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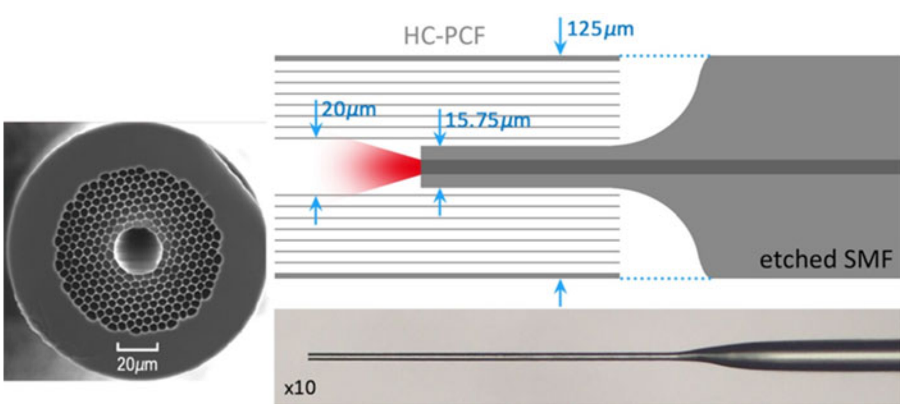
Danyun Fan
Zhiqiang Jin
Guanghui Wang
Fei Xu
Yanqing Lu
Dora Juan Juan Hu
Lei Wei
Ping Shum
Xuping Zhang



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Extremely High-Efficiency Coupling Method for Hollow-Core Photonic Crystal Fiber

Danyun Fan,[1,2] Zhiqiang Jin,[1,2] Guanghui Wang,[1,2] Fei Xu,[2] Yanqing Lu,[2] Dora Juan Juan Hu,[3] Lei Wei,[4] Ping Shum,[4] and Xuping Zhang[1,2]

[1]Institute of Optical Communication Engineering, Nanjing University, Jiangsu 210009, China
[2]College of Engineering and Applied Sciences, Nanjing University, Jiangsu 210093, China
[3]Institute for Infocomm Research, A*STAR, Singapore 138632, Singapore
[4]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore.

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Abstract: We report a novel low-loss splicing approach for hollow-core photonic crystal fiber (HC-PCF) and conventional single mode fiber (SMF) by inserting an etched SMF tip into the hollow core. If the divergence solid angle (DSA) of the inserted fiber tip is smaller than the guiding solid angle (GSA) of HC-PCF, all the radiated optical power from the tip will be collected by PCF with an extremely high coupling efficiency and guided by the PCF based on photonic bandgap effect. A DSA-GSA matching model is proposed to calculate the efficiency for different splicing situations. In the optimal condition of GSA $>$ DSA, the transmission loss could approach zero, only including the scattering loss of etched fiber. Then, we experimentally demonstrate the splicing between NKT HC19-1550-01 and SMF-28 with coupling efficiency of 84.5%, agreeing well with the theoretical result of 85%. In addition, our proposed method is coaxiality error free, angle deviation free, and insertion length insensitive. This new technique is expected to provide new possibilities in some special system designs for HC-PCF-based applications.

Index Terms: Fiber optics, fiber optics sensors, photonic crystal fibers, fiber optics components.

1. Introduction

Since the conception of hollow-core photonic crystal fiber (HC-PCF) was proposed, due to its flexible structures and tunable optical guiding properties, numerous relevant applications have sprung up in optical communication [1], optical sensing [2], [3], etc. Often inevitably, the issue of coupling HC-PCF with conventional single-mode fiber (SMF) is involved in most application systems. When come to this point, the transmission efficiency of the coupling is of most importance. To minimize the loss, apart from the choice of free space coupling which is not suitable for integration design, researchers have paid a lot of efforts in designing the fiber geometry [4], reducing the splicing microhole

