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Properties of tellurite-based high numerical aperture fibers with diamagnetic core and cladding glasses

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ABSTRACT

The fabrication and characterization of a tellurite based high numerical aperture magneto-optical glass fiber are presented. Different glass groups were investigated in terms of their structural, thermal, mechanical, optical and magnetic performance as a core/cladding pair and their refractive index contributions to the numerical aperture. A well matched core/cladding pair was selected: 75%TeO_2–20%ZnO–5%Na_2O (mol.%) for core glass, 42%TeO_2–18%ZnO–15%K_2O–20%Ge_2O–5SiO_2 (mol.%) for cladding glass. The fibers have a good cross section and a numerical aperture as high as 0.9. The Verdet constant of this high numerical aperture fiber was close to that of bulk glass.

1. Introduction

Specialty optical fiber, such as high numerical aperture (NA) fiber, is gaining more interest for photonics and magneto-optical (MO) applications [1]. The NA is a convenient way to measure the light-gathering ability of an optical fiber. High NA fiber exhibits a large acceptance angle and good confinement of light within the core and these ensure the high NA fiber has high light-gathering ability, low bend loss, smaller mode area and high light intensity. In addition, high NA fiber also finds applications in non-linear properties and supercontinuum generation [2].

Current high NA fibers are based on plastic optical fibers [3], crystal fibers [4–6], and tapered fibers [7,8]. Materials currently employed for high NA fiber are mainly pure silica and polymer both of which have drawbacks: pure silica is not cost-effective while polymer has high attenuation and low operating temperature which are very critical for many applications, and in addition, these fibers have no MO property. The advantages of particular interest in using MO fibers include high Faraday rotation, compactness and immunity to electrical interference, especially in components using Faraday effect such as MO current transducers [9], optical isolators [10] and Faraday rotators [11].

MO high NA fiber combining the merits of high NA and MO properties is the innovation of this study. Up to now no publications have reported on the implementation and characterization of the Faraday effect in high NA glass fiber. Common tellurite-based fibers [12], As–S glass fiber [13] and CdSe quantum doped Bi:YIG [14] glass fiber for Faraday rotation applications have been reported. As–S glass fiber is not stable and their MO property depends greatly on temperature, while CdSe Quantum doped Bi:YIG glass fiber is expensive, both for materials and the fiber drawing technique [15,16].

Thanks to the high polarizability of Te^{4+} ions and its high transparency from visible wavelengths up to the mid-IR, the TeO_2 based glass family and fibers exhibit the required characteristics for the development of efficient MO components [17,18]. Based on a previous study of MO glass and fibers [19–23], high NA glass candidates based on tellurite were studied and characterized with the purpose of obtaining matchable good mechanical, thermal, optical and magnetic properties core-cladding glass pair for high NA fiber fabrication and MO devices. According to fiber structure and drawing requirement, the precursor core and cladding glass must be well matched in parameters such as thermal expansion coefficient (α), glass transition temperature (T_g) and refractive index (n). According to the definition of NA ($\mathrm{NA} = (n^2_{\mathrm{core}} - n^2_{\mathrm{cladding}})^{1/2}$), the difference in refractive index of core and cladding glasses was critical for obtaining a high NA fiber.

2. Experiment

2.1. Fabrication of glass

Glasses under study are TeO_2 based glass systems. Based on a previous study, 75TeO_2–20ZnO–5Na_2O (TZN) was selected as the core glass. In order to find compatible core and cladding combinations for high NA fiber, 6 tellurite glass systems have been studied: TeO_2–ZnO–Na_2O–BaO (TZNB) group, TeO_2–ZnO–K_2O–GeO_2 (TZKGe) group which includes TeO_2–ZnO–K_2O–GeO_2–SiO_2 (TZKGeSi), TeO_2–ZnO–Na_2O–K_2O–GeO_2–SiO_2 (TZNKGe) and TeO_2–ZnO–Na_2O–Nb_2O_5 (TZNNb) which includes TeO_2–ZnO–Na_2O–Nb_2O_5–LaO (TZNNbLa). The presence of BaO, K_2O,

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GeO_2 and SiO_2 in the tellurite glass system is to increase the glass forming ability and adjust physical properties in terms of glass transition temperature (T_g), crystallization temperature (T_x), thermal expansion coefficient and refractive index.

Glasses of nominal compositions were fabricated by the melt-quenching method. Optical grade reagents (Aldrich, purity 99. 9%) TeO_2, ZnO, Na_2O K_2O, GeO_2, Nb_2O_5, LaO and SiO_2 were weighted and mixed in Pt crucibles in a glove box at melting temperatures ranging from 800 °C to 1350 °C (depends on different glass compositions) for 1 h and were cast on a 300 °C preheated brass plate followed with annealing at $T_g + 10$ °C for 2 h. Before the annealing process, the T_g was determined by differential scanning calorimetry (DSC) measurement. The glasses were cut into parallel slabs of about 1–3 mm thick and optically polished using a polishing instrument (Logitech PM5). The details of the glass composition, glass melt and annealing temperatures and periods are given in Table 1. Note that annealing was not performed on poor quality glasses or ceramics.

