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# Progress in the Fabrication of the Next-Generation Soft Glass Microstructured Optical Fibers

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**Abstract.** We report the fabrication of new soft glass microstructured optical fibers for sensing, high-nonlinearity and mid-infrared applications. The fibers were produced using the extrusion technique and a wide range of glass compositions. They demonstrate a wide variety of structural features and low propagation loss.

**Keywords:** soft glass, microstructured optical fibers, fiber fabrication
**PACS:** 42.81.Bm, 42.81.Dp

## INTRODUCTION

Soft glass microstructured optical fibres (MOFs) have attracted much attention in recent years, since they offer optical properties that cannot be provided with silica fibers such as high nonlinearity, high rare earth solubility and mid-infrared transmission [1]. Recently, significant progress in the development of MOFs with extremely high nonlinearities using high-index soft glasses such as lead silicate, bismuth and tellurite [1-3] has been achieved. First high-nonlinearity fibers with dispersion control were demonstrated [3]. Further, large mode area (LMA) MOFs for high power delivery and generation in the near-infrared were demonstrated using phosphate and tellurite glass [4,5].

In recent years, billet extrusion has been proven to be a versatile, single-step technique for the fabrication of soft glass MOF preforms. We developed a new die design concept and achieved significant advance in the extrusion process control. This has resulted in the successful extrusion of preforms with up to 162 holes in two different soft glasses and in polymer [6]. With this new die design concept, the maximum number of holes that can be achieved in a preform is only limited by the maximum die and billet size that can be used in the extrusion apparatus.

In this paper, we report on the fabrication of new extruded soft glass MOFs. Advances in die design, billet extrusion and fiber drawing has extended the variety of structural features that can be achieved in preform and fiber form. In addition to new structures, we extended the range of soft glass compositions that are used to fabricate MOFs. Further, the excess loss in extruded MOFs compared with unstructured extruded fibres has been minimized.

## EXPERIMENTAL

We used both commercial and in-house made glasses for the fiber fabrication (Table 1).

**TABLE 1** Glasses used for fiber fabrication.

| **Glass Label** | **Manufacturer** | **Main components** | **Refractive index at 633nm** |
|---|---|---|---|
| ZBLAN (fluoride) | in-house | $ZrF_4$-$BaF_2$-$Na_2F$ | 1.50 |
| F2 (lead silicate) | Schott Glass Co. | $PbO – SiO_2$ | 1.62 |
| SF57 (lead silicate) | Schott Glass Co. | PbO – SiO2 | 1.84 |
| Bismuth | Asahi Glass Co. | $Bi_2O_3 – SiO_2 – B_2O_3$ | 2.03 |
| Tellurite | in-house | $Na_2O – ZnO – TeO_2$ | 2.04 |

Preforms were extruded by heating bulk glass billets up to a temperature where the glass is sufficiently soft to be forced through a die structure into free-space to form a preform with a complex transverse profile. LMA fiber preforms were drawn in a single step down to the final fiber. Small core fibers were made in a two step process. First

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the structured preform is reduced in size to a so-called cane of 1-2mm outer diameter. This cane is inserted into an extruded jacket tube. Finally, this assembly is drawn down to the fiber [2]. The preform images were taken with a digital camera, whereas the fiber images were taken with a scanning electron microscope.

## SUSPENDED-CORE FIBERS

The concept of small-core high-NA fibers with a core suspended in air via 3 fine struts was developed for high-nonlinearity applications using high-index glasses [1-3]. We extended this concept to fibers for evanescent field based sensing, which requires low-index glasses to achieve a high power fraction of light in the air holes [7]. We commenced the work on low-index glass suspended-core fibers using the same die design that has been employed successfully for high-index glass fibers of the same type [2,3]. We used commercially available lead silicate glass F2, which exhibits both low index and sufficiently low softening temperature to be used for preform extrusion. Figure 1a-c shows cross-sectional images of suspended-core preforms extruded using the same die design but different glasses. The core size increases and the strut length decreases with decreasing refractive index of the glasses, which is correlated to decreasing content of heavy metal oxides. This increase in structure deformations is attributed to the increase of surface tension with decreasing heavy metal content in a glass [8]. In the fiber made from the F2 preform, the strut length to core diameter ratio is by a factor of two smaller than that of the preform.

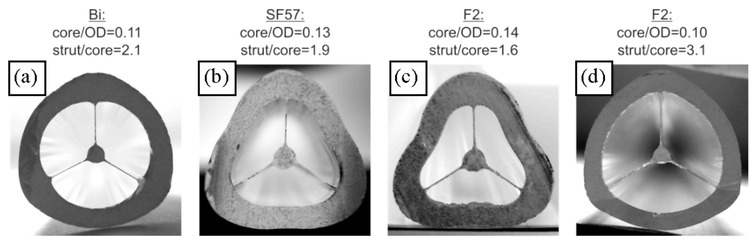


**FIGURE 1.** Cross-sectional images of preforms made from (a) bismuth glass, (b) SF57 glass, and (c,d) F2 glass. Preforms (a)-(c) were extruded using original die design, whereas perform (d) was extruded using 'upscaled' die design.

