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Fiber splicer convertible – mini preform fabrication system

W. J. Lai, and L. Zhang

Abstract— We downscale a lab-sized preform fabrication system to a benchtop miniature preform, hence short-length fiber fabrication system. The system, which is a large diameter fiber splicer convertible; is compact, low cost, fast and flexible as compared to standard preform fabrication processes. Using the proposed system incorporating with solution doping technique, we have successfully fabricated several ~ 1 mm thick, 40 ± 10 mm long Thulium doped silica and germania-silica preforms. The preforms were drawn to $400 \mu\text{m}$ diameter, sub-meter length low NA Thulium doped fibers. Encouraging absorption and emission behaviors were obtained. The technique is promising and suitable for rapid specialty optical fiber prototyping.

Index Terms— Optical fiber fabrication, optical fiber materials, optical fibers, thulium

I. INTRODUCTION

THERE are several methods currently available for the fabrication of optical fiber preforms, which can be broadly classified as either vapor or non-vapor based. The vapor based methods include vapor axial deposition (VAD) [1], outside vapor deposition (OVD) [2]-[3], modified chemical vapor deposition (MCVD) [4], and direct nano-particle deposition (DND) [5]. The non-vapor based methods include sol-gel processing [6], and powder sintering [7]. Among these, the MCVD process is well established and often employed for commercial optical fiber production. The process involves passing a mixture of gases through a rotating glass tube which is continuously heated at the surface via a moving burner. Chemical reactions in the gas result in a layer of fine soot being formed on the inner surface of the tube. This is subsequently sintered into a clear glass layer, and finally collapsed into the preform to be used for fiber fabrication. High precision of the process enables the production of high quality preforms and fibers. However, it often requires many iterations in order to arrive at the intended fiber design, which increases the cost and time needed for a successful fabrication.

Solution doping [8], a popular method of fabricating active fibers due to its simplicity and versatility, is known to suffer from poor control over the dopant incorporation and

reproducibility, even for commercial fiber production. For example, the concentration(s) of dopant ion(s) in solution changes over time due to factors such as solvent evaporation and ion clustering, while small variations in the glass tube's soot layer porosity affect percolation and dopant distribution. Hence it requires some 30 – 50 iterations to optimize a fabrication recipe. With the standard MCVD process, the bulk of preforms of the earliest iterations are often unsuitable for practical application and therefore wasted. As the early stages of fiber research involve experimenting with different glass hosts, dopants, mixture of dopants, doping concentrations, geometries, etc., small volumes of fiber are adequate for analyses.

In this letter, we propose and demonstrate a scaled-down version of the standard fabrication process for making mini preforms that can be drawn to short-length optical fibers suitable for prototyping, testing and the first order process optimization. The developed setup is compact and able to reduce the time and cost investment compared to the existing standard fiber fabrication process. The conventional process yields a 12 mm thick, 300 – 400 mm long preform that is used to draw to the required fiber. A single iteration from preform fabrication to fiber pulling takes approximately 2 working days. In contrast, our approach produces ~ 1 mm thick, 30 – 50 mm long preforms, which can be drawn to sub-meter length of fibers for initial testing and analyses. A single iteration of this process takes about 2 – 3 hours, which reduces excess time, cost and materials for greater research efficacy. We have successfully fabricated sub-meter lengths of Thulium doped silica and germania-silica fibers of $400 \mu\text{m}$ diameter by using the proposed system.

II. SYSTEM DESCRIPTION

We converted the existing commercial 3-electrode large diameter splicer (3SAE-LDS) into the main workhorse for this process. In principle, the proposed technique is not limited to multi-electrode plasma splicing system; it can also be applied to graphite- or CO_2 laser-based large diameter fiber splicers.

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The system consists of a three-electrode plasma discharge that provides a narrow isothermic heat zone around the circumference of the intended mini preform. This allows for directed heating of the preform. Instead of rotating the glass tube to achieve uniform heating as in the standard fabrication process, we create a ‘Ring of Fire’ around it. Tungsten electrodes with melting temperature of 3422 °C are selected to give a maximum processing temperature of about 3000 °C, which is sufficient and comparable to the oxy-hydrogen burner used in the MCVD lathe. Three electrodes are orientated in a ‘Y’ configuration such that the tips form an equilateral triangle. The electrode spacing can vary depending on the size of the plasma required for a given tube dimension. Each electrode is independently modulated 120 degrees out of phase relative to the other electrodes with a high voltage high frequency (~ 30 kHz) source. The process and schematic diagram of the experimental setup is summarized in Fig. 1.