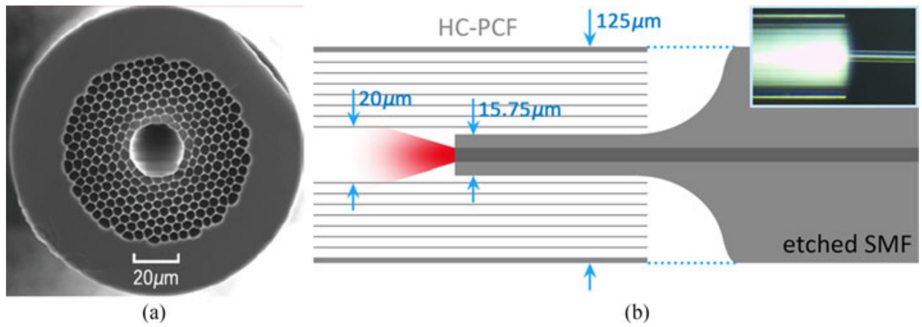

Fig. 1. (a) Cross-sectional view of the HC-PCF [10]. (b) Schematic diagram and experimental photo of the etching and inserting structure.

collapse [5], finding the mode-matched fiber [6], etc. In theory, mode field overlap calculation [7] or vector model [6] is commonly used in transmission analytical calculation of mode mismatching loss. Fusion splicing is one of the most popular methods in the HC-PCF/SMF coupling. To date, several investigations concerning the fusion splicing loss have been demonstrated. However, in practice, the butt joint displacement or the microhole deformation still exists in the fusion splice method. Furthermore, in order to reduce the modes mismatching and minimize the loss, a suitable intermediate fiber should be introduced for mode transformation. This process is very complicated and the yield rate is low. In addition, in some special applications [8], [9], the fusion method is not applicable. Usually, free space coupling is chosen, but the overall system integrity and flexibility is reduced.

In this letter, a novel coupling method between HC-PCF and SMF is proposed [see Fig. 1 (b)], by inserting an etched SMF tip with thinner cladding into the hollow core of PCF. Considering the HC-PCF's photonic bandgap mechanism, if the divergence angle of fiber tip is smaller than the numerical aperture angle of PCF, all the radiated light from tip will be collected and constrained within the hollow core. In this case, the coupling mechanism is very different from commonly used fusion or mechanical splicing method. Instead of mode overlap analysis, the divergence solid angle of light and numerical aperture solid angle matching theory is applied in this work. Theoretical calculation shows that the coupling loss is extremely low in our method. Furthermore, in the fabrication, the mode mismatching loss, microhole deformation induced scattering loss and coaxiality error are no longer the major issues in the design. Our method could provide an open, designable and universal approach for the coupling of single mode fiber and hollow core PCF, with very small coupling loss.

2. Coupling Efficiency Evaluation

First of all, the concept of numerical aperture (NA) in HC-PCF needs to be clarified. Different from the index-guiding photonic crystal fiber, the HC-PCF guides light using the photonic-bandgap mechanism rather than the total internal reflection mechanism. Given the geometry of fiber and the incident wavelength, we can determine the wavenumber k supported in HC-PCF. Then the largest angle $\theta_{\max}$ between k and fiber z-axis determines the value of NA, which is equal to $\sin\theta_{\max}$ [11]. The guiding area consisted of all the supported wavenumber is actually a solid angle, and we nominate it as PCF guiding solid angle (GSA). In the other way, the inserted fiber tip with thinner cladding introduces a light source inside the hollow core. For simplicity, it can be regarded as a point light source from the perspective of far field plane. Correspondingly, the solid angle consisting of all the radiated wavenumber from SMF tip is named as divergence solid angle (DSA). It is obvious that only the power in the intersection part (DSA ∩ GSA) could be coupled from SMF tip to HC-PCF, as shown in Fig. 2(a). Then, the coupling efficiency f could be simply expressed as

