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Study on thermal splicing of ZBLAN fiber to silica fiber

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Abstract. The precise control of the thermal splicing temperature of ZBLAN fiber and silica fiber was guaranteed by theoretical simulation, analysis, and experimental optimization. The thermal splicing model was established, and optimized thermal splicing parameters were obtained based on the simulation results. The thermal splicing parameters were finely repeatedly tuned and optimized further in the thermal splicing experiments according to simulation parameters. The achieved loss was measured to be about 0.3 dB in the thermal splice experiments. The offset thermal splicing method demonstrated a repeatable, low-loss, and promising technique for the splice of ZBLAN fiber to silica fiber. [DOI: 10.1117/1.OE.55.10.106119]

Keywords: ZBLAN fiber; silica fiber; thermal splicing.

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1 Introduction

ZBLAN fiber is one kind of fiber which has a glass composition of $ZrF_4 - BaF_2 - LaF_3 - AlF_3 - NaF$, so it is also called the heavy metal fluoride fiber. ZBLAN fiber has a broad optical transmission window from 0.25 μm in the ultraviolet to ∼7 μm in the midinfrared,[1] whereas the transparent transmission window for silica fiber is limited to ∼2 μm due to its intrinsic loss. The most important characteristic of ZBLAN fiber is its low phonon energy, which results in long lifetimes of many excited states of rare earth ions doped in ZBLAN fibers.[2] Thus, ZBLAN fiber is an effective active medium when doped with rare earth ions. These outstanding optical properties make ZBLAN fibers widely used within optical fiber systems in recent years, especially in the midinfrared fiber sources,[3–7] such as fiber lasers, superfluorescent fiber sources, and supercontinuum sources.

However, the low phonon energy of a ZBLAN fiber also results in its fragile mechanical properties[8] and low melting temperature.[2] As for the ZBLAN fiber with a diameter of 125 μm, its glass transition temperature, softening temperature, and melting temperature are ∼265°C, ∼320°C, and ∼340°C, respectively,[9–11] while that of silica fiber are ∼1100°C, ∼1300°C, and ∼1600°C, respectively.[9,11,12] The temperatures of ZBLAN fiber are much lower than that of silica fiber. These significant differences make it difficult to fusion splice ZBLAN fiber to silica fiber. Much work on the connecting of ZBLAN fiber to silica fiber has been done in recent years. A glue splicing method to join silica and fluoride fibers was utilized by Al-Mahrous et al.[2] A single-mode ZBLAN fiber was mechanically spliced to the silica fiber with angle-cleaves to prevent reflections by Yang et al.[4] Wu et al.[13] used a micro-objective lens and two planoconvex lenses to construct the pumping coupling system. Li et al.[14] and Lu[15] used the arc fusion splicers to splice ZBLAN fiber and silica fiber. The minimal loss could be 0.14 dB by optimizing the parameters of the arc fusion splicers, such as arc time and arc power. Mahrous et al.[16] and Zhi-Jian et al.[17] studied the thermal splicing method to join silica and fluoride fibers based on either a homemade filament heater or a commercial filament splicer. Conclusively, the connecting methods are either mechanical butt coupling methods or splicing methods heated by ARC fusion splicer or filament thermal splicer. The mechanical butt coupling methods are impermanent connecting methods, and the coupling efficiency is low. The arc fusion splicing is unreliable in that the low current arc is unstable and unrepeatable. Recently, research[12,16,17] has demonstrated the advantages of thermal splicing method for joining silica fiber to such low temperature fibers such as ZBLAN fiber and chalcogenide fiber. These may also benefit from the development of commercial filament thermal splicers.

Because of its slow, stable, and uniform heating properties, the thermal splicing may be the preferred method when joining ZBLAN fiber to silica fiber compared to other connecting methods, though there has no study report on the effects of thermal parameters of a filament thermal splicer while thermal splicing ZBLAN fiber to silica fiber so far. They were all obtained experimentally instead. The thermal splicing parameters optimization will be time-consuming and costly for various parameters of ZBLAN fibers if they are only obtained by experiments. In this paper, we will investigate and optimize the thermal splicing parameters, including splice time, splice power, and splice offset both theoretically and experimentally. The theoretical simulation and optimization will be based on the COMSOL multiphysics software. A commercial filament thermal splicer, Vytran FFS-2000, was used for the thermal splicing experiments study.