Fig. 1. Process and schematic diagram of the experimental setup: (a) vapor deposition, (b) solution doping, (c) benchtop preform fabrication system; where TC is the temperature control, MC is the mechanical clamp mounted on translational stage; with inset is a capillary tube within the three-electrode plasma discharge.

100 mm long synthetic quartz capillaries or tubes with inner / outer diameters of 0.5 mm / 1 mm were used throughout this work. These capillaries were cleaned in an ultrasonic acetone bath and heat-dried prior to vapor deposition. In most MCVD processes, the bubbler technique is used for vapor deposition: a carrier gas (typically oxygen) is fed through liquid precursors such as SiCl_4 and GeCl_4 , generating the respective vapors for further delivery towards the deposition chamber. In our case, we adopt the evaporator method, where no carrier gas is intentionally introduced, but positive pressure is applied to the liquid precursor by controlling the temperature of its container. Precursor vapor flow is therefore directed upwards via a negative pressure gradient extending towards the capillary. The volumetric flow rate of the vapor is $Q = AV$; where A is the cross sectional area of the tube and V is the average flow velocity. Assuming a constant average velocity, Q decreases with smaller tube diameter.

To fabricate the active fibers, rare-earth (RE) dopants need to be deposited on the inner side of the hollow tube. The solution doping technique was used to fabricate our mini preforms. 0.48 g of $\text{TmCl}_3 \cdot 6\text{H}_2\text{O}$ with purity of 99.9% and 0.32 g of

$\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ with purity of 99.999% were dissolved in 8 ml of methanol for this investigation. Post vapor-deposited tubes were immersed in the RE dopant solutions for 30 to 60 minutes, gently blow-dried with oxygen gas and heated at about 200 °C for 5 minutes to evaporate residual solvent and moisture. We then replicate the recipe-driven processes, such as fire polishing, sintering, collapsing and sealing in the three-electrode plasma system. The process is semi-automated using National Instruments LabVIEW software to improve its repeatability and efficiency. Instead of applying flame passes axially across a stationary tube that is typical of the standard fabrication process, the tube is moved back and forth within the stationary ‘Ring of Fire’.

Depending on factors such as thickness of deposited soot and RE layers, tube dimensions, and material properties of the tube, the process requires optimization of variables (e.g. plasma arc power, tube traversing speed) for good performance as well as the elimination of trapped air bubbles within the preform. Minimizing tube inner wall contamination, as well as good control of arc power and tube traversing speed, will ensure repeatable successful fabrication. It is also observed that the arc power level should relatively scale with the speed of traverse, i.e. higher power for faster speed.

For 30 – 50 mm long preforms with ~ 1 mm capillary tubes used in this study, the entire process from sintering to collapsing and sealing took between 30 to 50 minutes. A sample of the process parameters used in the fabrication, and its corresponding outer diameter is depicted in Fig. 2.

Fig. 2. Typical parameters used in the process and its corresponding outer diameter, and power level refers to the absolute digitized arc power value (0 – 255) used in the fabrication, which correlates to the flame of the arc.

In standard fiber pulling process, the preform is heated close to the melting point of silica in a furnace or oven at the top of the fiber drawing tower. A thin fiber can then be pulled from the lower end of the preform. The intended fiber diameter can be controlled by the pulling speed and furnace temperature. Before the fiber is wound up, it usually receives a polymer coating such as acrylate, silicone or polyimide for mechanical and chemical protection. Since our fabricated preforms are significantly smaller, horizontal tapering method [9] was used as a feasible alternative. Both ends of the preform were aligned and mounted horizontally onto two translational stages with stationary arc flame in the middle; where one stage feeds and

the other pulls the fiber during the heating process. Similarly, the pulling speed and power of the flame require optimization for desired fiber diameters. In principle, the fabricated preforms can be drawn into fibers of any diameter narrower than that of the preforms. The maximum fiber length from a given preform can be calculated based on $l_f = l_p (r_p/r_f)^2$, where l_p is the length of preform, r_p and r_f are the radii of the preform and desired fiber respectively.

III. RESULTS AND DISCUSSION

We have successfully fabricated several Thulium doped silica and germania-silica preforms with $\sim 900 \mu\text{m}$ diameter and 30 – 50 mm lengths. These preforms were pulled into fibers with a final diameter of $\sim 400 \mu\text{m}$ and lengths ranging from 100 to 200 mm, and the details are listed in Table 1.