$$f = \frac{P_{\mathrm{DSA} \cap \mathrm{GSA}}}{P_{\mathrm{DSA}}} \tag{1}$$

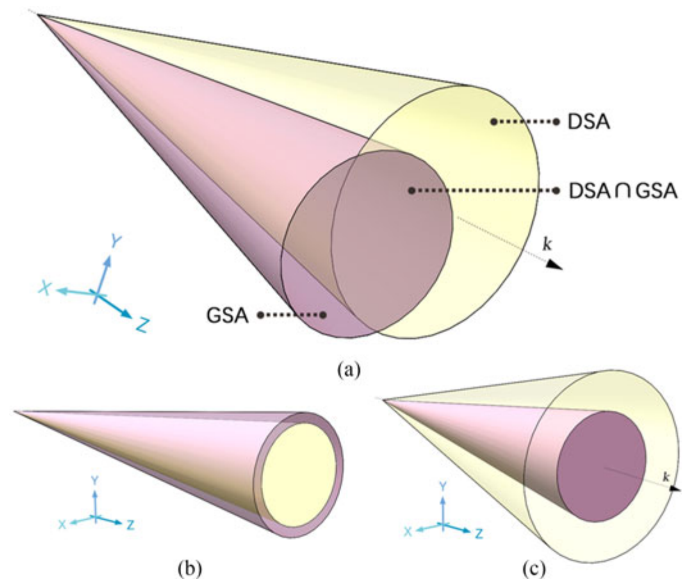

Fig. 2. Three-dimensional view of the DSA (the yellow solid angle) and GSA (the red solid angle) matching theory. Overlap area determines the coupling efficiency. (a) Axis angle deviation situation. (b) Optimal situation: GSA ≥ DSA. (c) Normal situation and the coaxiality error situation.

where P_{DSA} is the whole power radiated from fiber tip, while $P_{\mathrm{DSA} \cap \mathrm{GSA}}$ is the power in the intersection region, which could be collected by HC-PCF. Fig. 2(b) is the optimal situation where the GSA is larger than the DSA. In this way, all light could be collected by the HC-PCF, and it introduces nearly no coupling loss. Then taking the Fresnel reflection loss into consideration, it brings about 0.15 dB transmission loss at the fiber/air interface.

Traditionally, the theory of coupling is based on the mode field overlap calculation [6], [7]. Therefore, the coaxiality error and the axial angle deviation between fibers are primary factors in splicing loss. For the first kind of loss, the situation is different with our structure. The coaxiality error only introduces a displacement of the spot light source in the emitting surface, while the incident angle of any radiation beam keep unchanged as shown in Fig. 3(a) and (b). Due to the photonic bandgap mechanism, the confinement properties and guiding condition of the photonics bandgap structure for each incident beam keeps constant. No light in the cone of GSA can escape. Since the diameter of the fiber tip is slightly smaller than the hollow core size, the coaxiality error does not introduce extra loss in this coupling structure.

The second kind of loss for traditional splicing is axial angle deviation between two fibers' axis. Correspondingly, in our case, we need to consider the axial angle deviation between GSA and DSA. Under this circumstance, the intersection area of DSA and GSA, which is corresponding to the coupling efficiency, will change with the axis angle deviation shown in Fig. 2(a). The larger the axial angle deviation between GSA and DSA is, the smaller the intersection area and the coupling efficiency are. To quantitatively evaluate the coupling efficiency, we analyze the evolution of light beam radiated from the fiber tip, using Finite-difference time-domain (FDTD) method. The far field electric intensity distribution and its corresponding DSA are shown in Fig. 4. In other words, with the value of numerical aperture of HC-PCF, we can have the GSA cone, within which all the light beam could be guided. Both solid angles have a projection on a plane perpendicular to the fiber tip axis. With the parameter of axial angle deviation, the contour line of the GSA projection could be expressed as the curve S_p:

$$x^2 + (y\cos\theta - h\sin\theta)^2 = (y\sin\theta + h\cos\theta)^2 \tan^2\varphi \tag{2}$$

where θ is the axial deviation angle, φ is the half-angle of GSA cone, and h is the length from light source to the far field plane.