2 Thermal Splicing Model and Simulation

2.1 *Thermal Splicing Model*

The principle of the filament thermal splicer is based on a resistively heated tungsten filament. It is in the geometrical shape of an inverted "Ω." Fibers prepared for thermal splicing are exactly positioned in the center of the concentric, uniform, well-controlled heat source. The concentric filament

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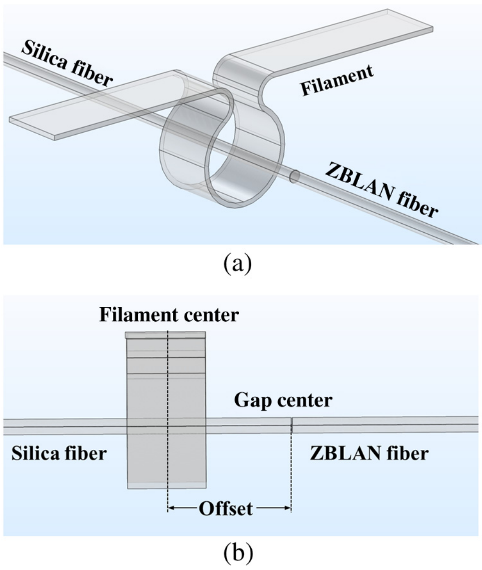


Fig. 1 Schematic of thermal splicing model: (a) the 3-D model and (b) the fiber axial view of the model.

heats and fuses the fiber ends mainly through thermal radiation.

Due to the great difference of temperatures between ZBLAN fiber and silica fiber, the heated tungsten filament must be set closer to the silica fiber. This is the offset thermal splicing method. The key parameter is the offset. It refers to the displacement of filament center to the gap center. The gap is the distance between the fiber ends before splicing. The schematic of thermal splicing model is shown in Fig. 1. The three-dimensional (3-D) model shown in Figs. 1(a) and 1(b) is the fiber axial view of the model. The sizes of filament and fibers in the thermal splicing model are the same as those of the real filaments and fibers. The diameters of ZBLAN and silica fibers used for simulations were 125 μm. The simulation was calculated in the 3-D model.

The thermal and mechanical glass properties of ZBLAN fiber and silica fiber used for modeling can be seen in Table 1.[9,18] Because of the different composition of the two fibers, their glass properties are obviously different. Especially for the coefficients of thermal expansion, the difference can be as large as 40 times.

The thermal splicer can be continuously tunable over a wide range of temperature by changing the splice power and splice time of the tungsten filament. The heat load that represents the splice power is loaded at the tungsten filament in the thermal splicing model. The time in the transient thermal simulation represents the splice time. Correctness of the thermal splicing model was validated by the following way. For the thermal splicing of two single-mode silica fibers, when typical thermal splicing parameters provided by the splicer specifications are set in the model, such as 5-s splice time, 20-W splice power, and 0-μm offset, the simulation results are in conformity with the recommended thermal splicing results specified in the thermal splicer specification, e.g., the temperature of the filament can reach 2600°C and the temperature of silica fibers is greater than 1600°C, the fiber's melting temperature. These temperatures are also in good agreement with the splicer specification, which means our thermal splicing model is correct.

Table 1 Glass properties of ZBLAN fiber and silica fiber.

Properties	ZBLAN	Silica
Thermal conductivity $[W/(m \cdot K)]$	0.628	1.38
Specific heat $[J/(g \cdot K)]$	0.15	0.75
Thermal expansion	$200 \times 10^{-7}/K$	$5.5 \times 10^{-7}/K$
Density (g/cm^3)	4.5	2.2
Young's modulus (GPa)	53	72
Poisson's ratio	0.31	0.17

2.2 *Simulation Results*

The key thermal splicing parameters that affect the fiber temperature when thermally heated are splice time, splice power, and offset. The simulation results will show the dependence of fibers' temperature on the three key thermal splicing parameters. The fiber end's gap is set at 8 μm during the simulation research. Because of the thermal splicing of two single-mode silica fibers, the gap set at 8 μm is a routine selection specified by the commercial thermal splicer. Here, the 8-μm gap between the ZBLAN fiber and silica fiber is also used, because the gap has little influence on the simulation results.

