Silica-clad crystalline germanium core optical fibers

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Silica-clad optical fibers comprising a core of crystalline germanium were drawn using a molten core technique. With respect to previous fibers drawn using a borosilicate cladding, the present fibers exhibit negligible oxygen despite being fabricated at more than twice the melting point of the germanium. The counterintuitive result of less oxygen when the fiber is drawn at a higher temperatures is discussed. The measured propagation loss for the fiber was 0.7 dB/cm at 3.39 μm, which is the lowest loss reported to date. © 2011 Optical Society of America

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Semiconductor core optical fibers have generated growing attention recently [1]. While the majority of studies to date have focused on silicon [2,3], fibers containing germanium [4–6] could have additional practical benefits. First, a simplified model for Raman gain based upon the refractive index (n) yields a $(n^2 - 1)^2/n^2$ proportionality [7]. Given published values for the refractive index of germanium as a function of wavelength [8], the ratio of Raman gain for germanium should be about 50% higher than silicon over the mid-IR spectral range. Additionally, germanium is transparent from about 2 to 15 μm, making it potentially useful for a wide range of mid-wave and long-wave IR applications [1].

Employed here is a molten core fabrication approach in which the cladding glass is chosen such that it draws into fiber at a temperature where the core is molten. Previously, a germanium core optical fiber, crystalline over its entire length [9], was fabricated using a commercial sodium borosilicate glass since this cladding drew at a temperature just above the melting point of the germanium core [5]. Attenuation in those fibers was too high to be measured due either to fairly low purity level of the germanium source rod or, possibly, dissolution of boron and other defect-level inducing impurities from the cladding glass into the germanium melt.

The purpose of this proof-of-concept work is to determine if germanium core optical fibers can be fabricated with a silica cladding; that is, processed at well-over twice its melting temperature. Additionally, does a cladding glass free of impurities such as boron aid in enhancing the transparency of the resultant fiber? That is, both scientific and a practical rationales are behind this work.

In order to directly compare results, a 3 mm rod was core-drilled out of a slab of polycrystalline optical grade n-type germanium (Novotech, Acton, Massachusetts). This rod was sleeved into a silica tube having an inner diameter of about 3 mm and an outer diameter of 30 mm, which had been predrawn in order to seal one end of the tube. Fibers were drawn at Clemson University using the Heathway draw tower at approximately 1925 °C. At this temperature, the Ge core is over twice its melting point (938 °C). For the results discussed below, the fibers had an outer diameter of 3 mm, yielding a core size of about 300 μm. While these dimensions are large by "fiber" standards, long lengths (>100 meters) of flexible crack-free glass-clad semiconductor core have been realized [5].

Fibers were cleaved and their cross sections observed under an optical microscope (Mitutoyo MFU 505B). Electron microscopy was performed using a Hitachi 3400 N scanning electron microscope operated at 20 kV and a working distance of 10 mm under variable pressure. Elemental analysis was performed using energy dispersive x-ray spectroscopy in order to examine the distribution of elements spatially across the core/clad interface.

In order to measure the fiber loss, a continuous wave He–Ne laser operating at 3.39 μm was focused using a CaF_2 lens of 25 mm focal length to a spot size of 50 μm. The beam was coupled into the silica-clad germanium fiber where both ends had been well-polished. The intensity of the light prior to and following propagation through the fiber was recorded using an indium antimonide (InAs) detector. After factoring out the Fresnel reflection of both germanium–air interfaces, the propagation loss was estimated. All measurements were made at room temperature.

Figure 1 provides an optical micrograph of the cross section of the as-drawn and cleaved fiber. Clearly observed is the core, which exhibits a strong Fresnel reflectivity as expected from germanium (refractive index, $n \sim 4$) under visible illumination. The core is circular and concentric within the silica cladding. The crescent-shaped feature in Fig. 1 is a gap between concentric silica cladding tubes resulting from an incomplete fusion at the draw temperature. Multiple tubes were layered together in order to achieve the desired core/clad ratio.

Figure 2 shows the elemental (Si, O, Ge) profile spatially from cladding (negative relative distance values), across the core/clad interface (zero relative distance), and into the core (positive relative distance values). The cladding is clearly stoichiometric silica with an atomic percentage of 1/3 silicon and 2/3 oxygen; i.e., SiO_2. An analogous germanium core optical fiber drawn at about 1000 °C in a borosilicate glass cladding exhibited an oxygen concentration of about 4 wt. % [5]. It is very counterintuitive that there would be less oxygen in the solidified product of a melt processed at nearly 2000 °C versus that processed at about 1000 °C.

