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Single-mode fluorotellurite glass fiber

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ABSTRACT

By multi-stage rod-in-tube fiber drawing process, a single-mode fluorotellurite glass fiber was fabricated and reported for the first time. Benefiting from chemical–physical dehydration process to remove water and OH^- groups, the propagation loss was decreased to 1.9 dB/m at 1550 nm and the infrared window is extended from 2.8 μm to 4.2 μm, i.e. a new kind of mid-infrared glass fiber. The fiber is with a small core of 3.52 μm in diameter to meet single-mode condition, and the effective nonlinear parameter γ was estimated to be 236.7 W^{-1} km^{-1} at 1550 nm by using continuous-wave self-phase modulation method. © 2015 Elsevier B.V. All rights reserved.

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1. Introduction

Single-mode fiber (SMF) is desirable for signal transmission and amplification in optical communication field [1–8]. Due to high refractive index, mid-infrared (mid-IR) solid-core soft glass fibers [7,8], such as chalcogenide, fluoride and tellurite glass fiber, are difficult to get suitable numerical aperture (N.A.) and meet single-mode condition only if small-size core is made and small refractive index difference is achieved. Mid-IR SMF in the range of 2–5 μm has many potential applications, such as signal regeneration in telecommunication, mid-IR supercontinuum generation, and frequency conversion by using Raman shifting [1–14].

Among multi-component soft glass fibers, fluoride and chalcogenide glass fibers have attracted a great deal of research interest because of their low background loss in the mid-IR region [1,15]. However, their applications are not straightforward so far due to inferior mechanical and chemical properties [3,7,11,14]. As an alternative choice, researches turn to mid-IR oxide glass fibers such as Bi_2O_3-based and TeO_2-based (tellurite) glass fibers, of which the IR cut-off wavelength is not beyond 3 μm due to the residual OH^- groups [16,17]. To remove water and OH^- groups by using physical and chemical dehydration (PCDH) technique, for example, fluorides (e.g. ZnF_2) are added into tellurite host glass to open mid-IR window. This kind of fluoride-modified tellurite glass is named by 'fluorotellurite glass' [18,19], and is found to be with good thermal stability ($\Delta T \sim 138$ °C) for fiberizing and mid-IR cut-off wavelength edge until ~6 μm [18,19].

Owing to heavy crystallization at the core-clad interface during fiber drawing process, Donnell et al. [20,21] could only draw unstructured fluorotellurite glass fiber with high loss of 2.1–4 dB/m at 1550 nm, and Savelii et al. [22] reported cumbersome fabrication of single index microstructured fluorotellurite glass fibers with very high loss of around 14 dB/m at mid-IR region. Recently, a core-clad structured multimode fluorotellurite glass fiber was successfully fabricated and reported by our group, but this fiber still has high propagation loss of 3.61 dB/m at 1550 nm [23]. We are striving hard to fabricate low-loss single-mode fluorotellurite glass fiber by overcoming possible contamination and crystallization at the interface between core-rod and clad-tube [1–9]. And the fabrication process involved with multi-stage rod-in-tube fiber drawing operations is not very difficult to carry out.

In this study, we reported on the fabrication of single-mode fluorotellurite glass fiber. The fiber is with relatively low loss of 1.91 dB/m, small core of 3.52 μm in diameter and an effective nonlinear parameter γ of 236.7 W^{-1} km^{-1} at 1550 nm. To the best of our knowledge, all the parameters are optimized to its best historical level.

2. Experiments

The core glass was developed with molar composition of $60TeO_2–30ZnF_2–10NaF$ (mol%, TZNF60). Well-matched TZNF cladding glass composition was $57TeO_2–33ZnF_2–10NaF$ (mol%, TZNF57). The glasses were prepared by traditional melting-

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quenching method along with optimized PCDH technique, and the fiber preforms were made by using built-in casting method [14,18,19,23]. The fabrication procedures of fluorotellurite glass and fiber preform were described and reported in detail by our group before elsewhere [14,18,19,23]. The core-clad preform was drawn into fiber canes with diameter of 2–6 mm as shown in Fig. 1(a) [14,23], and the fiber cane is with the same core-clad ratio to its mother perform. No obvious stripe and bubble were found in the core of fiber cane, which shows obvious advantages over the

