Photopolymer microtips for efficient light coupling between single-mode fibers and photonic crystal fibers

Limin Xiao, Wei Jin, M. S. Demokan, Hoi L. Ho, Hwa-yaw Tam, and Jian Ju

Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Jianming Yu

Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Received February 23, 2006; revised April 7, 2006; accepted April 7, 2006; posted April 10, 2006 (Doc. ID 68344)

A novel method for light coupling between single-mode fibers (SMFs) and small-core photonic crystal fibers (PCFs) is demonstrated. The method is based on growing photopolymer microtips directly on the end faces of SMFs. The shape and size of the tips can be controlled by adjusting the laser power and the exposure time for polymerization to match the mode field to the small-core PCFs. A 5 dB improvement in coupling efficiency between a SMF and a commercial small-core, highly nonlinear PCF is experimentally demonstrated. This compact and efficient butt-coupling method is particularly suitable for PCF gas sensor applications.

OCIS codes: 060.2390, 130.1750, 160.5320, 230.3990, 230.4000.

Photonic crystal fibers (PCFs), because of their freedom in design and novel wave-guiding properties, have resulted in a number of novel devices and sensing applications that are difficult to achieve with conventional step index fibers. To realize the full potential of PCFs, one needs to couple light efficiently from standard single-mode fibers (SMFs) to solid-core PCFs. For PCFs and SMFs that have similar mode field diameters (MFDs), low-loss connections have been achieved by directly splicing them using a conventional fusion splicer[1,2] or a CO_2 laser.[3] For small-core PCFs such as commercial highly nonlinear PCFs with a high air-filling fraction, because of the very poor mode match with SMFs, it is very difficult to achieve low-loss connection by direct splicing.[4,5] To overcome this mode mismatch problem, several methods have been proposed. Yablon and Bise[4] spliced a gradient-index fiber lens and a coreless pure silica fiber between a PCF and a SMF to achieve low loss and high mechanical strength connection. However, this approach is suitable only for PCFs that have MFDs larger than 3.5 μm. In addition, three splices and controlled lengths of fiber lens and coreless pure fiber are required, which makes this method complicated in practical operation. Wadsworth *et al.*[6] tapered PCFs to achieve a small core in the middle part of the PCF to avoid direct connection of a small-core PCF with a SMF. These methods solve the coupling problem with SMFs but also seal the holes of PCFs. Leon-Saval *et al.*[5] integrated a SMF with a PCF during the manufacturing stage of the PCF and achieved a loss of 0.6 dB. However, this method required fabrication of a special PCF preform. In some applications, such as gas or liquid sensing using PCFs,[7–9] it is preferred to use free-space coupling to keep the holes of PCFs open to allow efficient gas diffusion from the environment into the hole columns. Free-space coupling requires the use and alignment of lenses to achieve good coupling efficiency, which makes the fiber connection bulky and impractical. In this Letter we demonstrate the use of a photopolymer microtip directly grown on a SMF to achieve efficient coupling between small-core PCFs and SMFs, while still keeping the holes of the PCFs open, which can allow gas species to get into the hole columns.

The small-core PCFs used in our experiments are NL-3.3-880 and LMA-5 PCFs from Crystal-Fiber A/S. The MFD of NL-3.3-880 at 1550 nm is about 2.2 μm with a numerical aperture (NA) of about 0.41. The MFD and NA of the LMA-5 PCF are 4.1 μm and 0.23 at 1550 nm, respectively. The SMFs used in our experiments are SMF-28 from Corning, and the MFD and NA at 1550 nm are about 10.4 μm and 0.14, respectively. The butt-coupling loss α between a PCF and a SMF, for optimal alignment, may be estimated by

$$\alpha = -20\log\left(\frac{2\omega_{\mathrm{PCF}}\omega_{\mathrm{SMF}}}{\omega_{\mathrm{PCF}}^2+\omega_{\mathrm{SMF}}^2}\right), \tag{1}$$

where $2\omega_{\mathrm{PCF}}$ and $2\omega_{\mathrm{SMF}}$ are, respectively, the MFDs of the PCF and the SMF. The butt-coupling losses for light propagating from SMF-28 to NL-3.3-880 and LMA-5 fibers were experimentally measured at 1550 nm and found to be 8.14 and 3.62 dB, respectively, which agree well with the theoretical estimation given by Eq. (1), i.e., 7.85 and 3.32 dB. The good agreement between the theoretical and the experimental results indicates that the main loss mechanism is due to the poor mode match between the small-core PCFs and the SMFs. In the following, we will report using a photopolymer microtip integrated on the end face of a SMF-28 fiber to reduce the MFD and increase the NA of the light beam coming out from the SMF, so that there is a better match with the small MFD and the large NA of small-core PCFs.