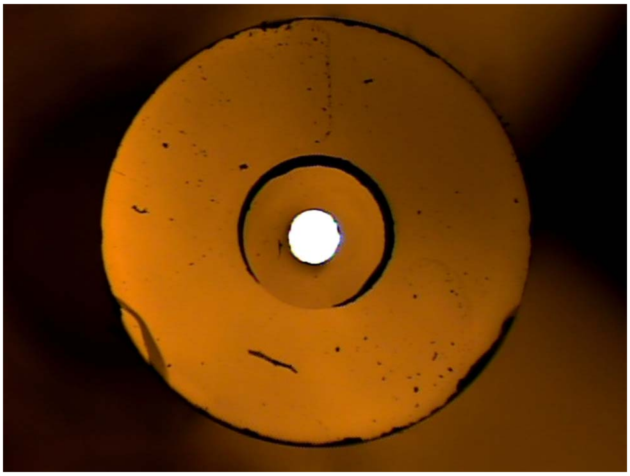

Fig. 1. (Color online) Optical micrograph of a cleaved cross section of the silica-clad germanium core optical fiber. Note the circularity and concentricity of the fiber and metallic appearance of the core. The crescent-shaped feature is a gap between concentric silica cladding tubes, used to achieve the desired core/clad ratio, that did not fully fuse together at the draw temperature.

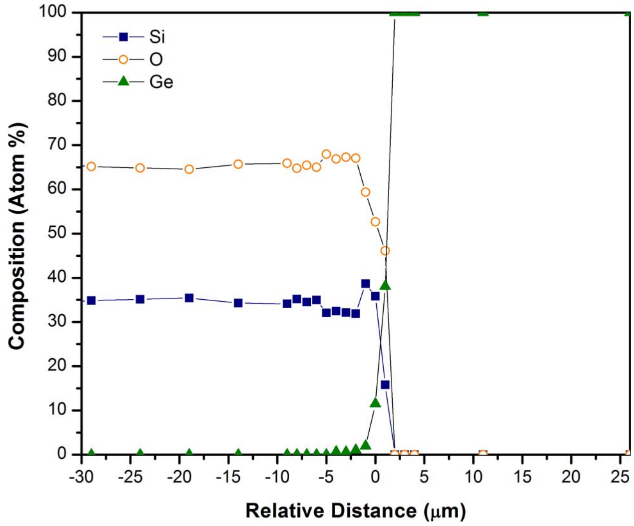

Fig. 2. (Color online) Elemental analysis of the silica-clad germanium core optical fiber. The cladding, negative relative distance, which represents the core/clad boundary, exhibits stoichiometric SiO_2. The core, positive relative distance, is found to be entirely germanium to within the tolerance of the measurement.

The most likely source of oxygen in these melt-derived fibers is dissolution of the cladding glass by the core melt during the fiber draw process [1]. While dissolution is a thermally activated process increasing with increasing temperature, the germanium and germanium oxide system have additional subtleties. Most notable is that germanium oxide is volatile at high temperatures [10], as is known from the core "burn-out" of germania (GeO_2)-doped silica optical fibers. Further, this volatile species likely then fines out of the molten core given the very low melt viscosity of germanium [11]. In other words, the thermodynamics of the Ge–O system favor a self-purification in the melt phase.

Previously fabricated borosilicate-glass-clad germanium core optical fibers [8] exhibited propagation losses that were too high to measure, most likely due to the low purity level of the germanium core or impurities diffusing in from the borosilicate glass. The measurable out-coupled intensity from the silica-clad germanium fiber was greatly improved, yielding a propagation loss of 0.7 dB/cm. This suggests that these silica glass-clad fibers possess fewer oxygen and defect-generating impurities. For completeness, it should be noted that the fiber samples employed in this work were ones with no observable cracks and discontinuities along the fiber. Given the significant expansion mismatch between core and clad, cracks were occasionally observed; typically every few centimeters. Further improvements, such as thermal expansion-matched cladding layers, are being developed in order to further reduce occasional cracking and related imperfections in the fibers. Last, while a dB/cm loss is reasonable for planar waveguides, dB/m loss values likely are necessary for practical fiber devices and tens of dB/km losses might be possible [1].

In summary, germanium core optical fibers have been fabricated using a pure silica cladding glass. The fibers exhibited a well-defined core/clad interface with negligible oxygen present in the core. The loss of the fiber was measured at 0.7 dB/cm, which, although high by comparison to conventional glass fibers, is a significant improvement over previous crystalline germanium fiber waveguides. Further management of the chemical interactions between the core melt and cladding glass are critical to the further improvement of melt-derived optical fibers.

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