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Fabrication and characterization of chalcogenide polarization-maintaining fibers based on extrusion

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ABSTRACT

The fabrication and characterization of IR chalcogenide polarization-maintaining (PM) step-index optical fibers with elliptical-core and 1-in-line-core have been reported for the first time. An improved isolated co-extrusion method was used to fabricate these core-shaped PM fibers. The elliptical core had a horizontal radius of a = 3.66 μm, vertical radius of b = 1.83 μm and the 1-in-line core of a = 4.83 μm, b = 1.42 μm, respectively. Single-mode PM beam spots were observed for the elliptical-core and 1-in-line-core fibers in the near-field energy distributions. The highest values of birefringence of the elliptical-core and 1-in-line-core fibers are 2.09×10^{-4} at 2.7 μm and 3.272×10^{-4} at 2.8 μm, respectively. The extinction ratios of −3.7 dB and −2 dB were achieved in fibers of 0.5 m long with elliptical-core and 1-in-line-core, respectively.

1. Introduction

In fiber optics, polarization-maintaining optical fiber (PMF or PM fiber) is a single-mode optical fiber in which linearly polarized light, if properly launched into the fiber, maintains a linear polarization during propagation, exiting the fiber in a specific linear polarization state; there is little or no cross-coupling of optical power between the two polarization modes. Such fiber is used in special applications where preserving polarization is essential, such as interferometry, fiber optic gyroscope, coherent optical communications, and integrated optics. Birefringence can be obtained through the introduction of anisotropy within the core of the PM fiber, either via geometric design of an elliptical core, or, more conventionally, through the application of a controlled uniaxial stress. The former two approaches are described as shape [1–4] and stress birefringence [5,6], respectively. Polarization-maintaining characteristics can be achieved in the elliptical-core fibers, due to the wave propagation constants changed with orthogonally polarized modes existing in the elliptical fiber core (noncircular shape of its cross-section, i.e. core shaped). Such PM fibers with form birefringence possess simpler structure, but exhibit higher thermal and mechanical stability than those fibers with the stress birefringence [7]. The elliptical-core fibers can be integrated into active elements of fiber-optic sensors for measuring various physical parameters conveniently [8–13].

Chalcogenide glasses (ChGs) are based on one or more chalcogen elements S, Se, and/or Te associated with other elements like As, Ge, Sb, and Ga, etc. These glasses are attractive because of their high nonlinearity (n_2 as high as 3×10^{-18} m^2/W) [14–16], high refractive indices (2.0–3.5), low phonon energies (down to 350 cm^{-1}) [17,18], and wide transmission region (up to 25 μm in the infrared (IR)) [19,20]. Therefore ChGs have been widely used in linear or non-linear optics such as mid-infrared (MIR) supercontinuum generation [21–24], endlessly single mode IR fibers[25], or IR Raman fiber laser [26]. In the IR range, PM fibers are of interest for devices where a broadband infrared source with high brightness and strong coherence is used [27,28]. PM fibers can generate higher signal-to-noise ratio, as that can reduce the demands of additional polarizing elements in optical systems, which would decline the intensity of the IR signal. Besides, A PM fiber can be used instead of a polarization controller coupled to a single-mode fiber to reduce the environmental instabilities due to temperature variations of the source and mechanical vibrations. ChG microstructured optical fibers (MOFs) are often used for polarization maintaining by designing an asymmetric arrangement of air holes. Zhang et al. reported a high birefringence by using gallium lanthanum sulfide chalcogenide glass

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(GLS) in Mid-IR region [29]. A highly birefringent chalcogenide As_2Se_3 glass photonic crystal fiber (PCF) was designed and analyzed with negative chromatic dispersion and low confinement loss [30]. Luke et al. designed and simulated a highly birefringent chalcogenide asymmetric solid core PCF [31]. Recently, a highly birefringent PM chalcogenide MOF has been realized [32]. However, most of ChG PM optical fibers reported above are PM-MOFs, that were usually made by methods of stacking or casting, and the fabricating processes of these ChG PM-MOFs preforms are complex and less robust. There are few reports about ChG core-shaped PM fibers whose structures are simple but robust to be fabricated (e.g., elliptical-core fibers).

In the past, ChG IR fibers were mainly prepared by the "rod-in-tube" or "double crucible" techniques [33,34]. However, the fiber structure and size are all restricted by the size of crucibles in the "double crucible" method, and the required surface smoothness and tightness of the combination of the core and cladding are difficult to achieve in the "rod-in-tube" method. Recently, an extrusion method has been adopted to produce ChG fiber preforms [35,36]. In this method, the assembled glass billets are loaded into an extrusion sleeve that is heated above the materials' softening temperature and extruded through a die under high pressure and a fixed speed to obtain a multimaterial preform with core and cladding. Most importantly, compared with the "rod-in-tube" method, a tight combination of the core and cladding can be obtained, as well as the fine interface between the core and cladding because the entire process of the fiber preform preparation is under high pressure.

In the present paper, two kinds of core-shaped PM fiber preforms based on As_2S_3 and $As_{38}S_{62}$ bulk glasses have been prepared by an improved two-step isolated co-extrusion method. The extruded preforms were drawn into elliptical-core and 1-in-line-core fibers with designated diameters. Then, the differences between the elliptical-core and 1-in-line-core fibers were systematically investigated. Finally, the PM behaviors of the elliptical-core and 1-in-line-core fibers were explored, and the extinction ratio measurements were performed with lively illustration.

