvent to ensure they are permanently attached.

3. RESULTS AND DISCUSSION

We found out that PMMA microfiber can be easily fabricated when the solid PMMA is heated at certain temperature that gives appropriate viscosity for the hand-drawn process. Figure 3(a) shows the microscope image of the fabricated PMMA microfiber using this direct drawing technique. Figure 3 illustrates the PMMA fiber that formed after pulling using a silica fiber tip. The big lump seen at the tip is the solidified PMMA that formed when the fiber tip is immersed into the molten PMMA. However only the uniform part of fiber is chosen for the splicing process. During the drawing process, a He–Ne 632 nm laser probes the microfiber for monitoring purposes. As the microfiber surface is relatively smooth, the leakage of light is probably due to dust; bending and transition region are more obvious rather than surface roughness [Fig. 3(b)]. The fabricated microfibers can easily bend and curl, which offers wide range of applications in optical sensors. Figure 4 shows the image of fabricated PMMA fiber under field-emission scanning electron microscopy (FESEM) (Quanta FE450) and Fig. 4 shows the fiber image at higher magnification, which indicates the high uniformity and smooth surface on the fabricated fiber. Figure 5 shows the fabricated microfibers with different waist diameter, which were obtained by varying the temperature of the heating plate and the speed of drawing. The uniform diameter and defect-free surface of the fibers are clearly seen, which make them ideal candidates for photonic applications. PMMA microfibers with diameter ranging from several micrometers to sub-100 nm and lengths up to 30 cm have been drawn by this method.

Two silica microfibers with diameter of 3.8 μm are spliced together with the help of hand-drawn PMMA microfiber of 1.5 μm diameter and length of about 3 mm. For this splicing method, any diameter of fabricated PMMA microfiber can be used, as the polymer will be removed after flame treatment process. Figure 7(a) shows the image of the splicing region after the first step of solvent vapor process. This process would dissolve PMMA and form a liquid droplet shape as a consequence of surface tension; dissolved PMMA gradually solidified when

![Fig. 3. Microscope image of the fabricated PMMA microfiber; (a) PMMA microfiber is formed between the solidified PMMA and the fiber tip; (b) middle part as a red laser is launched into the microfiber.](image)

![Fig. 4. (a) FESEM image on the surface of fabricated PMMA microfiber; (b) higher magnification of the fiber PMMA microfiber.](image)

![Fig. 5. PMMA microfibers with different waist diameter; (a) 8.58 μm; (b) 11.41 μm; (c) 12.56 μm.](image)

![Fig. 6. PMMA microfibers hand-drawn up to 250 mm long.](image)
191 evaporation of solvent occurred and formed a globule that caused serious scattering loss. The formation of globules could be minimized if the diameter of PMMA microfiber is reduced. However, if PMMA microfiber used is too thin, after dissolved process, it becomes harder to adhere to each other [18]. Since the solidified PMMA on the silica microfibers can be dissolved and removed using solvent, the spliced microfibers still can be pulled apart. Therefore, to obtain permanent joint with a reduced loss, a flame treatment process has been carried out. Splicing area is treated with blue flame to fuse the fiber together. Figure 7(b) shows the image of the splicing region after the flame treatment. As seen in Fig. 7, the globule formed on the microfiber can be burned off through this process.

To investigate the splicing loss, we cut a silica microfiber at the waist, splice the two ends together, and compare the transmission spectra before cutting and after splicing. The result is shown in Fig. 8. The transmission spectrum is obtained by launching an amplified spontaneous emission (ASE) light from erbium-doped fiber amplifier (EDFA) into the input silica microfiber and measure the transmitted light from the output microfiber using an optical spectrum analyzer. The spectrum shows ripples due to the resonance in the nonadiabatic microfiber. After the PMMA polymer is attached on the splicing region, a significant splicing loss around 12 dB is obtained in comparison with the spectrum before cut. This loss is attributed to the guide wave, which coupled out due to higher refractive index and attenuation from the absorption of PMMA. Furthermore, the PMMA microfiber might not smoothly attach on the splicing area and formed a globule on the surface of the microfiber.

After spraying solvent vapor and blue flame treatment, the splicing area is now permanently fused through heating process. Permanent splicing is achieved and PMMA microfiber is decomposed due to high temperature. This was tested by pouring excessive amount of acetone on the splicing region to ensure the strength of the joint. As shown in Fig. 8(b), the average splicing loss is about ~0.69 dB within wavelength range from 1520 to 1565 nm and transmission spectra for both shows loss that corresponds with splicing. The gain could be due to the change of fiber profile during flame treatment and this gain overwhelms the splicing loss. In this treatment, flame size was poorly controlled by using acetone as fuel. Such flame size would create uprising air flow that strains and elongates the adhered fibers. Nonadiabatic microfiber profile was changed and affects the transmission spectra. However, improvement can be done by tuning the flame size to be the size of splicing area.

Figure 9 shows the ring resonator fabricated by coiling a tapered of 6 μm diameter fiber with the coupling area spliced permanently using the proposed splicing method. A He–Ne red light source was initiated into a free-standing ring of diameter 2.6 mm in air. Figures 9(a) and 9(b) show the ring resonator that immersed into the water. Figure 10 illustrates the output transmission spectra of ASE light of the fabricated ring resonator. Maximum extinction ratio of the ring is about 4.8 dB, with Q factor and finesse measured to be 6298.04 and 1.407, respectively. Free-spectrum range is 0.171 nm at 1530.5 nm wavelength, which is approximately the calculated value (~0.196 nm).

The splicing technique proposed in this work is simple to use and can be applied to almost all kinds of microfibers with different structures such as ring resonators and Mach–Zehnder...
interferometers. Compared to other splicing methods, apart from simplicity, the whole the experiment can be done through a freestanding operation system. With this splicing technique, robust optical integration of microfibers for functional circuits or devices can be realized. Splicing region is now chemically inert and has remarkable temperature tolerance. As the whole splicing process does not involve any substrate, this technique offered more degrees of freedom in splicing process.

4. CONCLUSION

PMMA microfiber with diameter of 1.5 μm and length of 3 mm has been fabricated by one-step direct drawing process. The microfiber exhibits high surface smoothness and length uniformity. Subsequently, we have demonstrated splicing of silica microfiber with the help of fabricated PMMA microfiber to increase the robustness of the microfiber structure. It was done using two-step process of acetone vapor spray and flame treatment. The permanent splicing was achieved with average splicing loss of around -0.69 dB. We have also fabricated a microfiber ring resonator by coiling a tapered fiber and spliced at the overlap part.

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REFERENCES

Queries

1. COMP: Figures deleted to reduce file size.

2. AU: In the Abstract, does the sentence, “Permanent splicing has been achieved after fusing the silica fiber via flame treatment, and the polymer fiber is removed…,” retain your original intent?

3. CE: Please check and confirm the figure for Fig. 6 is not cited in the article.

Supplementary Material

This article has the following supplementary material items associated with it.