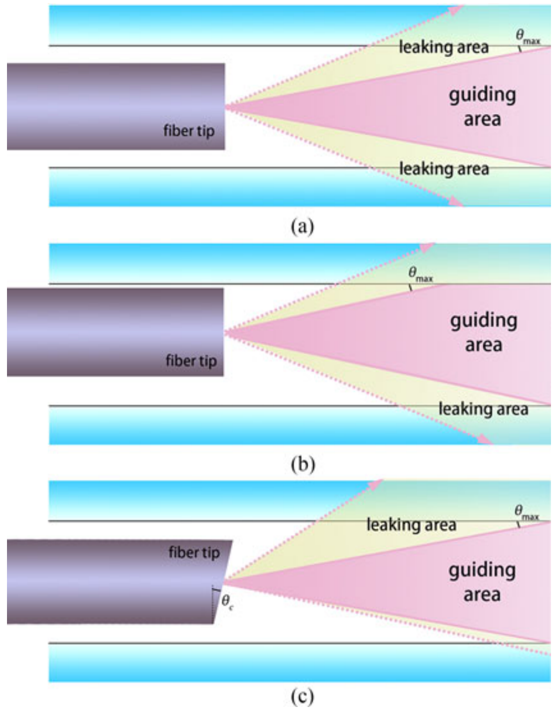

Fig. 3. Two-dimensional schematic diagram of the DSA (the yellow area) and GSA (the red area) matching theory. The overlap area determines the coupling efficiency. (a) Normal situation. (b) Coaxiality error situation. (c) Tip verticality deviation situation.

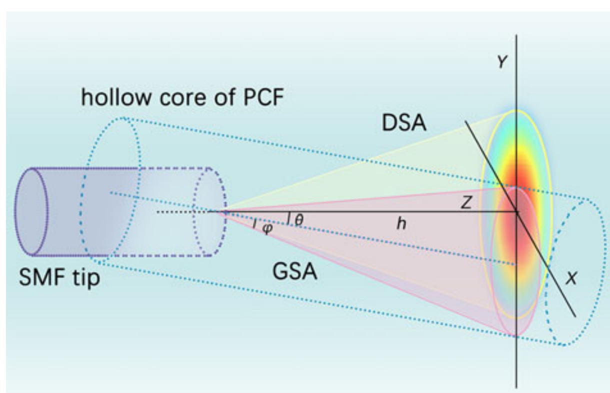

Fig. 4. Far field electric intensity distribution of the light from the fiber tip (FDTD) and projection surface integration calculation.

After a surface integration on their intersection region, we can obtain the total power collected by PCF, $P_{DSA \cap GSA}$. Then, with unit input power, the coupling efficiency calculation according to (1) is followed up with

$$f = \iint_{S_p} E^2(x, y)\, dx dy \tag{3}$$

where $E(x, y)$ is the far field electric intensity distribution. For example, with the fiber tip of common used Corning SMF-28, and a widely used HC-PCF with NA of 0.13 (HC19-1550-01, NKT Photonics), the coupling efficiency for different axial deviation angle is plotted in Fig. 5. The minimum theoretical

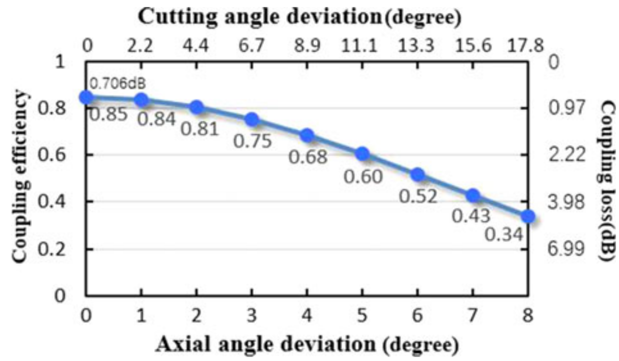

Fig. 5. Theoretical calculation of the coupling efficiency influenced by axial angle deviation between GSA and DSA.

loss is about 0.706 dB, since the divergence angle of SMF-28 is slightly larger than 0.13 rad. From the figure, we can see that the angle deviation affects a lot in this coupling structure, and only 6 degrees of deviation may induce a 3 dB coupling loss. Fortunately, thanks to our structure design, where the SMF tip has a diameter very close to the HC-PCF's core diameter. This inserting structure only allows a little inserting angle deviation, which guarantees the high efficiency coupling.