The splice time, splice power, and offset are first set at 5 s, 5 W, and 1000 μm, respectively, and the simulation results of fiber temperature distributions along the axial distance away from fiber ends are shown in Fig. 2. Obviously, the ZBLAN fiber and silica fiber show different temperature distributions with the offset thermal splicing method. As is shown in Fig. 2(b), the maximum temperature of the ZBLAN fiber along the fiber axis occurs at the ZBLAN fiber end. Whereas in Fig. 2(c), the maximum temperature of silica fiber occurs around the offset position rather than silica fiber end. Fiber temperatures along the fiber axis decrease monotonously with the axial distance away from the maximum temperature position.

Effects of splice time and splice power on maximum fiber temperatures of silica and ZBLAN fiber are shown in Figs. 3 and 4, respectively. The splice power is 5 W for Fig. 3 and the splice time is 5 s for Fig. 4. Their offset is 1000 μm. The maximum fiber temperatures of silica and ZBLAN fiber increase with splice time and splice power. But the maximum fiber temperatures will show a slow increase with splice time when the splice time reaches 5 s, especially for the silica fiber. This thermal splicing temperature saturation characteristic is in great agreement with the recommended 5 s to 7 s splice time of the thermal splicer. It means that a 5-s splice time is enough for thermal splicing. At the 5-s splice time, the maximum fiber temperature of silica fiber will exceed 1200°C when the splice power is greater than 6 W. The 1200°C silica fiber temperature is greater than its glass transition temperature and is approaching its softening temperature. This is adverse for the offset thermal splicing method. Because of the maximum temperature of silica fiber occurring around the offset position rather than the silica fiber end, it will soften silica fiber around the offset position and make the section around the silica fiber end bend slightly under

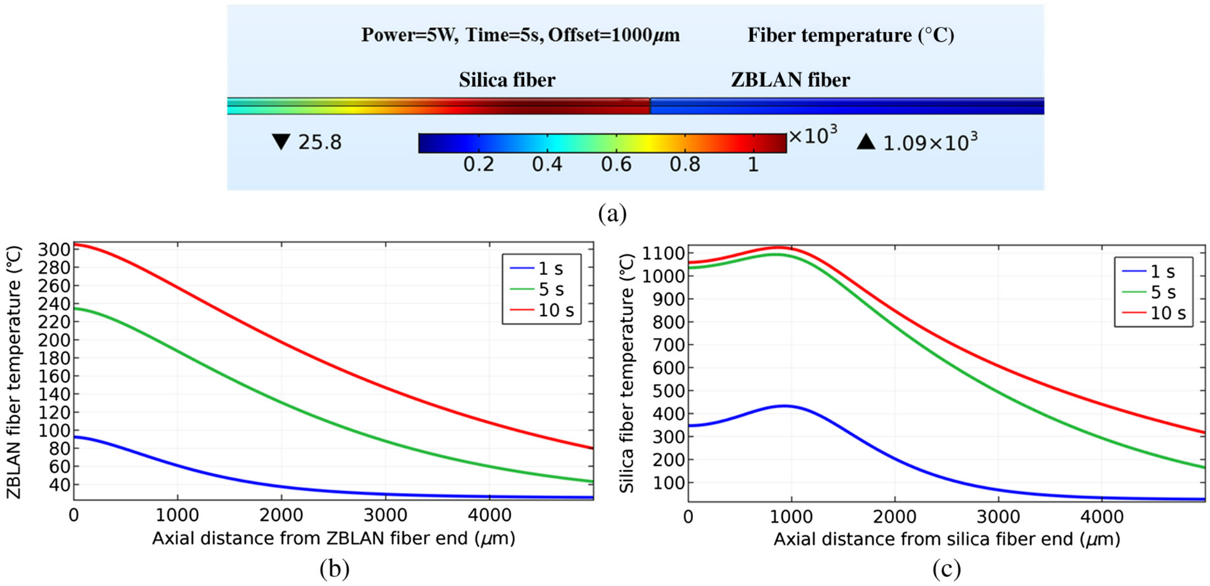


Fig. 2 Fiber temperature distributions along the axial distance away from fiber ends: (a) nephogram of fiber temperature distributions after thermal splicing, (b) ZBLAN fiber temperature distribution, and (c) silica fiber temperature distribution.

