Ultralow-Loss, Plug-and-Play Hollow-Core Fiber Interconnection

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Abstract: An ultralow-loss, plug-and-play single-mode hollow-core fiber (HCF) connector is developed. Insertion loss of 0.13 dB and 0.10 dB for HCF to itself @1550 nm and to a standard single-mode fiber @1489 nm, respectively, is demonstrated.
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1. Introduction

High-performance, convenient interconnection between single-mode hollow-core fibers (HCFs) and conventional single-mode solid-core fibers (SCFs) is highly demanded for developing the future HCF-based communications, all-fiber gas- or liquid- lasers, high-power laser delivery, as well as remote sensing. Current HCF interconnection techniques include arc discharge fusion splicing [1, 2], fiber array (FA) assembly [3, 4], and fiber connector [5]. However, fusion splicing technique does not allow functional coating (e.g., anti-reflection coating) at end facets. As a result, the Fresnel reflection is hardly eliminated. In addition, case-by-case optimization to splicer parameters is ineluctable for HCFs that have various outer diameters and air filling ratios. The difficulty of FA assembly lies in the complicated 5-axis (X, Y, Z, pitch, and yaw) adjustment, which needs a high precision positioning stage and skillful operation. Moreover, both fusion splicing and FA assembly offer only permanent interconnection between fibers, which are single-use components. The third method of HCF interconnection is based on a connector-style arrangement [5]. Comparing with FA assembly, the drawback of this method is the lack of position adjustment. Considering the poor core-clad concentricity and the random offset of HCF relative to the ferrule axis, the best-ever reported insertion loss (IL) of this method is 0.3 dB between a hollow-core photonic bandgap fiber (PBGF) and a custom-made large mode area single-mode fiber (SMF) [5].

In this study, in order to reduce the lateral offset, we develop a new method for fabricating HCF connectors and multi-orientation mating sleeves to connect fibers with extra rotation freedom. Interconnection losses of 0.13 dB for a CTF-to-itself joint @1550 nm and 0.10 dB for a CTF-to-SMF-28 joint (or vice-versa) @1489 nm are reported.

2. Design and Fabrication

Considering two single-mode optical fibers, one SMF-28 SCF and the other conjoined-tube HCF (CTF for short), the fundamental mode field profiles are simulated by using COMSOL Multiphysics. The structural parameters of the CTF are taken from Ref. [6] with the core diameter of 30.5 μm. As depicted in Fig. 1(a), the Gaussian fits to the intensity profiles yield the mode field diameters (MFDs, measured at the $1/e^2$ of the peak intensity) of the two fibers to be 10.4 μm and 27.9 μm, respectively. When two fibers are butt coupled, the deviations in the three translational and the two rotational degrees of freedom need to be minimized [Fig. 1(b)]. Assuming an ambient refractive index of $n_{amb} = 1$, Figs. 1(c) and 1(d) calculate the coupling losses (in unit of dB) as a function of the lateral/longitudinal offsets (x, y, z), the tilting angles (θ, ϕ), and the ratio of the two MFDs (w'/w). It is clearly seen that in order to keep the coupling loss in a low level (e.g., < 0.5 dB or < 0.25 dB), the tolerance to the 3 displacement deviations in the CTF is much greater than in SMF-28, while the tolerance to the 2 angle deviations in the CTF is smaller than in SMF-28. This can be attributed to the fact that the MFD of the CTF is larger than SMF-28 and indicates that the primary challenge of a low-loss HCF/SMF-28 joint will be to minimize the angle deviations.

A fiber-optic mating sleeve together with two fiber connectors not only provide plug-and-play interconnection but also enable auto-collimation of two fiber ferrules. As shown in Fig. 2, when a fiber is inserted into a 10.5 mm ferrule, the mismatch between the bore size and the fiber outer diameter may result in tiny offset (e.g., d ~ 10 μm) or tilt (θ ~ 0.002 rad) of the fiber axis. However, according to the calculation in Fig. 1(f), if the mode-field discrepancy of the two fibers (in both diameter and shape) can be neglected, such a small angle tilt will not yield a big loss. Therefore, the connector-style interconnection provides a convenient solution for precise angle alignment, actually constitutes the most difficult and time-consuming step in other HCF interconnection techniques.

To fabricate a HCF connector, the HCF end facet must be protected from contamination. As outlined in Fig. 3, we design a funnel structure on the end of a ceramic ferrule to inhale glue. After flat cleaving the protruding segment of the HCF, a UV-curable glue is adhered on the outer surface of the fiber. Then, the HCF is pulled back into the flush position and the glue is cured by an UV lamp.