After inserting the fiber, the inserting axial angle deviation between two fibers' axes can lead to the same angle deviation between GSA and DSA. Similarly, the deviation of fiber tip cutting angle can also introduce an effective axial angle deviation between GSA and DSA. When the SMF tip's cutting angle is not absolutely vertical, due to the Snell 's Law, the radiated beam will be refracted with a DSA deviation as in Fig. 3(c). If the cutting angle deviation of the tip is θ_c, the corresponding axial angle deviation of DSA θ could be expressed as

$$\theta = \arcsin(n \sin\theta_c) - \theta_c \approx \theta_c(n - 1) \tag{4}$$

where n is the tip's refractive index of silica ($n = 1.45$). Since the angle deviation is very small, the beam deviation angle θ is proximately equals to 0.45 times of θ_c, which is quite smaller than the actual cutting angle. The relation between cutting angle and the coupling efficiency is also shown in Fig. 5, as the upper x-axis. From the figure, even with 11 degrees of cutting angle deviation, it only has a loss smaller than 2.22 dB.

3. Experimental Results

In addition, the sidewall scattering is critical for etched fiber, which may introduce tremendous loss especially for rough surface case. Due to the etching mechanism, the etched surface roughness is unavoidable. In order to reduce the surface roughness, some etching technologies have been investigated [12]. In the experiment, highly diluted HF is used to guarantee the surface quality. As shown in Fig. 6, a bent SMF is immerged in 10% hydrofluoric acid at 45 centigrade. Furthermore, in order to reduce energy leakage, the thickness of thinner cladding should be much larger than the incident wavelength in silica medium. Tests show that if the thickness is more than 3 μm, the scattering loss could be negligible, and in this condition, the mode profile of SMF can still be preserved. Under the precondition that the fiber tip could be inserted into the hollow core, the gap between fiber tip and the sidewall of hollow core should be as small as possible, in order to minimize the axial angle deviation. So, our method is insertion angle free. Those commonly encountered problems in fusion splice method such as coaxiality error and axial angle deviation are not the issue in our inserting method. In experiment, under the real time microscope observation system, the SMF is etched down to around 16 μm, which is just smaller than the hollow core of PCF of 20 μm. From the experimental measurement, the transmission loss of this 10 mm etched SMF is only about 0.054 dB. The result certainly meets our requirements.

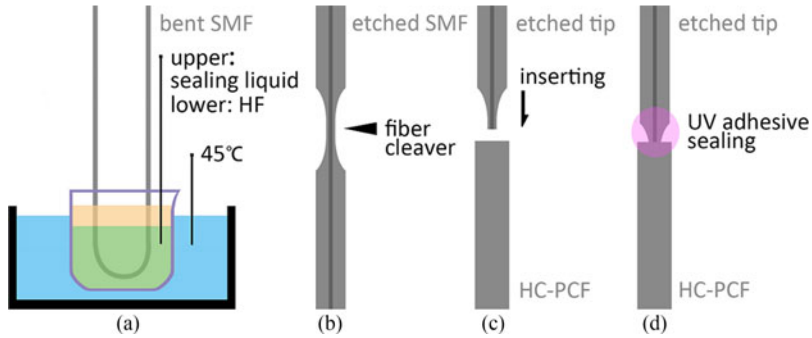

Fig. 6. Experimental process for the new splice method (from left to right). (a) Etching. (b) Cutting. (c) Inserting. (d) Packaging.