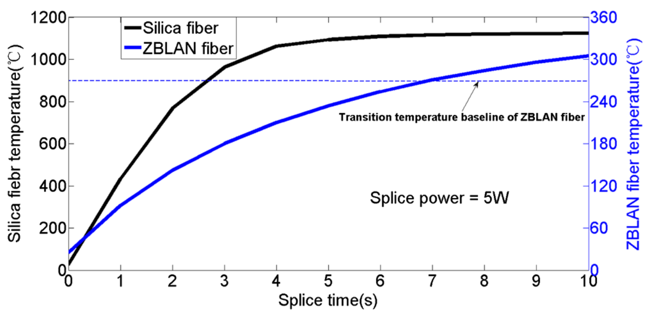


Fig. 3 Effects of splice time on maximum fiber temperatures of silica and ZBLAN fiber along the fiber axis.

gravity. This can not only lead to misalignment of fiber ends between silica fiber and ZBLAN fiber, but can also decrease the mechanical strength of the thermal splicing point. Therefore, the splice power cannot be greater than 6 W. Within the offset thermal splicing method, only the ZBLAN fiber softens and splices with the silica fiber. The temperature of the silica fiber end is greater than the melting temperature of ZBLAN fiber, so when the softening ZBLAN fiber end touches the silica fiber end, it will melt and bond with the silica fiber end, then the ZBLAN fiber is thermal spliced with the silica fiber.

Figure 5 reveals the dependence of the maximum ZBLAN fiber temperature on offset. The splice time is 5 s and splice power is 5 and 6 W. The maximum ZBLAN fiber temperature decreases approximately linearly with the offset. The maximum ZBLAN fiber temperature is 230°C and 270°C for 5 W and 6 W splice power at the 1000 μm offset, which are not yet the softening temperature of the ZBLAN fiber. The offset can be reduced to ∼800 μm for 5 W splice power and ∼900 μm for 6 W splice power so as to make the temperature of the ZBLAN fiber end reach its softening temperature. Only then can the success of thermal splicing be guaranteed. Moreover, it is essential to precisely control the splice temperature of fiber ends. Before the fiber ends bond together, the ZBLAN fiber end cannot be heated to be much greater than its melting temperature. Otherwise the ZBLAN fiber end will be damaged. So the offset cannot be reduced too much, and an offset of around 800 to 900 μm is reasonable.

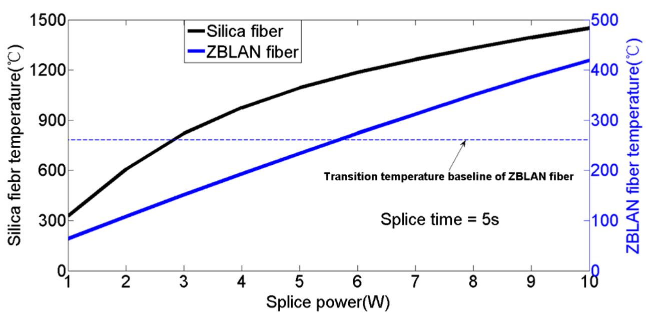


Fig. 4 Effects of splice power on maximum fiber temperatures of silica and ZBLAN fiber along the fiber axis.

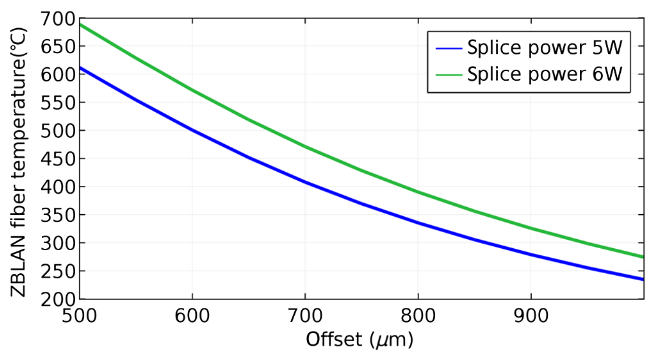


Fig. 5 Effects of offset on maximum ZBLAN fiber temperature along the fiber axis.

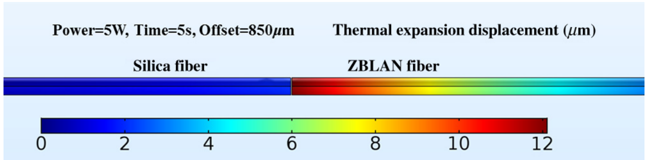


Fig. 6 Thermal expansion displacements of ZBLAN fiber and silica fiber.

