New Approach for High Reliability, Low Loss Splicing between Silica and ZBLAN Fibers

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ABSTRACT

In the past decade, ZBLAN (ZrF4-BaF2-LaF3-NaF) fibers have drawn increasing interest for laser operations at wavelengths where Fused Silica-based (SiO_2) fibers do not perform well. One limitation to the expansion of ZBLAN fiber lasers today is the difficulty to efficiently inject and extract light in/from the guiding medium using SiO_2 fibers. Although free space and butt coupling have provided acceptable results, consistent and long lasting physical joints between SiO_2 and ZBLAN fibers will allow smaller, cheaper and more robust component manufacturing.

While low loss splices have been reported using a traditional splicing approach, the very low mechanical strength of the joint makes it difficult to scale. Difficulties in achieving a strong bond are mainly due to the large difference of transition temperature between ZBLAN and SiO_2 fibers (~260°C vs. ~1175°C).

This paper presents results obtained by using the high thermal expansion coefficient of the ZBLAN fiber to encapsulate a smaller SiO_2 fiber. A CO_2 laser glass processing system was used to control the expansion and contraction of the ZBLAN material during the splicing process for optimum reliability.

This method produced splices between 125 µm ZBLAN to 80 µm SiO_2 fibers with average transmission loss of 0.225 dB (measured at 1550 nm) and average ultimate tension strength of 121.4 gf. The resulting splices can be durably packaged without excessive care. Other combinations using 125 µm SiO_2 fibers tapered to 80 µm are also discussed.

Keywords: ZBLAN Fiber, Glass Processing, Fiber Laser, Fiber Splicing, CO_2 Laser, Soft Glass, Fluoride fiber, Adiabatic taper

1. INTRODUCTION

The use of fiber lasers in material processing and medical sciences is growing due to advantages in size, reliability and electrical efficiency. SiO_2 fiber lasers are limited in spectral range (high attenuation above 2 µm), as well as in dopant concentration. ZBLAN based fiber lasers do not experience these limitations because ZBLAN fibers exhibit low attenuation up to 4 µm and allow higher dopant concentrations.[1,3]

The challenge to the wide scale implementation of the ZBLAN fiber laser is the difficulty of efficiently coupling light between ZBLAN and SiO_2 fibers, the latter being widely used in optical components. The difference in transition temperature between the two types of glass[1, 3] (Table 1) makes conventional splicing impossible.

Conventional splicing methods rely on softening both stands of glass and using surface tension to build a seamless, strong and permanent joint, while minimizing transmission loss. This method cannot be directly applied to a ZBLAN/SiO_2 splice as the transition temperatures of the SiO_2 fiber (~1175°C) and ZBLAN fiber (~260°C) are too far apart. This method has proven impractical due to the extreme weakness of the resulting splice joint.[2,3,4,5,9] Alternate methods employing special coatings[6] or adhesives[2,5] can produce stronger joints, at the cost of making the manufacturing process more complex.

The presented new approach relies on the difference of thermal expansion coefficient between SiO_2 and ZBLAN glass to mechanically bond the SiO_2 and the ZBLAN fibers without an intermediate material. The process requires a high level of process control provided by the AFL LZM-100 CO_2 laser-based glass processing station. The LZM-100 allowed precise heating and expansion of the ZBLAN fiber, a controlled push of the SiO_2 fiber into it, and a gradual cool down of the ZBLAN fiber. As the ZBLAN fiber contracts during cooling, the SiO_2 fiber is held captive by the compressive forces applied by the ZBLAN fiber.

PROPERTY	UNIT	SILICA FIBER	ZBLAN FIBER
Transmission Limit (Loss <100 dB/km)	μm	2.2	3.8
Transition Temperature	°C	1,175	260
Thermal Conductivity	$W \cdot m^{-1} \cdot K^{-1}$	1.38	0.63
Specific Heat	$J \cdot g^{-1} \cdot K^{-1}$	0.17	0.15
Expansion Coefficient	$10^{-6} \cdot K^{-1}$	0.5	20
Density	$g \cdot cm^{-3}$	2.2	4.5

Table 1 — Typical values of Silica and ZBLAN fibers basic physical properties.

