Fusion splicing small-core photonic crystal fibers and single-mode fibers by repeated arc discharges

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We demonstrate a novel method for low-loss splicing small-core photonic crystal fibers (PCFs) and single-mode fibers (SMFs) by repeated arc discharges using a conventional fusion splicer. An optimum mode field match at the interface of PCF–SMF and an adiabatic mode field variation in the longitudinal direction of the small-core PCF can be achieved by repeated arc discharges applied over the splicing joint to gradually collapse the air holes of the small-core PCF. This method is simple and offers a practical solution for light coupling between small-core PCFs and SMFs. © 2006 Optical Society of America

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Photonic crystal fibers (PCFs), because of their novel designs and unique properties, have attracted much attention since they appeared in the mid-1990s.[1] However, low-loss splicing a PCF with a single-mode fiber (SMF) remains a key problem that limits the widespread development of PCF devices and sensors. The splicing loss is, in general, due to two reasons: one is the mode field mismatch between PCFs and SMFs; the other is that the air holes in PCFs at the splice joint are often collapsed during the splicing process, which significantly increases the coupling loss by destroying the light guiding structure of the PCF near the joint interface. For PCFs and SMFs having similar mode field diameters (MFDs), low-loss splices were achieved by minimizing hole collapse using fusion splicers[2,3] or CO_2 lasers[4] to maintain the MFD match; another type of low-loss high-strength splices between large-MFD PCFs and SMFs is to use gradient index fiber lenses.[5] However, these methods are not suitable for small-core PCFs. For splicing small-core PCFs and SMFs, several indirect splicing methods have been proposed, such as tapered intermediate PCFs,[6,7] integrating a SMF with a PCF during the manufacturing stage of the PCF[8] and using microtips.[9] However, special manufacturing platforms needed in these methods limit their widespread applications. Another approach to overcome the coupling problem between small-core PCFs and SMFs is to design small-core PCFs with doped cores,[10] which will guide light even when the air holes are completely collapsed during splicing; however, this will significantly limit the flexibility in PCF design.[5]

Collapsing of air holes of PCFs during fusion splicing is generally considered as a lethal drawback to avoid or minimize. However, for small-core PCFs to be spliced to SMFs, controlled collapse of air holes will reduce, to some degree, the effective refractive index contrast between core and cladding. This will expand the guiding mode field to a desired size to match that of the SMFs, and hence improve the coupling efficiency. Lægsgaard and Bjarklev[11] have numerically investigated the relationship between the collapse of air holes and the splicing loss between PCFs and SMFs and suggested the use of laser irradiation to collapse holes. However, the main experimental challenge[11] is how to control the rate of air-hole collapse and obtain the optimum air-hole size. Here we propose a simple and practical method to control the degree of the air-hole collapse to realize low-loss splicing between small-core PCFs and SMFs by repeated arc discharges.

The principle of the method is to control the collapse of the air holes of the PCF gradually, using a fusion splicer to obtain an enlarged mode field at the interface of the PCF that matches the mode field of the SMF, and at the same time, to optimize the rate of hole collapse in the PCF to achieve an adiabatic mode field variation in the longitudinal direction to reduce the transition loss. The fusion splicing process is shown in Fig. 1. To avoid substantial collapse of the air holes at the end face of the small-core PCF, a single arc discharge with a weak fusion current and a short fusion time is first applied to joint mechanically the small-core PCF and the SMF; a suitable offset as shown in Fig. 1(a) is introduced between the joint and the central axis of the arc discharge to make it easier to control the collapse of the air holes. Figure 1(b) illustrates the temperature distribution near the end of the small-core PCF during fusion splicing. The temperature decreases gradually along the fiber axis away from the splicing joint,[12] which will cause an adiabatic air-hole collapse along the longitudinal direction of the small-core PCF, so an adiabatic mode field enlargement toward the splice interface can be formed. To achieve the optimum mode field match between the PCF and the SMF at the splice interface, as shown in Fig. 1(c), repeated weak arc discharges with a short duration are applied over the splice joint to gradually collapse the holes in the PCF.