During the study on the thermal splicing of ZBLAN fiber to silica fiber, another problem that should be paid attention is the great mismatch in the fibers' coefficients of thermal expansion. As is listed in Table 1, the difference of the two fibers can be as large as 40 times. The displacement of thermal expansion deformation of the ZBLAN and silica fibers when heated before melting is shown in Fig. 6. The splice parameters are 5-s splice time, 5-W splice power, and 850-μm offset. The displacements of fiber ends are 12 μm for the ZBLAN fiber and 2 μm for the silica fiber. It is obvious that the ZBLAN fiber end expands more rapidly than silica fiber along the fiber axis during thermal splicing. Because of the potential disintegration of the thermal splice as the fiber cools down from the splicing temperature,[19] the sufficient difference of thermal expansion coefficients of the two fibers may affect the bond strength of the thermal splice point. The fiber gap may also be carefully set in the thermal splicing experiments according to this simulation result.

3 Experimental Results and Discussion

3.1 *Experimental Setup and Splicing Procedure*

The experimental setup for our thermal splicing is shown in Fig. 7. It consists of a pigtailed broadband super luminescent diode (SLD) source emitting the 1310-nm signal, a commercial filament thermal splicer Vytran FFS-2000, and an optical power meter. The ZBLAN fiber and silica fiber used in our study are single-mode fibers. Their parameters are listed in Table 2. The stripping and cleaving of ZBLAN fiber are different from that of the silica fiber. A certain length of ZBLAN fiber end was soaked into di-chloromethane (CH_2Cl_2) for about 5 min so as to remove its coatings. The EFC-11 Ericsson fiber cleaver set to 40 g (4 N) of fiber tension was used to cleave ZBLAN fiber. The precise alignments of fibers were controlled in the FFS-2000. The entire thermal splicing process was in the protection of a controlled argon flow. This can not only protect the tungsten filament from being oxidized in high temperatures, but also prevent moisture from condensing in the ZBLAN fiber while splicing. Moreover, the inert argon atmosphere can prevent harmful reactions of the hot surface of the ZBLAN fiber with water vapor.[16]

In order to precisely control the thermal splicing temperature, the thermal splicing parameters were set to be 5-s splice time, 5- to 6-W splice power, and 800- to 900-μm offset according to simulation results. The gap was set to 12 to 14 μm considering the simulation results of thermal expansion displacements of the fiber ends. The gap was set to match the thermal expansion displacement of the ZBLAN fiber end exactly. This will ensure that the fiber ends will not touch together only because of the thermal expansion. Moreover, the overlap of fiber ends and speed of overlapping were finely tuned during the thermal splicing process by the controlling software. The fire polish is activated so as to clean the splice region after the splice time. The fire polish parameters were similar to that of the post-splice mentioned by Thapa et al.[12] The argon flow rate should be set lower during the splice. Otherwise the softening ZBLAN fiber will bend and cannot align with the silica fiber under the high argon gas flow.

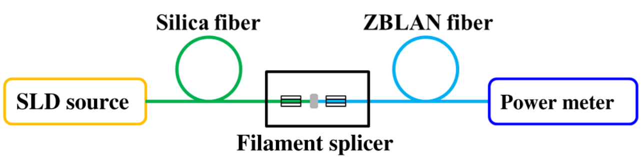


Fig. 7 Experimental setup for thermal splicing of ZBLAN fiber to silica fiber.

Table 2 Parameters of ZBLAN fiber and silica fiber.

Fiber	Core/cladding diam.	MFD@1310 nm	NA
ZBLAN	2.7/123 μm	4.3 μm	0.25
Silica	3.4/125 μm	4.9 μm	0.22

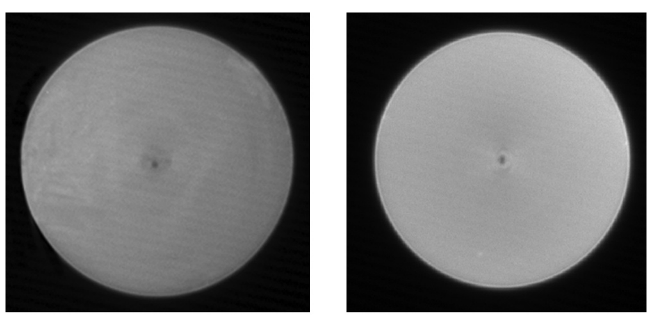
3.2 *Results and Discussion*

The thermal splicing parameters stated above were carefully tuned and repeatedly optimized in the thermal splicing experiments. Figure 8 shows the end surfaces of ZBLAN fiber and silica fiber after cleaved. Photographs with the low loss thermal splicing are shown in Fig. 9. Apparently, the ZBLAN fiber was softening gradually, melting when the fiber ends touched together, and then the ZBLAN fiber wrapped onto silica fiber because of the overlap process. This cap-like bulge could enhance the mechanical strength of thermal splicing.