2. EXPERIMENT

To take full advantage of the ZBLAN expansion and contraction during the splice process, it is necessary for the SiO_2 fiber to have a smaller cladding diameter than the ZBLAN fiber. This experiment focused on the splice between a ZBLAN fiber with a cladding diameter of 125 μm, and a SiO_2 fiber with a cladding diameter of 80 μm. The main experiment consisted of splicing a FiberLabs ZSF-9/125-N-0.26 Single-mode (SM) ZBLAN fiber to a Fujikura RCSM-PS-U17C reduced cladding SM fiber. The study was then extended to Corning SMF-28e+ and Nufern SM-1950 SM fibers, tapered down to a cladding diameter of 80 μm using the LZM-100 CO_2 Laser Glass Processing Station. The main properties of each fiber are shown in Table 2.

	ZBLAN ZSF-9/125-N-0.26	FUJIKURA RCSM-PS-U17C	CORNING SMF-28E+	NUFERN SM-1950
Active Dopant	N/A	N/A	N/A	N/A
Core Diameter (μm)	8.6	—	8.2	7.0
Cladding Diameter (μm)	125	80	125	125
Coating Diameter (μm)	468	166	245	245
Numerical Aperture	0.26	—	0.14	0.20
Cutoff Wavelength (μm)	3.10	1.30	1.26	1.72
Mode Field Diameter at 1550 nm (μm)	—	9.0	10.4	8.0
Attenuation at 1550 nm (dB/km)	83	0.38	0.20	—

Table 2 — Main physical and optical properties for all fibers used in this experiment

2.1 Splice Progress

To allow for efficient splice loss optimization, the joint tensile strength was first optimized by precisely adjusting the CO_2 laser power before, during and after pushing the SiO_2 fiber into the ZBLAN fiber. A schematic of the process steps is shown in Figure 1.

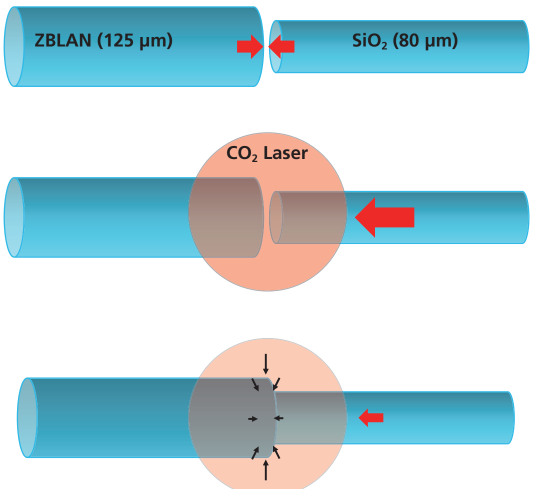


Figure 1 — Schematic of the main steps of the splice process. The fibers are (a) gapped and aligned to minimize transmission loss, (b) the CO_2 Laser causes expansion of the ZBLAN fiber as the 80 µm SM fiber is pushed inside it, and (c) the splice is slowly cooled down to prevent cracking of the ZBLAN fiber.

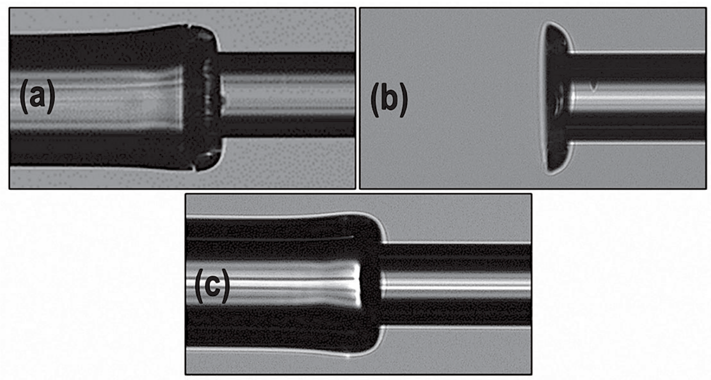


Figure 2 — A failed splice (a) shows fiber separation due to the ZBLAN fiber structure cracking during a fast, non-controlled cooling process. The break always occurred at the tip of the inserted SiO_2 fiber (b). For comparison, a successful splice process (c) allowed the ZBLAN to gradually compress around the SiO_2 fiber without cracking.