The small-core PCFs used in our experiments are LMA-5 and NL-1550-POS-1 from Crystal-Fiber A/S. The MFD and NA of the LMA-5 are, respectively, 4.1 μm and 0.23 at 1550 nm. The NL-1550-POS-1 has an average core diameter of ~2.1 μm. The MFD and NA of the NL-1550-POS-1 are ~2.8 μm and 0.4, respectively, at 1550 nm. The SMFs used in our experiments are SMF-28 from Corning; the MFD and NA at

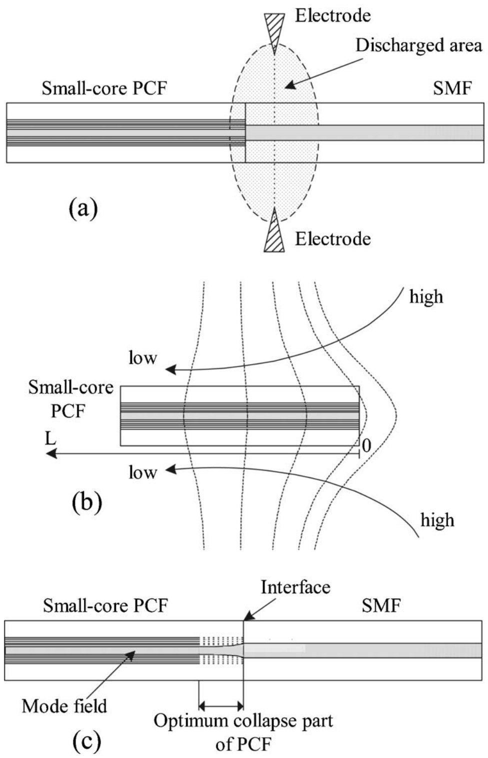

Fig. 1. Illustration of the fusion splicing process: (a) splicing a small-core PCF and a SMF with an offset of the joint to the central axis of arc discharge; (b) the temperature distribution field along the longitudinal direction of the small-core PCF when fusion splicing; (c) a side view of an optimum mode field match at the interface of PCF–SMF and an adiabatic mode field expansion in the longitudinal direction of the small-core PCF.

1550 nm are ~10.4 μm and 0.14, respectively. The butt-coupling loss from SMF-28 to LMA-5 and to NL-1550-POS-1 were experimentally measured to be, respectively, 3.62 and 6.30 dB at 1550 nm, which agree well with the theoretically estimated values of 3.32 dB (Ref. 9) and 5.98 dB. These results indicate that the main loss mechanism is due to the poor mode match between the small-core PCFs and the SMFs.

An Ericsson FSU-975 fusion splicer was used to splice small-core PCFs and SMF-28 fibers. During prefusion, the fiber ends are cleaned by low-level heating, and the main fusion parameters are fusion time 2 and fusion current 2, which are the duration and magnitude of discharge current applied to the electrodes when the two fiber ends are pushed together. Hence we set the fusion time 1 and 3 to zero and then set fusion time 2 to 0.3 s and varied fusion current 2 to perform discharge tests. The prefusion current was set to 5.0 mA instead of 10 mA to avoid significant heat collapse of the holes at the PCF end face. We set the center position to 205, corresponding to an offset distance of 50 μm and set the overlap to 1 μm (instead of 10 μm) to avoid destroying the structure of the PCF during fusion splicing.