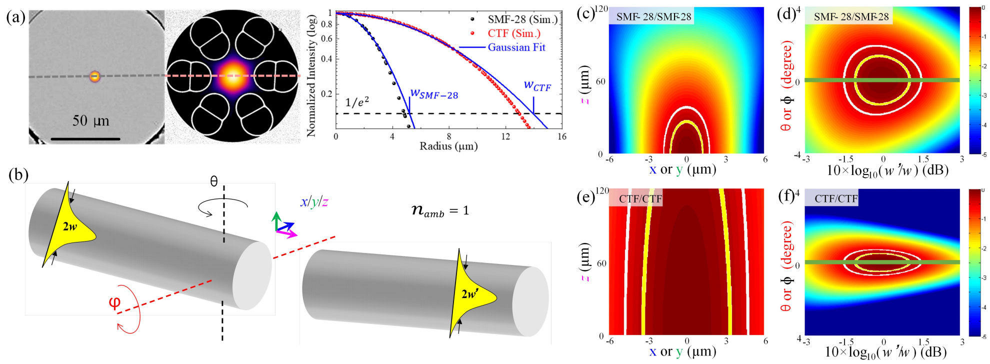

Fig. 1. (a) Scanning electron microscope images, simulated mode fields, and intensity profiles (along the marked axes) of a SMF-28 and a CTF. (b) Sketch of fiber alignment, which involves 3 translational and 2 rotational degrees of freedom. (c-f) Calculated coupling losses (in unit of dB) of two SMF-28 and of two CTFs as a function of the structural parameters. In (c, e), θ, ϕ = 0 and $w' = w$. In (d, f), x, y, z = 0. The white and the yellow contours represent the losses of 0.50 dB and 0.25 dB, respectively. The green bands represent |θ, ϕ| < 0.002 rad.

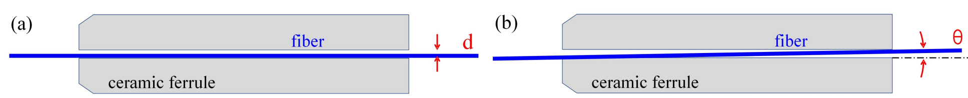

Fig. 2. (a) Offset and (b) tilt of an optical fiber inside a ceramic ferrule.

After fabricating two connectors for CTF with the outer diameter of 290 μm, our efforts are paid to reduce the lateral offset. A fiber-optic mating sleeve with 3 × 4 key slots [see Fig. 4(a)] is machined. These slots are uniformly arranged over the full azimuthal angles, providing 12 optional lateral offsets (Δd, as shown in Fig. 4(b)). Ignoring the longitudinal separation and the angular tilt of the two CTFs and using the formula of coupling coefficient $T=(\frac{2w_1w_2}{w_1^2+w_2^2})^2\exp[\frac{-2(\Delta d)^2}{w_1^2+w_2^2}]$ [7], the IL can be approximately expressed as $\exp[-\frac{d_1^2+d_2^2-2d_1d_2\cos(\varphi)}{w^2}]$, with $w_{1,2} = w \approx$ 27.9/2 μm and the two biases of the CTF cores relative to the central axis being $d_{1,2}$. As depicted in Fig. 4(c), the experimental results of the IL at 1550 nm agree well with the fit line derived from d_1 = 6.5 μm and d_2 = 4 μm. Invoking Fig. 1(e), the multi-slot mating sleeve offers a simple but effective solution for decreasing Δd. Here, two 10.5 mm-long ceramic ferrules with the bore diameter of 300 μm have been used.

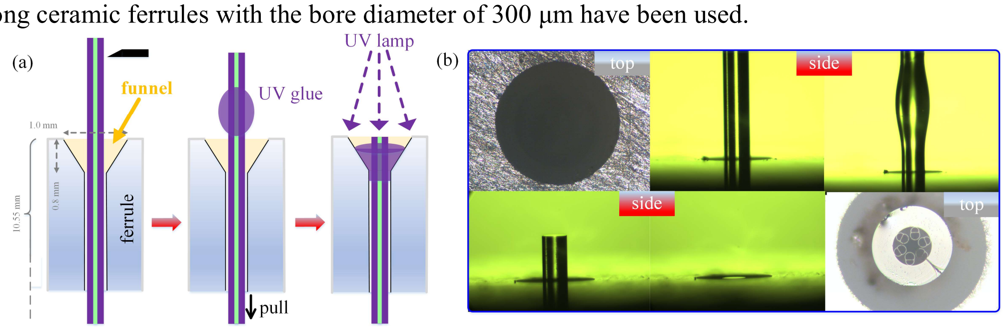

Fig. 3. (a) Flow chart and (b) photographs of the assembling procedure of a CTF connector.

3. Measurement

Repeated plugging test has been conducted to the above CTF-to-itself joint. As shown in Fig. 4(d), the best IL is measured to be 0.13 dB with the standard deviation of 0.03 dB. The blue dashed line in Fig. 4(d) represents a PBGF-to-itself fusion splice with the record IL of 0.16 dB [2]. The IL of our CTF-to-itself joint seems difficult to further decrease, probably because of the misalignment of two hexagonally-shaped mode fields.