Controlled heating ensured the ZBLAN deformation was kept to a minimum while preventing the ZBLAN glass structure from cracking during the cooling process. Fine control over the tensile strength and softness level of the ZBLAN fiber during the cooling process was critical in order to consistently achieve high reliability splices. Figure 2 shows the different results between a controlled and uncontrolled cooling process.

2.2 Tension Test Setup

After the splice was completed, it was transferred to the tensioning mechanism illustrated in Figure 3. This mechanism consists of two holding blocks that clamp securely on the coating of each fiber such that the bare cladding of each fiber and the splice sit straight between the two blocks.

When the tensioning process was initiated, the first block moved outward, gradually increasing the linear tension applied to the splice. A calibrated load cell attached to the second block displayed the applied tension in gram force (gf). The tension on the splice joint was increased until the splice broke, and the ultimate tension was recorded. For comparison, the test was first performed on a straight piece of non-stripped ZBLAN fiber and an ultimate tension of 837 gf was recorded, which corresponds to an ultimate tensile strength of 97 kpsi.

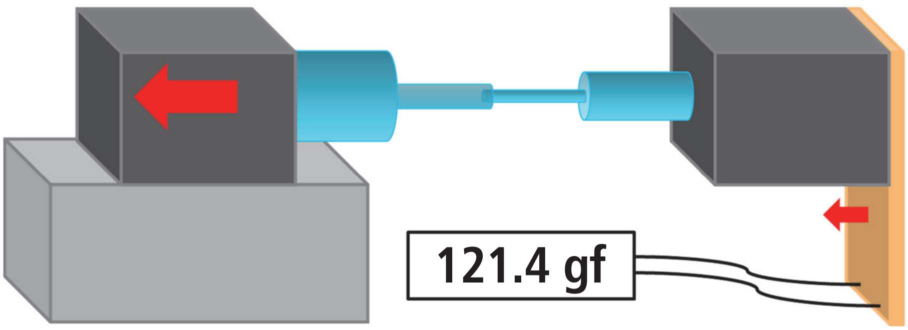


Figure 3 — Tensioning Mechanism to measure the ultimate tension of a splice. The left stage slowly moves outward while a load cell on the right stage records the applied tension. The maximum force before breakage is recorded.

Inspection of the ZBLAN fiber after the splice break (Figure 4a) confirmed that the push of the SiO_2 fiber left a clear imprint on the ZBLAN fiber end face, and that the ZBLAN fiber contraction applied radial forces to the SiO_2 fiber. A qualitative bend test showed that the SiO_2 fiber broke before separating from the ZBLAN fiber (Figure 4b).

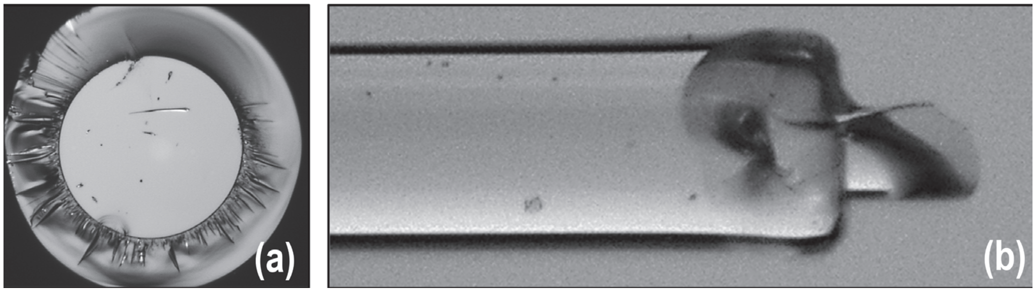


Figure 4. Microscopic images of (a) the ZBLAN end face after a linear tension test, showing clear inward stress lines around the SiO_2 fiber imprint, and (b) the ZBLAN fiber after a bend test, showing a piece of the SiO_2 fiber imbedded in the ZBLAN fiber.

2.3 Insertion Loss Test Setup

Using the above process as a base, the splice transmission loss at 1550 nm wavelength was optimized using the setup shown in Figure 5.