The splicing between the LMA-5 and the SMF-28 fibers was first investigated. To illustrate the degree of air-hole collapse, we first observed the end face of the LMA-5 by a scanning electron microscope (SEM) after a different number of arc discharges. The fusion current used was 10.0 mA. By withdrawing the SMF just before the start of the arc discharge, the end face of the LMA-5 fiber was not spliced to the SMF-28 but was only heated by a weak arc discharge that caused the air-hole's collapse to some degree, then we continued to repeatedly apply the same arc discharges to heat the LMA-5. Figures 2(a)–2(d) show the SEM images of the MLA-5 end face after, respectively, two, five, seven, and nine discharges; the time gap between two consecutive discharges is 2 s. We observed that the average hole diameter was 0.83 μm when the number of arc discharges was 2, the hole shrunk to 0.70 and 0.24 μm after five and seven discharges; almost all the holes are closed after nine discharges.

We then performed fusion splicing between LMA-5 and SMF-28. It should be mentioned that the collapse of holes is expected, for the same number of discharges, to be slower during the actual splicing process. This is because more heat will apply to the end of the LMA-5 due to the exposure of the end face when they are not fused together. The splicing losses measured at 1550 nm, for light propagating from SMF-28 to LMA-5, as functions of the number of discharges and the fusion current, are shown in Fig. 3(a). The splicing losses, after a single discharge, are, respectively, 3.38, 3.19, and 2.77 dB for fusion currents of 9.5, 10, and 11 mA. The single discharge splice loss for 11 mA fusion current is considerably lower than the theoretical value (3.32 dB). This is because of the hole collapse induced by the relatively larger current, which enlarges the mode field area and makes it match more to that of the SMF. However, it is difficult to achieve optimal hole collapse and hence minimum splice loss. It would be much easier to apply repeated weak discharges and to optimize the splice loss by controlling the number of discharges. It can be seen from Fig. 3(a) that, for fusion currents of 9.5, 10.0, and 11 mA, the minimum splice loss of 1.1, 0.9, and 1.8 dB can be obtained after 23, 13, and 4 arc discharges. Figure 4 shows that the side views of the splicing joints with 10.0 mA discharge current after 1, 13, and 21 times of dis-

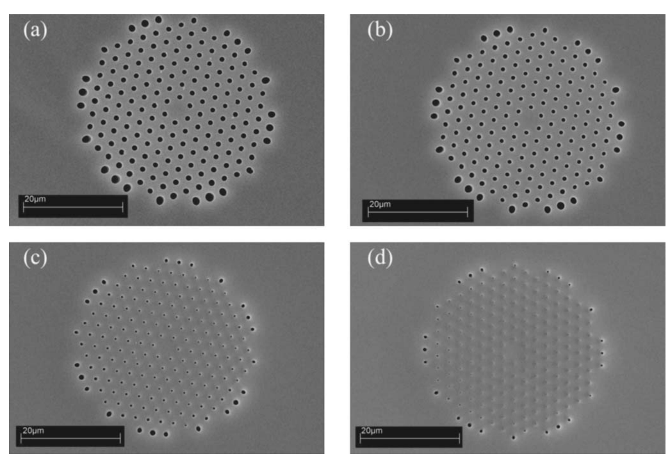

Fig. 2. End views of the LMA-5 after (a) two, (b) five, (c) seven, and (d) nine discharges. The fusion time, current, and offset distance are, respectively, 0.3 s, 10 mA, and 50 μm.