By using TEC fiber mode-field adapters (MFA), several low-loss CTF/SMF-28 joints have been fabricated. Our TEC fiber MFA is a heat-treated SMF-28 with the expanded MFD of ~30 μm at 1550 nm. In order to minimize the Fresnel reflection at end facets of the SMF-28, TiO_2/TaO_2 8-layer AR coatings are deposited on both ends of a TEC SMF-28. In principle, the Fresnel reflections at two glass-air interfaces amount to an IL of ~0.30 dB. Fig. 4 (e) shows the measured ILs from CTF to SMF-28 as a function of the relative rotation angle. The minimum IL at 1550 nm is 0.22 dB (0.20 dB from SMF-28 to CTF). It is worth to mention that in order to exclude higher order modes from our measurement, the CTF length has been chosen to 180 m.

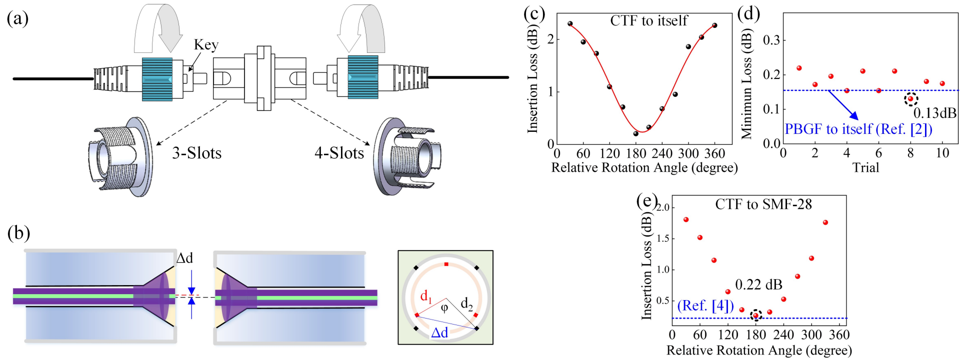

Fig. 4. (a) Schematics of a 3×4 slot mating sleeve and two CTF connectors with funnel-shaped structures on their ends. (b) Illustration of the 12 optional relative positions of two CTF cores. (c) Measured ILs of a CTF-to-itself joint versus the relative rotation angle. (d) Minimum ILs of 10 plugging trials. (e) Measured ILs of a CTF/SMF-28 joint versus the relative rotation angle. A TEC fiber MFA and two AR coatings are used.

Our HCF interconnection is further modified by discarding the metal shell [see Fig. 5(a)], which not only decreases the weight of a CTF/SMF-28 joint to ~1.5 g, but provides continuous angular adjustments. Using such miniaturized joints, a SMF-28/CTF/SMF-28 chain with a ~0.6 m CTF in the middle exhibits a total loss of 0.19 dB @1489 nm, corresponding to the lowest-ever reported IL of ~0.10 dB per interface. Here, we have used two TEC fiber MFAs and AR coatings. The measured IL has approached the limit of 0.074 dB (according to our simulation) and is even lower than that of a CTF-to-itself interconnection.

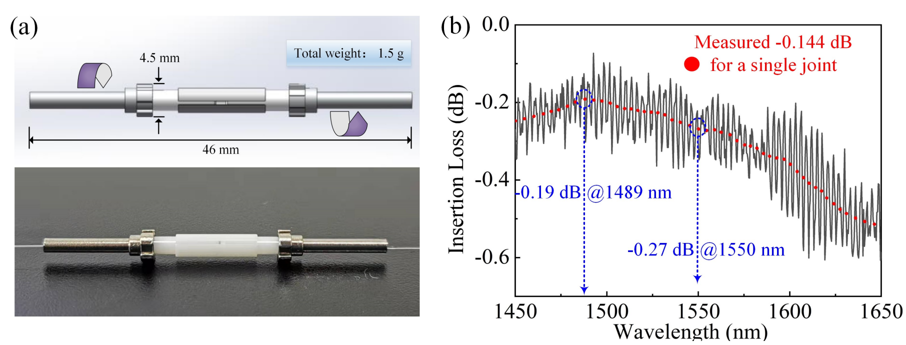

Fig. 5. (a) Miniaturized ferrule mating sleeve providing for continuous angular adjustment. (b) Loss spectrum of an AR-coated SMF-28/TEC/CTF/TEC/SMF-28 chain with a ~ 0.6 m CTF in the middle, the red solid dot denotes the measured loss of a single CTF/SMF-28 joint.

4. Conclusion

An HCF interconnection technique featured with simultaneously having ultralow loss, pluggability, and low cost is developed. Record-low ILs of 0.13 dB in CTF-to-itself joint @1550 nm and 0.10 dB (in average) for CTF/SMF-28 (SMF-28/CTF) joint @1489 nm have been realized. Such a low IL, plus the plug-and-play property, indicate that the HCF interconnection technique has been ready for real-world field applications.

5. References

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