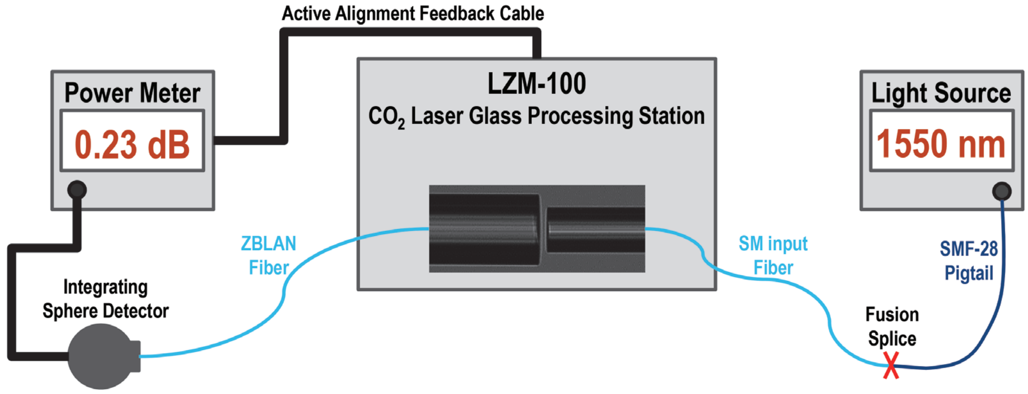


Figure 5 — Experimental setup for low insertion loss splicing between ZBLAN and SiO_2 fibers. Fiber alignment was performed actively at the gap stage using an active feedback loop.

In this setup, 1550nm light was generated from an Agilent HP-81554SM module in an Agilent 8163A optical chassis and coupled into a SMF-28e+ pigtail. Prior to starting the experiment, the beam quality of the source was checked using a DataRay Beam'R2 slit scan beam profiler (Figure 6a) as well as a LD8900 far field scanner from Photon-Inc. to ensure operation in the single-mode regime.

Loss measurements were performed using an Agilent 8163A optical chassis fitted with an Agilent HP-81533B module and connected to an Agilent HP 81521B Power Detector Head fitted with an Agilent HP-81002FF integrating sphere. The total drift of the source over the test period was established to be <0.02 dB.

After referencing the detector, a piece of the selected SM fiber was spliced to the SMF-28e+ pigtail. The beam quality was checked again and a new reference was made on the detector. The output beam profiles for all three SM fibers after splicing to the SMF-28e+ pigtail are shown in Figure 6.

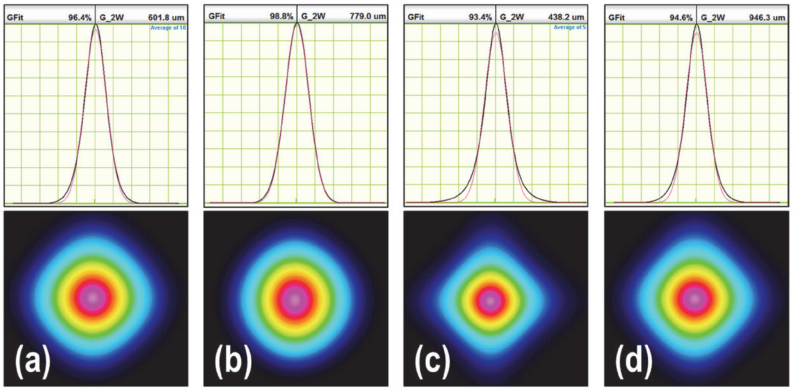


Figure 6 — Output beam profile for (a) the SMF-28e+ pigtail (no taper), (b) the Fujikura RCSM-PS-U17C, (c) the Corning SMF-28e+ (tapered to 80 µm), and (d) the Nufern SM1950 (tapered to 80 µm).

To measure the splice loss, one end of the ZBLAN fiber was stripped and cleaved using a Fujikura CT-101 Tension-Scribe cleaver set to 125 g tension, and subsequently inserted in the integrating sphere detector. The automatized splice process used an active power meter feedback loop to optimize insertion loss prior to splicing. This was necessary due to the very high eccentricity of the ZBLAN fiber (>5 µm). The final loss was measured, and the splice loss L_{splice} was calculated using Equation 1. $L_{measured}$ refers to the loss measured by the detector in dB, l is the length of ZBLAN fiber after the splice in meters, and α_{ZBLAN} is the attenuation of the ZBLAN fiber in dB/m. The value of α_{ZBLAN} was provided by the manufacturer as being 0.083 dB/m at 1550 nm.