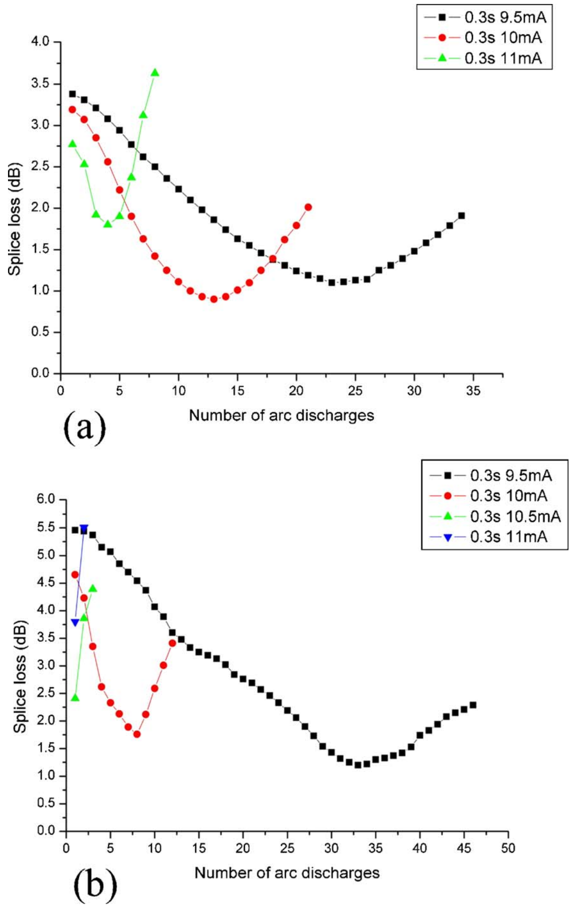

Fig. 3. (Color online) Splicing losses between SMF-28 fibers and (a) LMA-5, (b) NL-1550-POS-1 against the number of arc discharges.

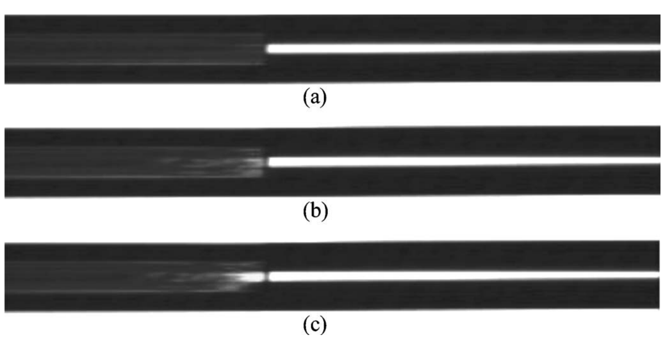

Fig. 4. Side views of the splicing joints between LMA-5 and SMF-28 fibers after (a) 1, (b) 13, (c) 21 discharges. The fusion time, current, and the offset distance are, respectively, 0.3 s, 10 mA, and 50 μm.

charges. In Fig. 4(a), the hole collapse is minimal, and the splice loss is large (3.19 dB) due to the mode field mismatch. In Fig. 4(b), the holes of the PCF collapse to a certain degree that enlarges the mode field in the PCF and optimizes the mode field match between the two fibers and hence minimizes the splicing loss (0.9 dB). In Fig. 4(c), the holes are collapsed significantly, which makes the mode field area in the PCF larger than that of the SMF and hence increases the splice loss. The same method was used to splice NL-1550-POS-1 and SMF-28 fibers. The results are shown in Fig. 3(b).

As expected, the number of arc discharges required to reach the minimum splicing loss was reduced when using a larger fusion current because the degree of air collapse is proportional to the heating power. The use of a smaller fusion current is easier to achieve than the minimum splicing loss by controlling the step of collapsing more precisely. The minimum experimental loss (0.9 dB) obtained may be caused by nonperfect mode field mismatch at the PCF–SMF interface and by the mode field expansion (transition) loss in the gradual hole-collapsing part of the small-core PCFs. Because of the short transition length as can be observed from the side views of the collapsed part in Fig. 4(b), the mode field transition loss may not be neglected. We believe the splicing loss should be further reduced by optimizing the transition length through the use of a wider electrode gap as has been used in splicing the SMF and the small-core Er-doped fiber.[13]

In conclusion, we demonstrated a novel method for low-loss splicing small-core PCFs and SMFs. By applying repeated arc discharges over the splicing joint after the initial arc discharge to gradually collapse the air holes of the small-core PCF, an optimum mode field match at the interface of PCF–SMF and an adiabatic mode field transition in the longitudinal direction of the small-core PCF can be achieved.

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