2. Experimental

2.1. Glass preparation

ChGs of As_2S_3 and $As_{38}S_{62}$ as the core and cladding materials, respectively, were prepared in silica ampoules under vacuum (10^{-3} bar) using a distillation method [37]. Commercially available high purity sulfur (5 N) and arsenic (5 N) were used as starting materials and they were further purified with a certain amount of magnesium for the removal of water and surface oxide impurities. They were then sealed before they were agitated and maintained at 750 °C for 12 h in a rocking furnace to ensure homogeneity. Finally, high-purity glass rods could be obtained through the traditional melt-quenching method. The glass rods were cut into 2 mm-thick slices that were then polished for optical measurements. Each glass was also prepared in the form of cylindrical rods ($As_{38}S_{62}$: Φ46 mm × 20 mm, As_2S_3: Φ9 mm × 20 mm).

2.2. Fabrication of fiber preforms

We adopted an improved two-step isolated co-extrusion method to fabricate the fiber preforms [38]. The first-step co-extrusion process was shown in Fig. 1(a) and (b). Two pairs of the core and cladding glasses (As_2S_3: Φ9 mm × 20 mm, $As_{38}S_{62}$: Φ46 mm × 20 mm) were prepared to produce elliptical-core and 1-in-line-core fiber preforms in the first-step co-extrusion. Here, the bulk glasses of the core and cladding were placed firstly into the extruder sleeve, while the core glass was placed in a sleeve with a specialized elliptical (or in a 1-in-line shaped hole) outlet on top of the cladding glass, and the cladding glass in a sleeve with an out diameter of 9 mm. Secondly, the entire area of the extruder sleeve was heated to a temperature at 300 °C, and an appropriate force was applied to the core sleeve (Fig. 1(a)). Then, another force was applied to obtain the preform (Fig. 1(b)). Finally, the preform was annealed at 30 °C below T_g for four to six hours to minimize inner stress and then cooled to room temperature. The preform (Φ9 mm × 20 mm) obtained above and the same cladding glass ($As_{38}S_{62}$: Φ46 mm × 20 mm) were co-extruded again to produce preform with smaller core/cladding diameter ratio, as shown in Fig. 1(e) and (f). All the above experiments were under a protective N_2 atmosphere condition.

2.3. Fiber drawing

Due to the fragile nature of chalcogenide glasses, we rolled 1 mm-thick polyethersulfone (PES) films around the extruded rod and consolidated the films with glass rod under a vacuum of 10^{-2} Pa at 206 °C for 5 h to form a preform with a diameter of 10 mm. Then the fiber preforms coated with PES were drawn into fibers of a few hundred micron diameters in the fiber drawing tower (SG Controls, UK). During the drawing, the preforms were protected in an inert gas atmosphere.

2.4. Optical measurements

The IR transparency spectra of the $As_{38}S_{62}$ and As_2S_3 glasses were measured using Fourier transform infrared spectroscopy (FTIR) (Thermo Scientific, Nicolet 380, USA) over a range from 2.5 to 15 μm at room temperature. The refractive indices of the samples were recorded by an Infrared Variable Angle Spectroscopic Ellipsometer (IR-VASE; J. A. Woollam Co., Lincoln, NE) at different wavelengths. The losses of the fibers were calculated by the secondary truncation method using the FTIR (Thermo Scientific, Nicolet 5700, USA) [39]. The cross sections of the fibers and preforms were observed by an Ultra-Depth Three-Dimensional Microscopy (Keyence, VHX-1000E, Japan).

2.5. Experimental set-up for the near-filed energy distributions and extinction ratio measurement

A 1480 nm pulse laser (Calmar Laser, FPL-04CFFNBU, USA) was used to measure the near-field energy distributions of the fibers. The laser output passed through polarizer and then was collimated and coupled into the fiber by the ZnSe lens. Intensity distribution at the end cross section of the fibers was monitored using a NIR optical field beam analyzer (Xenics, XEN-000298, Belgium). While rotating the polarizer, the beam intensity of the fiber core was measured by the beam analyzer.

3. Results and discussion

Photographs of the extruded core/cladding preforms with different shapes and dimensions of the fiber cores are shown in Fig. 1(c), (d), (e), and (f). The fiber preforms were well polished to show more details on the fiber cross-sections. The distinctions of the core and cladding are clear. No bubbles, cracks, or gaps could be found in the preforms.

The transmission spectrums of the cladding and core sample glasses (thickness of 2 mm) are shown in Fig. 2(a) and (b), respectively. The spectrums are flat with only a few absorption peaks.

The PES jacket can be removed by organic solvents. Considering the fragility of naked chalcogenide fibers, we handled the fiber cross-sections via a cutting method instead of the traditional polishing method. Fig. 3(a) shows the cross section of an elliptical-core fiber with an elliptical core of horizontal radius a = 3.66 μm, vertical radius b = 1.83 μm and a cladding diameter of 265 μm, and Fig. 3(b) shows its inner-cladding and core. Fig. 3(c) shows the cross section of a 1-in-line-core fiber with a 1-in-line core of a = 4.83 μm, b = 1.42 μm and a cladding diameter of 160 μm, and Fig. 3(d) shows its inner-cladding and core.