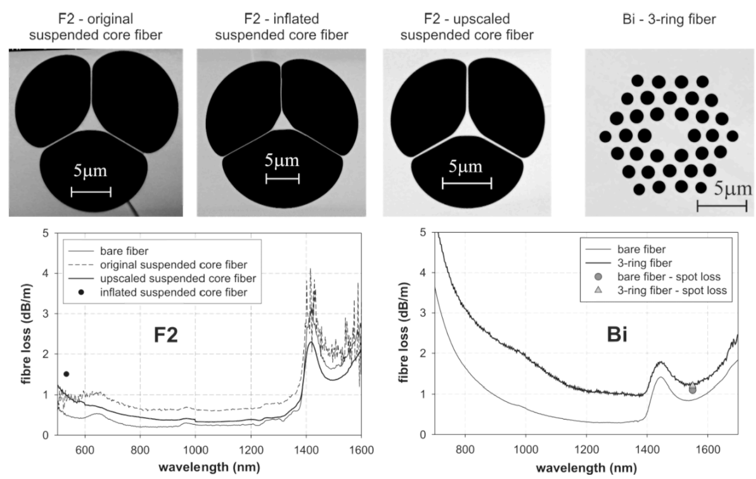


**FIGURE 2.** Cross-sectional images of F2 and Bi MOFs, and fiber loss spectra for F2 and Bi bare fibers and MOFs.

To counteract the detrimental structure deformation in the F2 fiber, we initially employed pressurization of the preform during drawing it down to a cane. This resulted in a pronounced increase in strut length relative to the core size at the cost of the strut thickness. The strut elongation or hole inflation was preserved in the final fiber (Fig. 2). The drawback of the hole inflation method is that the 'inflated' fiber has enhanced loss (Fig. 2). The 'inflated' fibers made were prone to fiber breakage during the drawing process, which is due likely to the small strut thickness.

As alternative to the hole inflation method, we explored die design modification. In the modified die (also referred to as 'upscaled' die), the core size and strut thickness were maintained but the strut length was doubled, resulting in a larger (upscaled) outer diameter of the die exit. Using the same glass (F2), and the same extrusion speed and temperature, the extrusion pressures for both the original and the 'upscaled' die design were similar, indicating similar glass flow behavior through both die types. The 'upscaled' fiber drawn using the preform extruded



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through the ‘upscaled’ die exhibits similar strut length relative to the core size as the ‘inflated’ fiber. However, the ‘upscaled’ fiber has the lowest loss of all three suspended-core fiber types made (Fig. 2). Further, the ‘upscaled’ fiber demonstrates negligible excess loss over an unstructured bare fiber, which was drawn from an extruded rod. Other advantages of the ‘upscaled’ fiber are higher coupling efficiency and good stability during fiber drawing.

Bismuth glass is a promising candidate for high-nonlinearity fibers in the near-infrared. Using the suspended-core fiber concept, extremely high fiber nonlinearity coefficient $\gamma = 1100W^{-1}km^{-1}$ was previously achieved [2]. For many nonlinearity applications, not only high nonlinearity but also good dispersion control is required. Suspended-core fiber allows only limited dispersion tailoring via alteration of the core size, whereas an array of several air holes in the fiber cladding enables wider dispersion control via adjustment of both the hole pitch and the hole size [3]. Therefore, we explored fabrication of the latter fiber type for bismuth glass using a die exit structure corresponding to a haxagonal array of circular holes with relative hole size (i.e. hole diameter to hole pitch ratio) $d/\Lambda=0.5$ and hole pitch $\Lambda\sim2\mu m$. We produced several preforms and fibers using our recently developed new die design concept [6]. Good reproducibility in both the preform and the fiber structure was achieved: The variation of $d/\Lambda$ was 0.42-0.45 in the preforms and 0.57-0.64 in the fibers. The variation of the hole pitch $\Lambda\sim2\mu m$ relative to the outer diameter of the fibers was only 1.5-1.7%. The preform structure variations are due to slight variations in the extrusion temperature. The larger relative hole size and structure variations in the fibers are due to self-pressurization effect within the cane during fiber drawing [9]. As for the suspended-core F2 glass fibers, the small-core bismuth MOFs with larger number of transverse features exhibit low excess loss (Fig. 2).

## LARGE MODE AREA FIBERS

Tellurite glasses are promising candidates for high power lasers operating in the mid-infrared. They exhibit high transmission up to ~5µm [1], high rare earth solubility without clustering and high laser gain. Recently, our research group developed a new tellurite glass compositions, which enables index matching for active (e.g. Er doped) core and passive holey cladding in a microstructured fiber laser [10]. The new glass composition also exhibits enhanced crystallization and thermal stability compared with established tellurite glass compositions for mid-infrared applications [11]. Fibers with a hexagonal array of small air holes around a large core are widely used for silica large mode area (LMA) fibers for high power applications. We extended the same concept to the development of tellurite LMA fibers. Initially, we have chosen relative hole size $d/\Lambda=0.3$. The minimum feature size in the corresponding extrusion dies can be readily machined. In addition, modeling demonstrated that for $d/\Lambda=0.3$ single mode guidance at 1550nm is maintained even for large hole pitch. Partial hole closure during perform extrusion and fiber drawing resulted in considerably reduced relative hole size of $d/\Lambda\sim0.1$ (Fig. 3). Due to the small hole size this fiber is expected to show very high bend loss. Therefore, as the next step to counteract the hole closure we extruded a perform using a die corresponding to $d/\Lambda=0.5$. The fiber drawn from this preform ($d/\Lambda\sim0.5$) exhibits a hole size gradient (Fig. 3), whereby the two inner rings have similar $d/\Lambda$ as the preform. For this fiber, we measured the mode profile and area at 1550nm to be $M^2=1.6$ and $A_{eff}=700\mu m^2$ [12].