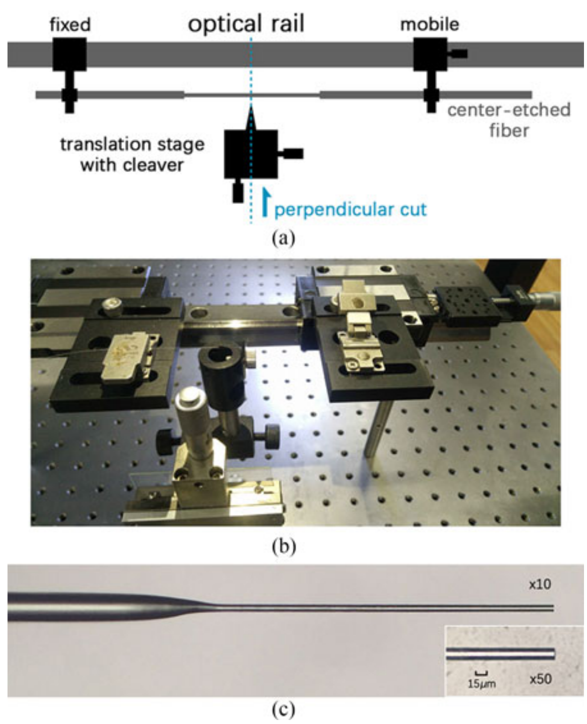

Fig. 7. Homemade microfiber cutting platform. (a) Schematic diagram of the platform design. (b) Experimental cutting platform. (c) Thinner cladding microfiber tip cut on the platform.

With the thinner cladding fiber of tens micrometers in diameter, tip cutting is another problem. Traditional fiber cleaver is not fine and accurate enough. A Focused Ion Beam (FIB) was used for microfiber cutting by some other research group, but the yield is low and very expensive [13]. We setup a microfiber cutting platform as shown in Fig. 7(a) and (b). An optical rail and a displacement table are used to straighten the etched fiber and achieve the vertical cleaving of this extremely thin fiber. A segment of SMF with a middle-etched region is settled on the optical rail by pair of fiber clamps. One of them is slidable along the rail to straighten the fiber with suitable tension. And a translation stage is used to fix the cleaver, which is moving perpendicularly to cut the microfiber gently. Finally, a light knocking can break the microfiber with a very smooth cutting surface. Shown in Fig. 7(c) is the etched SMF tip we achieved. Our method is a simple but general method for microfiber cutting.

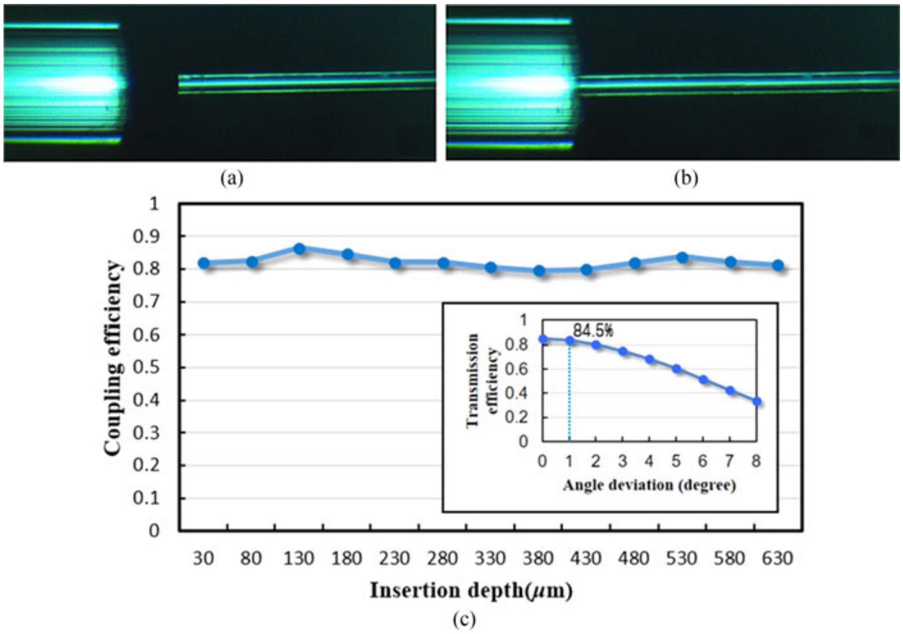

Fig. 8. Tip insertion process. (a) Before inserting. (b) Inserted. (c) Measured coupling efficiency at different insertion depths. (Inset) Corresponding 1 degree insertion angle deviation.