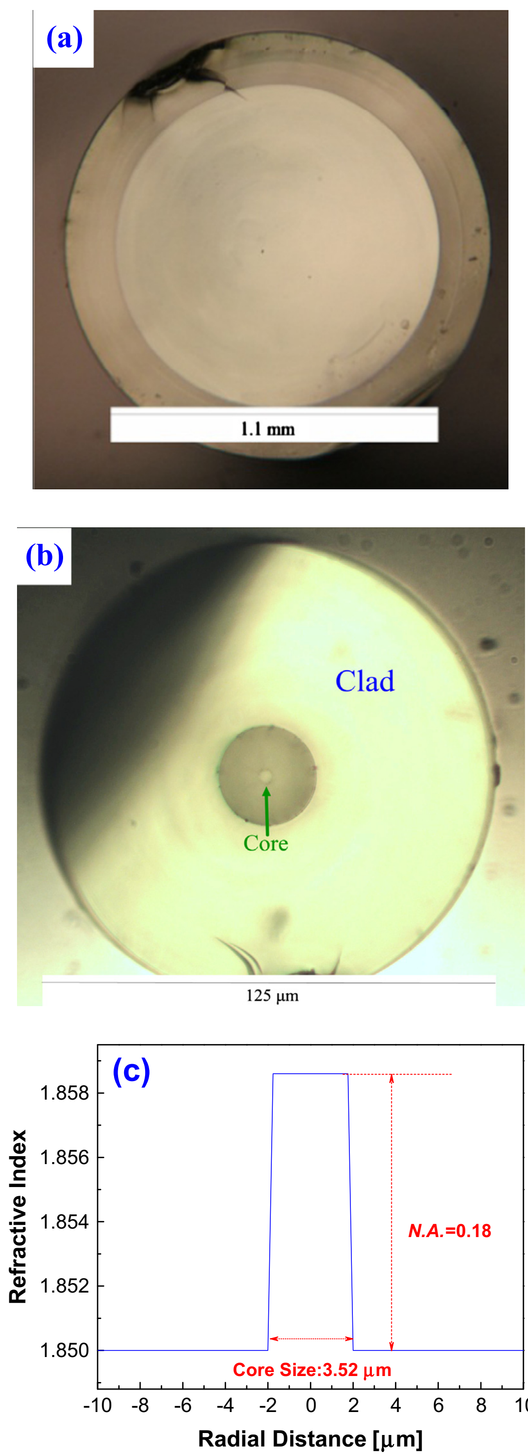

Fig. 1. Cross-section micro-graphs: (a) TZNF60/57 fiber cane, (b) single-mode fluorotellurite glass fiber; (c) refractive index profile of TZNF60/57 fiber.

cane in our previous work [23]. To remove impurities and defects on the glass surface, original TZNF fiber preform and the drawn fiber canes were well-polished and disposed by multistage acid-etching process [24,25], which is believed to be the key step to decrease fiber loss.

In order to obtain small core size to meet single-mode condition, the fiber cane was inserted into TZNF57 glass tube made by high-speed rotational casting method. By using rod-in-tube fiber drawing method to decrease fiber core size for a few times [14,23,25], a single-mode fluorotellurite glass fiber was successfully fabricated in the end (see Fig. 1(b)). As proposed in Fig. 1(c), the fiber has a small core of ~3.52 μm in diameter with a numerical aperture (N.A.) of 0.18, and normalized frequency parameter V was calculated to be around 1.28 at 1550 nm, indicating single-mode behavior. A series of experiments were done to characterize this fiber accordingly [14,23].

3. Results and discussion

3.1. Mid-infrared transmission properties of bulk glass and fiber cane

Fig. 2 presents transmission spectra of tellurite bulk glass $60TeO_2$–$30ZnO$–$10Na_2CO_3$ (mol%, TZN60, thickness: 5.144 mm) [14], fluorotellurite bulk glass TZNF60 (thickness: 5259 mm) and fiber canes measured by a Fourier transform infrared spectroscopy (FTIR, Bruker, Vertex 70 series). In Fig. 2(a), OH^- absorption at around 3.3 μm was not almost observable in TZNF60 fluorotellurite glass but strong in TZN60 tellurite glass, demonstrating the effectiveness of PCDH method to remove residual water and OH^- [18,19]. Compared with tellurite glass fiber cane TZN57/60, the IR cut-off wavelength λ_R of fluorotellurite glass fiber cane

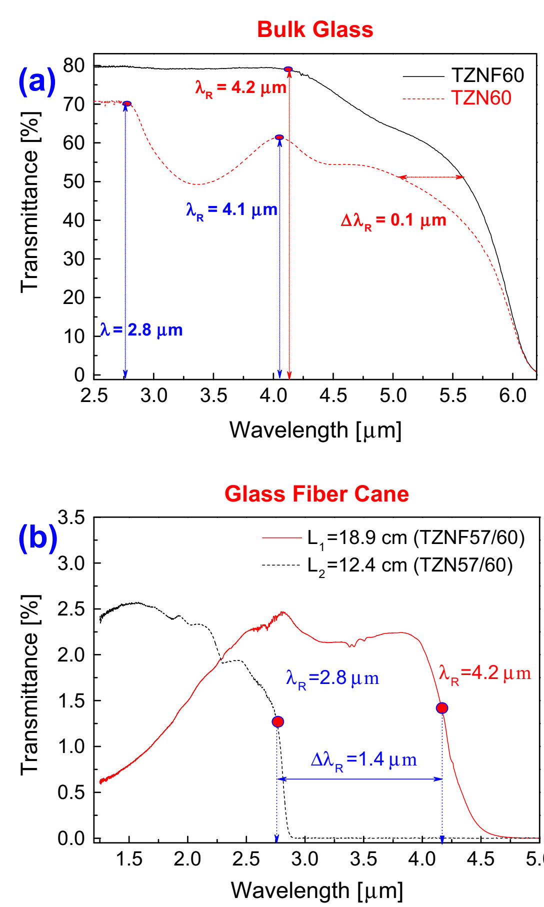

Fig. 2. Transmission spectra of tellurite and fluorotellurite glasses and fiber canes.

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