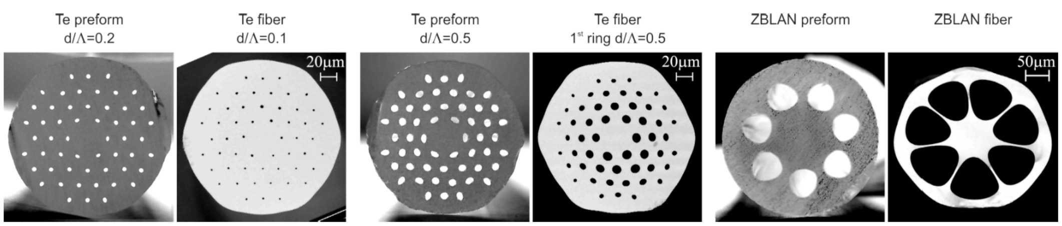


**FIGURE 3.** Tellurite and ZBLAN preform and fiber images.

In contrast to tellurite glass, fluoride glass exhibits a low refractive index and low nonlinearity, making them particularly suited for high power transmission fibers [1]. We investigated fabrication of a LMA fiber using the well established fluorozirconate glass ZBLAN [13]. To the best of our knowledge, we used for the first time ZBLAN glass for preform extrusion. Since the ZBLAN glass has a lower crystallization stability than the oxide glasses we used to date, we have chosen a relatively simple preform and fiber structure with a single ring of 7 holes. The single mode guidance in this structure is achieved through the significantly higher confinement loss of the higher order modes. The details of the preform fabrication are described in Ref. [14]. The extruded preform was successfully drawn into a LMA fiber with ~100µm core (Fig. 3). Due to the low surface tension of the fluoride glass [15], the relative hole size in the fiber is larger than in the preform. The propagation loss of the fluoride MOF is 3.2dB/m at 4µm. In comparison, the loss of a bare fiber made from an extruded ZBLAN rod is 2.1dB/m at 4µm.



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## HOLLOW-CORE FIBERS

Using our new die design concept [6], we extended the range of preform and fiber structures that can be made via extrusion to hollow-core structures with segment-shaped holes arranged circularly around the core. This fiber type is of great interest for photonic bandgap fibers [16]. We fabricated preforms and fibers using F2 and bismuth glass. Initially we used a structure comprising cladding holes of similar size. The struts between the circular glass layers were aligned radially in a line (Fig. 4a). The die exit structure was well preserved in the preform. However, the shape of some holes in the fiber was deformed into triangular shapes (Fig. 4b), which destroyed the target pattern of circular glass layers. To counteract this detrimental hole deformation, we aligned all the struts in radial lines for the next structure (Fig. 4c). As for the previous structure, the die exit structure was well preserved in the preform. In the fiber, the strut alignment prevented indeed severe hole shape deformation. The structural deformation is restricted to rounding of sharp edges as observed for the suspended core fibres with non-circular holes (Fig. 4d).

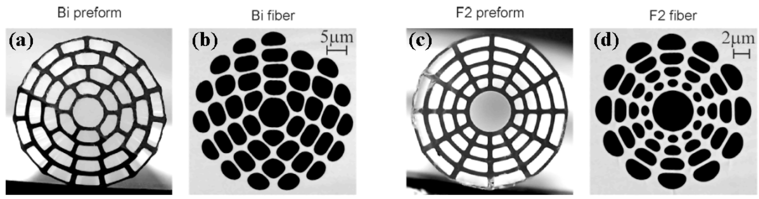


**FIGURE 4.** Bismuth and F2 hollow-core preform and fiber images.

## SUMMARY AND CONCLUSIONS

Advancement in extrusion die design, preform extrusion and fibre drawing process control has resulted in new soft glass MOFs that demonstrate a large variety of structures. These fibers were made from glass compositions that has been used for MOF fabrication for the first time and span a wide range of glass properties such as refractive index, transmission window and nonlinearity. The preform and fiber structure deformation due to different glass surface tensions were counteracted by die design modifications and preform pressurization. For different structures and glasses, the excess loss of our extruded MOFs is small or negligible (≤1dB/m), which demonstrates the great potential of our extrusion and fibre drawing technique for low-loss soft glass MOF fabrication. Further progress in MOF fabrication will ultimately result in new practical fibers for sensing, nonlinearity and mid-infrared applications.

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