Equation 1

$$L_{splice} = L_{measured} - l\alpha_{ZBLAN}$$

2.4 Extension to SM Fibers with 125 µm Cladding Diameter

In an effort to extend the study to more standard SM fibers with 125 µm cladding diameter, tapering was first employed to reduce the SiO_2 fiber diameter to 80 µm. This was done using the tapering function of the LZM-100 CO_2 laser glass processing station to produce an adiabatic taper[8,9] (Figure 7), then accurately cleaving it in its 80 µm waist region using a Fujikura CT-101 Tension-Scribe cleaver set to 125 g tension . The resulting adiabatic taper was spliced to the ZBLAN fiber using the setup shown in Figure 5. This process facilitated the successful splicing of Corning SMF-28e+ and Nufern SM-1950 fibers to the ZBLAN fiber.

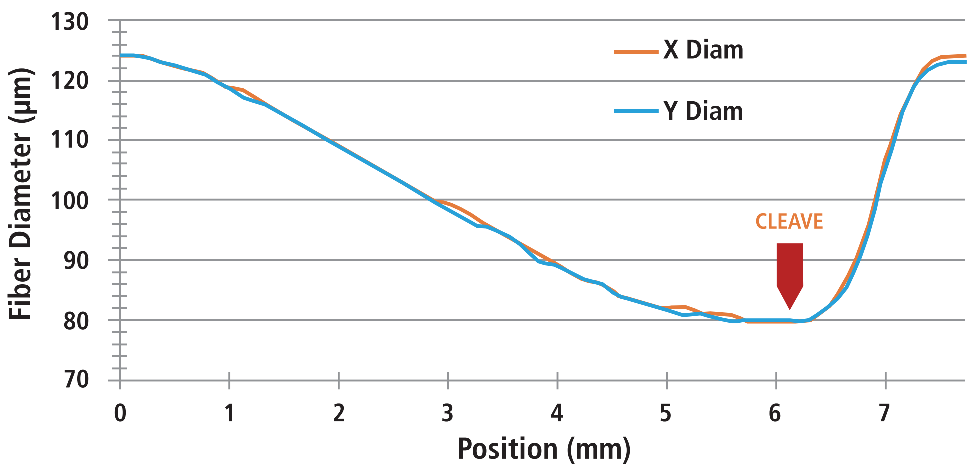
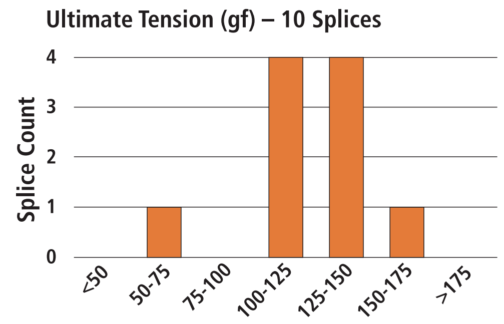


Figure 7 — Adiabatic taper profile as measured by the LZM-100 measurement tool in two orthogonal directions. The red arrow indicates the location where the taper was cleaved.

3. RESULTS

3.1 Splice Tension Strength

To determine process repeatability, a set of 10 consecutive splices between FiberLabs ZSF-9/125-N-0.26 ZBLAN and Fujikura RCSM-PS-U17C were performed using the same optimized and automated splice process. Tension strength was measured using the setup illustrated in Figure 3 and the results are displayed in Figure 8. The average ultimate tension measured was 121.4 gf, with 90% of the samples with ultimate tension above 100 gf.



	TENSION (GF)
min	61
max	161
average	121.4
stdev	28.4

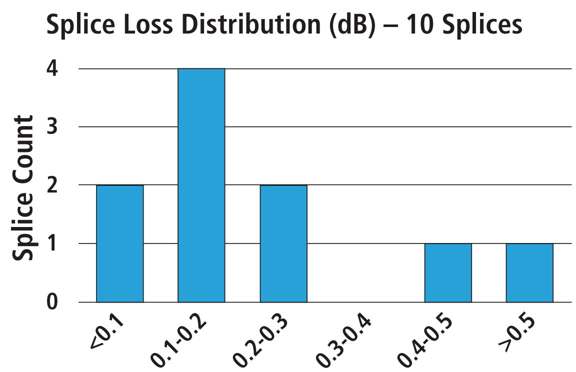
Figure 8 — Histogram of the ultimate tension for a set of 10 consecutive splice samples, expressed in gram force (gf)

It is worth noting that the ultimate tension was recorded in gf, as it can be difficult to define an area of application for a splice between a 125 µm and 80 µm fiber in order to convert it into tensile strength units. For comparison an ultimate tension of 100 gf corresponds to ultimate tensile strengths of 11.6 kpsi (79.9 MPa) and 28.3 kpsi (195.1 MPa) for 125 µm and 80 µm fiber diameters respectively.