Table 1: Fabricated fiber details: core refers to the estimated core diameter and Δn is the index difference, loss refers to the estimated background loss at 850 nm, power refers to plasma arc power, and speed refers to the tube traversing speed. All values have a maximum deviation of $\pm 10\%$.

FID	Host	Preform Length (mm)	Core (μm) / $\Delta n (\times 10^{-3})$	Loss (dB/m)	Fabrication Parameters	
					Power	Speed
F1	Si/Ge	45	35 / 6.5	3.5	High	Fast
F2	Si/Ge	30	28 / 3.0	0.8	Low	Slow
F3	Si	50	26 / 0.5	0.4	High	Fast

Fig. 3. (a) Fiber end face of F2; (b) refractive index profiles of F2 around both ends of the fiber

The microscopic image of fiber end face and refractive index profiles of fiber F2 are depicted in Fig. 3. The core can be seen, albeit not perfectly circular in shape and slightly off-centered. This may potentially be due to the unevenness in the solution doping, slight misalignment of tube within the ‘Ring of Fire’, and / or tube material creep during fabrication. The refractive index difference, Δn , ranged from $\sim 0.5 \times 10^{-3}$ to 6.5×10^{-3} , which corresponds to low NA fibers. This is attributed to small amount of deposited soot, which results in low Tm and Al incorporation within the fiber. Index measurements around both ends of fiber F2 were taken to monitor the index uniformity. Evidently, the results showed low index uniformity, which is likely due to arc variation or thermal instability during fabrication. A tighter temperature control and / or additional feedback control can be employed for better uniformity.

We performed absorption measurements for the fabricated Thulium doped fibers using cut-back method with tungsten halogen light source of spectral range from 360 nm to 2000 nm. The results are shown in Fig. 4 (a). The amplified spontaneous emission (ASE) spectrum of the fibers when pumped at 793 nm

Fig. 4. (a) Absorption and (b) emission behavior of the fabricated Thulium doped fibers

are also shown in Fig. 4 (b).

Although the fibers fabricated show promising spectral results, background losses of several orders of magnitude higher than that of the standard fibers were observed. This is mainly due to the material quality of capillary tubes, the purity of solutions and salts used, and the preparation environment of the samples. GeCl_4 and SiCl_4 with purity of 99.0 % and 99.998 % respectively were used in this study. Better quality of quartz tubes as well as higher purity of solutions and salts should alleviate background losses of the fiber. In addition, since a clean room environment was not utilized throughout the work, there is a higher risk of sample contamination by dust or other impurities in between the processes. Nonetheless, while high precision is not possible due to these limits, it is also not mandatory during the early stages of prototyping.

In practical situations, not all photonics related research groups are privileged to have access to the expensive preform and fiber fabrication facilities. The degree of stringency in controlling process parameters should hence scale according to the stage of research development. This “quick and dirty” system and processes can be adopted for initial analyses until the desired doping solution composition and / or glass host selection, etc., is found. Standard fabrication can then be employed for the production of longer and higher quality fibers.

Though we demonstrated preforms of ~ 1 mm diameter, the system should be capable of scaling up to larger dimensions of tubes / preforms. This is subject to the handling limit of the splicer system, which is about 2.5 mm based on current technology. Due to differences in fabrication systems and environment, a few pre-runs for recipe / parameters matching or offsetting will be required when scaling up to the standard perform fabrication. Despite so, the advantage of reduced total time, cost and materials remains.

Lastly, one major drawback of this setup is the undesirable generation of ozone gas during the prolonged period of plasma arcing action. As ozone gas is highly corrosive and toxic, a proper exhaust system or fume extractor must be installed for safety.

IV. CONCLUSIONS

We have demonstrated a miniaturized benchtop version of the fiber fabrication process, and successfully fabricated several Thulium doped fibers using this method incorporating with the solution doping technique. The absorption and emission spectra

obtained resemble the spectral behavior of the standard Thulium doped optical fibers, albeit with high losses. Undeniably, the length and quality of the fibers are traded-off by the time and cost involved. This process is hence beneficial for acquiring small quantities of specialty optical fibers for rapid prototyping purposes, and especially so for the less mature optical fiber fabrication, such as rare earth doped or soft-glasses fibers. It also opens up the possibilities of exploring other exotic glass hosts with various material choices and compositions on a smaller scale.

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