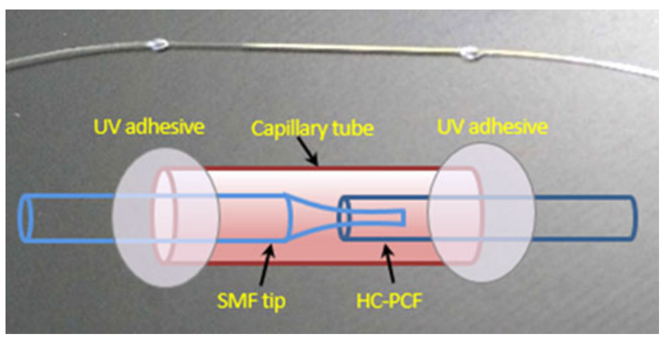

Fig. 9. Schematic diagram and the real photo of the packaging structure, which is protected by a capillary tube.

In the inserting step, it should be carried out on a pair of translational stages with the help of two microscopies. As shown in Fig. 8(a), even there is a small axial angle deviation between fiber tip and PCF, our method have the self-correcting ability. Because the size of etched SMF tip is a little bit smaller than the hollow core of PCF, the deviation could be gradually reduced during the inserting process (see Fig. 8(b)). The influence of axial angle deviation is minimized in our method. Now, the overall coupling loss is about 0.786 dB. Not including the loss of fiber tip etching, the pure loss of this inserting structure is about 0.732 dB. This agrees well with the theoretical prediction mentioned previously (0.706 dB), and in our case this loss is induced by the mismatch of GSA and DSA (GSA $<$ DSA). The 0.26 dB gap between the experiment result and the optimal case is corresponding to the axial angle deviation between GSA and DSA of 1 degree. From the physical aspect, we can conclude that the extra 0.26 dB loss in the experiment actually is induced by 1 degree of the inserting axial angle deviation between two fibers' axes, or 1.45 degree of the deviation of fiber tip cutting angle. Furthermore, our method also has the merit of inserting depth insensitive. No matter how long you inserted, the coupling efficiency keeps constant as in Fig. 8(c). Therefore, such tiny deviation after inserting shows our method is not only insertion angle free, but in addition, insertion length insensitive, suggesting high stability. Moreover, the coupling efficiency could be extremely high for the optimal condition. Even in our experiment with GSA $<$ DSA, the coupling efficiency of 84.5% is also very close to the theoretic limit of 85%, and also comparable with traditional fusion splice records [6], [14].

Packaging of the device is also very important for a practice application. As shown in Fig. 9, the inserting structure is protected by a capillary tube, and both sides are sealed with UV adhesive. In practical applications, this packaging part could be designed as needed. The photo of the packaged device shows that this coupling device is very compact and robust.

4. Conclusion

In conclusion, considering the HC-PCF's photonic bandgap mechanism, we proposed a novel splicing method between HC-PCF and SMF by etching and inserting. Also, we introduced a DSA and GSA matching theory to analyze its coupling efficiency, and its extremely high coupling efficiency for HC-PCF is guaranteed. Furthermore, we do not need to worry about the coaxiality error, axial angle deviation and the splicing microhole collapse. The experimental results match well with the theoretic prediction. For the splicing between NKT HC19-1500-01 and SMF-28, the experimental coupling efficiency is 84.5%. While, it is 85% based on DSA and GSA matching theory. We can further predict that this 0.5% difference is most probably induced from the cutting angle deviation of fiber tip. In the optimal condition with GSA $>$ DSA, the transmission loss could approach zero, only including the scattering loss of etched fiber. It offers a novel way for HC-PCF to achieve extremely high coupling efficiency coupling, which provides new possibilities in some special HC-PCF application system design.

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