To the best of our knowledge at the time of writing, the highest reported tensile strength for a splice between ZBLAN and SiO_2 fibers using an intermediate coating was 70 MPa[6] (10.2 kpsi).

3.2 Splice Loss

Process loss repeatability was determined from another set of 10 consecutive splices between FiberLabs ZSF-9/125-N-0.26 ZBLAN and Fujikura RCSM-PS-U17C. The transmission loss at 1550 nm was measured using the setup illustrated in Figure 5 and the results are shown in Figure 9.



	LOSS (dB)
min	0.06
max	0.54
average	0.225
stdev	0.158

Figure 9 — Histogram of the splice loss between FiberLabs ZSF-9/125-N-0.26 ZBLAN fiber and Fujikura RCSM-PS-U17C fiber, for a set of 10 consecutive splice samples.

With an average loss of 0.225 dB, a minimum of 0.06 dB and a maximum loss of 0.54 dB, this data demonstrates the described method achieved consistent, low loss splice joints between ZBLAN and SiO_2 fibers.

Additional loss tests performed on Corning SMF-28e+ and Nufern SM-1950 fibers using the tapering method are shown in Table 3. Although the loss recorded was not as low as for the 80 µm reduced cladding SM fiber, it demonstrates the feasibility of applying this method to a larger range of SM fibers.

SM FIBER	SAMPLE SIZE	AVERAGE LOSS (dB)
RCSM-PS-U17C	10	0.23
SMF-28e+	4	0.99
SM-1950	4	0.65

Table 3 — Summary of average splice losses measured at 1550 nm for all SM fibers used in this study.

For all splice combinations tested, the beam quality at the end of the ZBLAN fiber was checked with a beam profiler and a far field scanner to ensure the ZBLAN fiber was operating in the single-mode regime. An example is shown in Figure 10.

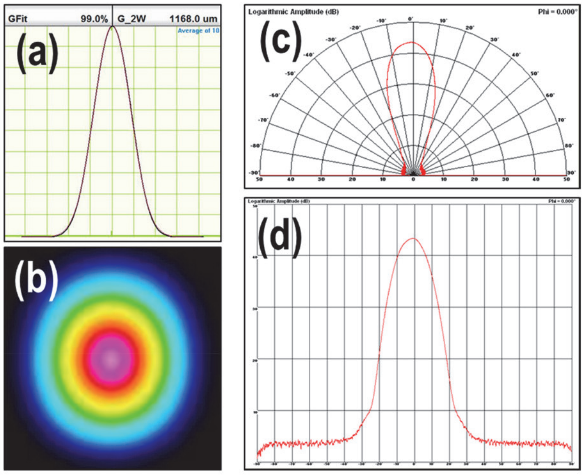


Figure 10 — ZBLAN output beam 99% Gaussian fit (a) and profile (b) captured using a beam profiler. The right plots show the same beam captured in logarithmic scale using a far field scanner, and displayed in polar (c) and linear (d) coordinates on a range of ±90°.

4. SUMMARY AND DISCUSSION

A new process using a CO_2 laser-based glass processing station to splice ZBLAN fibers to Silica-based fibers without intermediate medium or external mechanical support was demonstrated. This paves the way for large scale manufacturing of high reliability, low loss splices between glasses with widely different transition temperatures.

An average loss of 0.23 dB at 1550 nm with an average ultimate tension of 121.4 gf was demonstrated. This is, to the best of our knowledge, the highest tension strength reported for a direct splice between ZBLAN and SiO_2 fibers without compromising transmission loss.

Following our efforts to extend this study to more standard 125 µm fibers, we now believe employing conventional mode field adaptor technology and tapering processes to Silica-based fibers will allow this method to be extended to a great variety of single-mode and multimode fibers. Anticipated manufacturing of more consistent and robust ZBLAN fibers would also allow expanded application of this method.

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