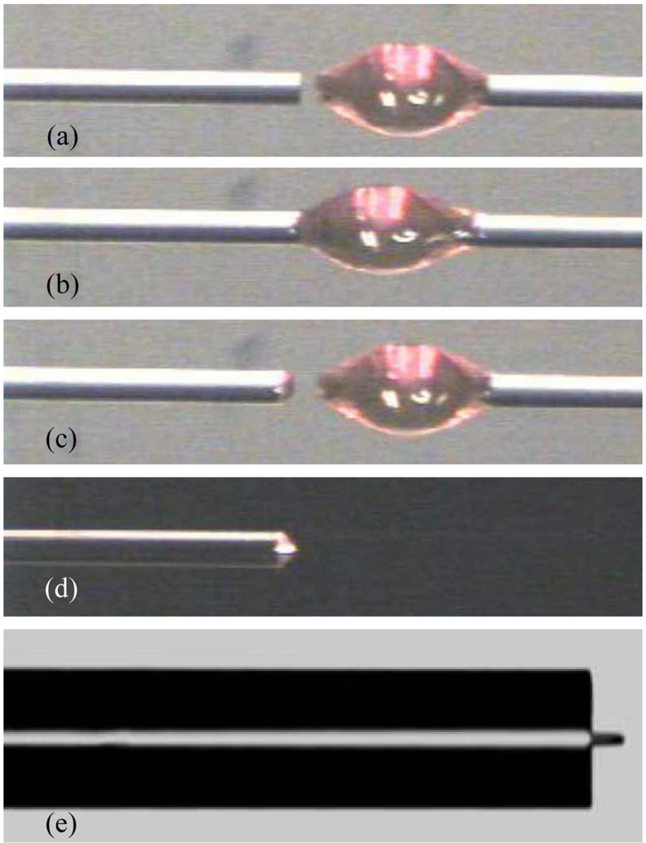


Fig. 1. (Color online) Images of the photopolymer microtip fabrication process: (a) a drop of liquid formulation is deposited at the end part of a SMF that is aligned with a freshly cleaved SMF; (b) the left SMF, which is prepared to grow the tip, is moved to touch the drop; (c) a droplet is deposited at the end face of the left SMF; (d) a green laser with suitable power is coupled from the other end of the left SMF; (e) the liquid that is not polymerized is washed off by a few drops of ethanol.

Bachelot and co-workers[10,11] introduced the method of self-growing photopolymer microtips at the ends of fibers. The detailed principle of the photopolymerizable formulation can be found in Ref. 10. Here we simply introduce our microtip fabrication process. As shown in Fig. 1, a drop of liquid formulation was first deposited at the end part of a SMF, as shown in Fig. 1(a) on the fiber on the right-hand side; a freshly cleaved second SMF that was prepared to grow the tip was then aligned and moved to touch the drop [Fig. 1(b)]; the fiber was then moved away and a convex-shaped liquid was deposited at the end face of the fiber because of liquid surface tension [Fig. 1(c)]. The height of the droplet is about 30 μm, and the shape of the droplet fabricated with this method has good reproducibility. A green He–Ne laser with wavelength 543.5 nm was then coupled from the other end of the fiber, and laser light interacted with the liquid at the end face. As a consequence of polymerization, a tip grew from the core of the SMF within the liquid, as shown in Fig. 1(d). The refractive index of this polymer is 1.52.[10] After exposure, the part of the liquid that did not interact with laser light was washed off by a few drops of ethanol, and a robust microtip was integrated at the end face of the SMF, as shown in Fig. 1(e). The advantages of this microtip fabrication method are its simplicity, controllability, reproducibility, and inexpensiveness. The shape of the microtip can be controlled by adjusting the green laser power, exposure time, and oxygen diffusion concentration.[10,11]

Here we investigated the effect of laser power on the size of the tip growing at the end of the SMF-28 fiber and found the suitable tip to best match the small-core PCF. As the SMF-28 fiber is multimode at the green light wavelength, we applied mechanical stress to attenuate the higher-order modes to only allow the fundamental mode to reach the microtip. The laser power from the fiber was detected before depositing the liquid. When the power is at the level of several microwatts, e.g., 3 μW, the end of the tip is very small and the radius of curvature is very sensitive to the exposure time, as mentioned in Refs. 10 and 11. When the power is above the level of 15 μW, the tip's radius of curvature becomes flat in about 3 s, which can be explained by the polymerization threshold at the air-formulation boundary.[10,11] The oxygen diffusion concentration at the interface boundary is higher than that inside the liquid formulation, hence more energy is needed for polymerization. When the laser power is lower than the polymerization threshold at the air-formulation boundary, the shape of the microtip is sensitive to the exposure time. When the laser power is higher than the polymerization threshold at the air-formulation boundary, the tip's end will be flat in about 3 s. Figure 2 shows two examples of the fabricated microtips. When the laser power is 3 μW and the exposure time is 60 s, the microtip's end is flat, and the diameter of the tip at its base is 11.43 μm and decreases gradually to 2.85 μm at the end of the tip of polymer protrusion over 32 μm length [Fig. 2(a)]. From the dimension of the tip's base, it should be deduced that it is not really single mode at the wavelength 543.5 nm, although we applied mechanical stress to attenuate the high-order modes. When the laser power is 15 μW and the exposure time is 3 s, the diameter of the tip decreases gradually from 11.71 to 5.71 μm over 29 μm length [Fig. 2(b)].

