Hybridized Fabrication of Robust Low-Loss Multimaterial Chalcogenide Fiber for Infrared Applications

Soroush Shabahang[1], Felix Tan[1], Joshua Perlstein[1], Guangming Tao[1], Mohammed Algarni[2], Yuanli Bai[2], Oseas Alvarez[3], Gene Tsvid[4], Kumar Patel[4], François Chenard[3], Kenneth L. Schepler[1] and Ayman F. Abouraddy[1]
[1]*CREOL, The College of Optics & Photonics, University of Central Florida, Orlando, FL 32816*
[2]*College of Engineering and Computer Science, University of Central Florida, Orlando, FL 32816*
[3]*IRflex Corporation, Danville, VA 24540; [4]Pranalytica Inc., Santa Monica, CA 90401*
schepler@creol.ucf.edu

Abstract: Double-crucible cane fabrication of highly purified chalcogenide-glass was combined with multimaterial thermal fiber drawing to produce robust low-loss 0.2 NA chalcogenide fibers monolithically provided with a polymer jacket and featuring losses <1 dB/m across the infrared.

OCIS codes: (160.2290) Fiber materials; (120.7000) Transmission; (140.3070) Infrared and far-infrared lasers

Chalcogenide glasses are well known to be highly transmissive throughout the infrared spectral region and are of interest for a wide range of applications [1]. Unlike telecommunications fibers that are thermally drawn from a preform, commercial chalcogenide glass (ChG) fibers are produced from the melt via a double-crucible technique [2], which requires an inert environment during the draw and adding a low-temperature protective cladding post-draw. In contrast, a recently developed multimaterial ChG fiber-drawing technique [3] is carried out in an ambient environment and provides a robust polymer jacket built into the preform prior to the drawing process. This approach has several salutary features: control over the fiber outer diameter, access to ultra-large numerical apertures (NAs) that are critical for nonlinear optical applications, and facilitating the fabrication of robust, dispersion-controlled, highly nonlinear nano-tapers [4]. Despite these advantages, the lowest-loss ChG fibers have all been produced to date via the double-crucible approach.

Here, we have bridged the gap between these two distinct fiber fabrication strategies – double-crucible and tradiational thermal fiber drawing – in a two-step process that combines the advantages of both. We first exploit the double-crucible technique to produce high-purity canes with a controllable core-to-cladding diameter ratio [Fig. 1(a)]. We next make use of the multimaterial fiber fabrication approach by adding a thick, thermoplastic, thermally compatible polymer outer-cladding or jacket to produce a hybrid monolithic ChG-polymer preform that is then thermally drawn in a standard draw tower in an ambient environment [Fig. 1(b)]. The preform outer diameter and the draw-down ratio are adjusted to produce a robust fiber of desired outer diameter [Fig. 1(c-e)]. We also report on characterization of this new multimaterial ChG fiber demonstrating a unique combination of features: low transmission loss, high tensile strength, and outstanding coating adhesion and durability and facile coupling of a variety of laser sources including quantum cascade lasers (QCLs) [Fig. 1(f,g)].

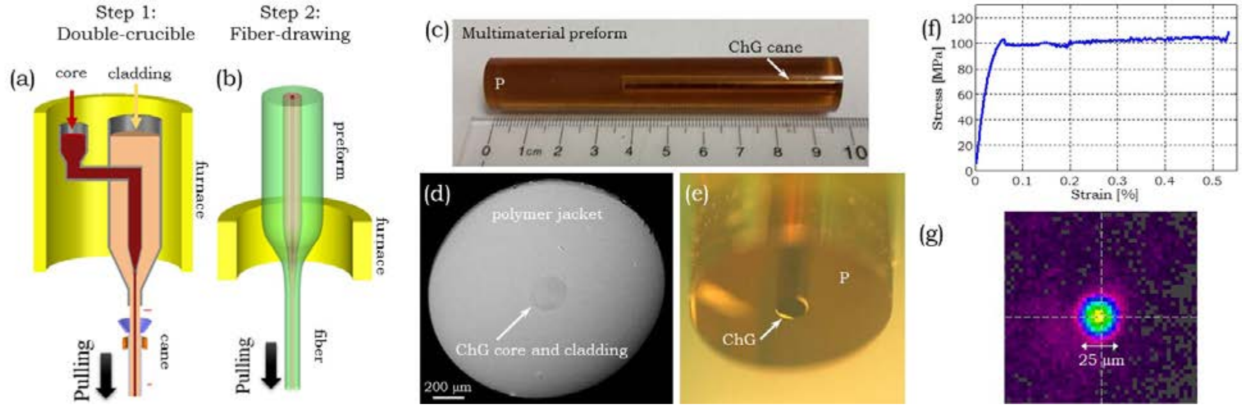

Figure 1. (a) Double-crucible fabrication of a high-purity ChG cane. (b) Thermal fiber drawing of a preform into a fiber. (c) Assembled preform showing 60-mm-long, 2.6-mm-diameter ChG cane in 15.5-mm-diameter PEI cladding. (d) SEM micrograph of the fiber end with 1.5-mm diameter PEI outer cladding and 260-µm-diameter ChG cladding (the ~20-µm-diameter core does not have sufficient contrast to be visible). (e) Optical micrograph of one of an AR-coated fiber tip. (f) Stress-strain measurement to determine the tensile strength of a PEI:ChG fiber. (g) Measured output optical beam at 4.6-µm-wavelength QCL coupled into a 12-µm-diameter core.