The thermal splice loss was calculated by measuring the optical power attenuation of the SLD source before and after splice. The estimated equation is

$$\alpha_{\mathrm{loss}} = P_{\mathrm{in}} - P_{\mathrm{out}} - \alpha_{\mathrm{ZBLAN}} L, \tag{1}$$

where P_{in} is the output power of silica fiber and P_{out} is the output power of ZBLAN fiber after splice, and α_{ZBLAN} and L are the attenuation and length of ZBLAN fiber, which are 0.1 dB/m and 10 m in our case.



(a) (b)

Fig. 8 End surfaces of the ZBLAN fiber and silica fiber: (a) ZBLAN fiber and (b) silica fiber.

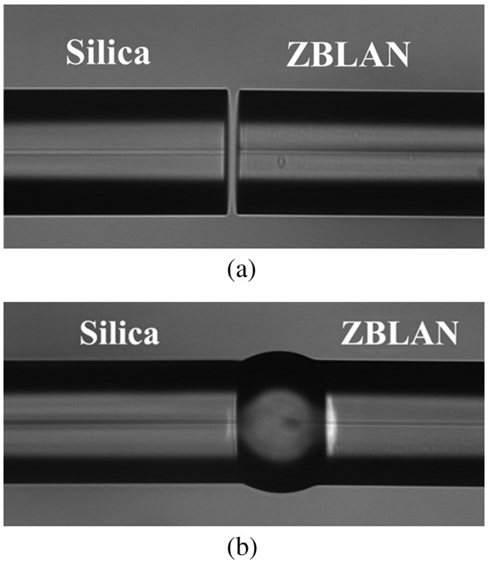


Fig. 9 Photographs of the thermal splicing of ZBLAN fiber to silica fiber: (a) microphotograph before thermal splicing and (b) microphotograph after thermal splicing.

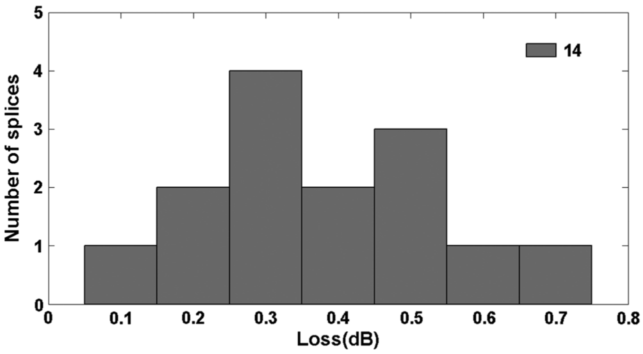


Fig. 10 The thermal splice loss histogram.

The thermal splice loss histogram is shown in Fig. 10. We have gotten good experimental results after a dozen thermal splice experiments. The mean thermal splice loss was about 0.37 dB. The achieved minimum loss was 0.1 dB. These results are better than the published results.[16,17] These benefit from the optimized thermal splicing parameters of the simulation model and our finely repeatedly tuning and optimizing in the thermal splicing experiments. All these have guaranteed the precise control of thermal splicing temperature of fibers. The losses are mainly due to mode field mismatch and fiber core deformation of ZBLAN fiber core. The repeatable low loss results proved the thermal splicing of ZBLAN fiber to silica fiber a promising method.

4 Conclusion

In conclusion, the low loss thermal splicing of a ZBLAN fiber to silica fiber has been demonstrated. The thermal splicing model was established and optimized thermal splicing parameters were obtained based on simulation results. The thermal splicing parameters were finely repeatedly tuned and optimized further in the thermal splicing experiments. The precisely control of the thermal splicing temperature of fibers was guaranteed by theoretical simulation and analysis, as well as experimental optimization. The achieved losses were measured to be about 0.3 dB in the thermal splice experiments. This study has ensured an offset thermal splicing method that is a repeatable, low-loss, and promising technique for the splicing of ZBLAN fiber to silica fiber.

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Biographies for the authors are not available.