Because the microtip is perfectly aligned with the core of the SMF and the length of the tip is short, only the fundamental mode of the 1550 μm light propagates in the SMF and the tip. The theoretical values of MFD and NA of the tip end in Fig. 2(a) are, respectively, about 2.25 μm and 0.40, which approximately match that of the NL-3.3-880 fiber; the theo-

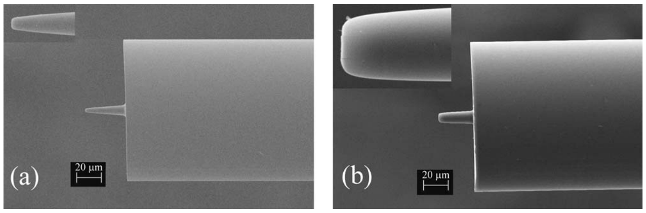
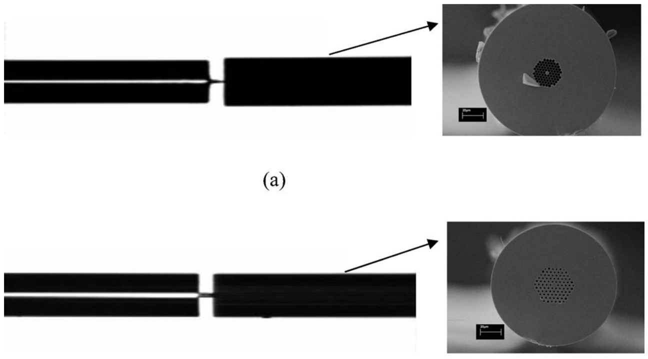


Fig. 2. Scanning electron microscope images of photopolymer microtips fabricated with different green laser power and various exposure times. The insets are close-ups of the ends of the microtips. (a) 3 μW, 60 s; (b) 15 μW, 3 s.

retical loss due to mode mismatch is estimated to be about 0.07 dB between the tip and this PCF, which is calculated from Eq. (1). The theoretical mode mismatch loss between the SMF and the base of the microtip is about 0.27 dB. The theoretical values of MFD and NA of the tip in Fig. 2(b), about 4.20 μm and 0.23, respectively, match the MFD and NA of the LMA-5 fiber, and the theoretical mode mismatch loss is calculated to be about 0.003 dB between the tip and the LMA-5 fiber. However, the theoretical mode mismatch loss between the SMF and the base of the microtip is about 0.22 dB.

To examine the improvement of coupling efficiency by using microtips, we conducted a coupling experiment by using the alignment platform of a commercial fusion splicer. First, the power of the 1550 nm source at the output of a SMF-28 fiber without a polymer tip was measured, and then a PCF with one end coupled to a powermeter was aligned optimally with the SMF-28 fiber to detect the coupling power. The coupling loss thus measured was 8.14 dB when the PCF was NL-3.3-880, and it was 3.62 dB when the PCF was LMA-5. Then the SMF-28 fiber, on which a microtip as shown in Figs. 2(a) and 2(b) had been grown, was spliced at the nontipped end with the output fiber of the source, and the tipped end of the SMF-28 fiber was aligned, in turn, with the small-core PCFs, while keeping the alignment between the PCFs and the powermeter unchanged. Care was taken to touch the PCF fiber lightly with the tip; otherwise it was possible that the tip would be broken, even though the polymer tip is elastic and strong. Figure 3 shows a side view of the aligned SMF/NL-3.3-880 and SMF/LMA5 fiber pairs. The coupling loss was reduced from 8.14 to 2.98 dB for NL-3.3-880 and from 3.62 to 1.80 dB for LMA-5. The reduction of the loss is totally from the improvement of mode match, because the other experimental conditions are the same. The experimental loss is larger than the theoretically calculated value above because of the unperfected edge of the microtip, the interface reflection loss between the microtip and the SMF, the two end-face Fresnel reflection loss of PCFs, and possible misalignment loss. Whether the coupling losses reported above can be reduced further is under investigation.

In conclusion, we have demonstrated using a photopolymer microtip to improve the light-coupling efficiency from a SMF to small-core PCFs. Experiments show that the coupling efficiency can be improved by up to 5 dB compared with direct SMF/PCF joints without using the microtips. This compact and efficient butt-coupling method is particularly suited for SMF/PCF connections for gas sensor applications where holes in the PCF need to be kept open at the joint for easier access to the evanescent field, and this method may also be suitable for connecting a SMF to a PCF with the central hole filled with a liquid sample[8] for liquid sensor applications.


(a)

(b)

Fig. 3. Optical images of butt coupling between SMFs integrated with different-sized microtips and small-core PCFs. (a) Coupling between a SMF with a tip as shown in Fig. 2(a) and NL-3.3-880. (b) Coupling between a SMF with a tip as shown in Fig. 2(b) and LMA-5.

L. Xiao's e-mail address is xiaolimin.ee@polyu.edu.hk.

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