The ChGs used in the core and cladding were prepared from highly purified precursors in a controlled atmospheric environment to minimize impurities that would otherwise increase fiber loss [5]. The selected ChG chemical compositions were $As_{39}S_{61}$ for the core and $As_{38.5}S_{61.5}$ for the cladding, resulting in an NA of 0.2. The core and cladding ChGs were loaded into a double-crucible furnace and pulled slowly into cane diameters of 2 – 3 mm and a cladding/core ratio of ~12.6 at speeds of 10 – 20 cm/min. A ChG cane section was placed inside a PEI (polyethylimide) rod provided with a stepped hole to produce a preform. Figure 1(c) shows a 6-cm-long ChG cane inserted into the stepped hole of a PEI rod. Fibers were drawn in a two-zone furnace: the first (second) zone was held at 250 °C (385 °C), and drawing speeds up to 50 cm/min were employed to produce fibers with a core diameter in the range 10 to 12 μm. Using these parameters, as much as 20-m of useful fiber was drawn from every 6-cm-long, 3-mm-diameter ChG cane. Figure 1(d) is an SEM micrograph of a polished fiber tip.

Optical transmission losses were determined at wavelengths of 1.5 µm (a single-mode-fiber coupled laser diode) and 2 µm (a thulium-fiber laser), both low-power Gaussian-profile laser beams. Losses for several fiber samples of different lengths and diameters were consistently ~ 0.95 dB/m at both wavelengths. These losses are upper limits for the true loss since we have not accounted for coupling losses, and are consistent with the losses reported for commercial fibers produced directly by the double-crucible approach, which indicates that our fabrication process did not introduce additional losses. Furthermore, we have carried out measurements using a QCL (10 mW average power at λ=4.6 μm). The QCL beam is collimated (5 mrad divergence angle) and coupled into the fiber core via a 6-mm-focal ZnSe lens. The fiber output is imaged (Spricon Pyromam III) and the power is measured by an MCT detector connected. Using the cutback approach, the optical loss is estimated to be ~1.1 dB/m.

Since ChGs have high refractive indices, substantial Fresnel reflection losses are incurred in ChG fibers (e.g., $n \approx 2.4$ at 1.5 μm for As_2S_3, 17% reflection per surface). Several approaches have been recently investigated, such as nano-imprinting on the ChG fiber facet. In our fibers, the large outer diameter enables facile deposition of dielectric anti-reflection layers. Water adsorption on coating and substrate surfaces can result in heating of optical surfaces at mid-IR wavelengths. Differences in expansion coefficient of substrate and coating materials during heating by even relatively low IR laser powers can result in flaking, pealing and damage of IR coatings. Thus AR coatings that are durable under temperature changes and high humidity are a necessity for practical use. We chose to use a simple, one-layer quarter-wavelength AR coating on our fiber to test its durability and effectiveness. A Temescal FC-2000 electron beam evaporator was used to deposit a single layer of Al_2O_3 [Fig. 1(e)]. The thickness design for minimum reflection at 1.5 μm wavelength was 230 nm. Durability testing procedures were adapted from MIL-F-48616. Adhesion (cellophane tape), humidity (>90% @ 50 °C), moderate abrasions (cheesecloth), temperature 20-71 °C) and solubility (deionized water and isopropanol) were used to test the coating durability. There was no visible change to the coating.

Transmission at λ=1.5 μm through a 20-μm-diameter core fiber with AR coatings applied to both tips was 97.6% before durability testing (approaching the theoretical limit). Transmission after testing was 96.7% with the 0.9% change within the 1% margin of error of our instrumentation. Thus our coating is very durable and adheres well to both the polymer and the ChG areas of the fiber tip surface. While our test AR coating was a single layer with limited bandwidth coverage (< 1% reflection at 1500 ± 200 nm) multi-layer coatings can provide broader wavelength AR coverage if needed.

Finally, the tensile strength of 16-cm-long PEI-clad fibers with 1.2-mm outer diameter was measured with a MTS Insight Electromechanical Testing Machine. Loading rates were 3-8 mm/min. The inner ChG materials began to fragment at 15 MPa but the maximum strength of the PEI cladding was ~100 MPa. It was previously shown that PES (polyether sulfone) increases tensile strength of ChG core fiber by a factor of 1000, i.e. to ~ 6.5 MPa [6]. We have confirmed that our PEI-clad ChG fiber is similarly robust.

In conclusion, we have described a class of robust multimaterial ChG fibers fabricated in a two-step process that bridges the gap between the double-crucible approach and traditional thermal fiber drawing from a preform. Our new fabrication strategy produces fibers that may provide reliable, low-cost, efficient and versatile laser power delivery for numerous emerging mid-infrared applications.

References

1. G. Tao, H. Ebendorff-Heidepriem, A. M. Stolyarov, S. Danto, J. V. Badding, Y. Fink, J. Ballato, and A. F. Abouraddy, “Infrared fibers,” Adv. Opt. Photon. **7**, 379-458 (2015).
2. J. S. Sanghera, *et al*., "Development of low-loss IR transmitting chalcogenide glass fibers," (1995), pp. 71-77.
3. G. Tao, *et al*., "Multimaterial preform coextrusion for robust chalcogenide optical fibers and tapers," Opt. Lett. **37**, 2751-2753 (2012).
4. S. Shabahang, *et al*., “Octave-spanning infrared supercontinuum generation in robust chalcogenide fiber nanotapers using picosecond pulses,” Opt. Lett. **37**, 4639-4641 (2012).
5. F. Chenard, O. Alvarez, and H. Moawad, "MIR chalcogenide fiber and devices," Proc. SPIE **9317**, 93170B (2015).
6. G. Tao, *et al*., "Multimaterial disc-to-fiber approach to efficiently produce robust infrared fibers," Opt. Mat. Express **4**, 2143-2149 (2014).