The fiber preform can be fabricated using the modified rod – in – tube technique that proposed by this group for the manufacturing of tellurite glass fibers [22]. A tube made of the cladding glass, 11 mm outer diameter and 4.5 mm inner diameter, can be made by a rotational casting technique at 3000 r.p.m. The core glass melts were then casted into the tube and formed the preform using modified the rod-in-tube technique. After polishing, the preform can be mounted in a fiber drawing tower. During the fiber drawing process, an online monitoring system can track the fiber diameter. The fiber diameter along the entire spool is around 125 ± 5 μm with an internal core of 45 ± 5 μm [23].

2.2. Characterization of the glass and fibers

The T_g and T_x of fabricated glasses were measured by differential scanning calorimetry (Perkin-Elmer DSC7), under N_2 atmosphere at a heating rate of 10 °C/min. Thermo-mechanical analysis (TMA) (Perkin Elmer DMA-7) was employed to measure the thermal expansion coefficient. The refractive index was measured by the prism coupling method using Metricon 2010. The absorption spectra were recorded from 400 nm to 3000 nm wavelength by means of a UV–VIS–IR spectrophotometer (Varian Cary 500), the samples for the absorption test were optically polished with a thickness of approximately 2.5 mm. Optical absorption in the Fourier transform infrared (FT-IR) region from 2.8 μm to 5.0 μm were recorded for core and cladding glasses. The mechanical hardness of the glasses was tested by a Vickers hardness instrument using the diamond indenter applied to the glass at 100–200 g load. From the square indent formed on the glass, the Vickers hardness can be calculated by the formula: $HV = 0.1891F / d \cdot 2$, where F is the applied load and d is the diagonal of the indentation. Raman spectra were measured on the core and cladding glasses using a Raman spectrometer (RSI 2001 B, Raman system, INC) equipped with a 532 nm solid-state diode green laser.

The Verdet constant was measured using a home-made optical bench which has been described in the literature [23]. The glass was mounted on the optical bench as shown in Fig. 1 [24]. A He–Ne laser was focused on the glass using a ×10 microscope objective with NA = 0.28, resulting in a launching efficiency of 29%. The polarization extinction ratio of the laser beam was measured to be better than 1 in 5000. The glass was surrounded by an in-house-made solenoid, consisting of a copper electrical wire, 2 mm in diameter, coiled into 300 turns around a 30 cm long PTFE tube with a radius of $r_1 = 11.5$ mm. The overall outer radius of the electrical coil was $r_2 = 17$ mm. From the Biot–Savart law, the theoretical magnetic field density distribution along the glass is given by Eq. (1). The magnetic field density was measured using a teslameter (PHYWE, 13610-93), at several positions along the solenoid, which was excited by a current of 10 A [23]. Eq. (1):

$$B_{th(x)} = \frac{\mu \cdot I \cdot N}{2l(r_2 - r_1)} \left(\left(x + {}^{l}/_{2}\right) \cdot \ln \frac{\sqrt{{r_2}^2 + \left(x + {}^{l}/_{2}\right)^2} + r_2}{\sqrt{{r_1}^2 + \left(x + {}^{l}/_{2}\right)^2} + r_1} - \left(x - {}^{l}/_{2}\right) \cdot \ln \frac{\sqrt{{r_2}^2 + \left(x - {}^{l}/_{2}\right)^2} + r_2}{\sqrt{{r_1}^2 + \left(x - {}^{l}/_{2}\right)^2} + r_1} \right). \tag{1}$$

As seen in Fig. 1, the beam propagates through the glass and then passes through a polarizing filter, which was mounted on a rotational stage graduated with a precision of 3×10^{-4} rad and that acts as a polarization analyzer. The power of the output beam was then measured using a photo-detector (Ophir PD300) having a dynamic range of 30 dB down to a power level of 0.02 nW.

The profile and the preform core and cladding interface were observed using an optical microscope (Reichert-Jung MeF3), and the scanning electron microscopy (SEM, FEI Quanta Inspect 200).

3. Results and discussion

3.1. Glass forming

Table 2 shows the properties of all fabricated glasses and their glass-forming ability. From Table 2, TZNB and TZNNb systems have good glass forming ability and good mechanical properties. All the glasses belonging to these two groups are good quality, transparent and not crystalline. However, the thermal expansion coefficient of TZNNb group glasses is

Table 1
Composition (mol.%) of the prepared glasses and glass forming appearance.

CODE	Composition of glasses	Melting T × 60 min	Annealing T × 120 min
TZN	$75TeO_2–20ZnO–5Na_2O$	875 °C	290 °C
TZNB	$70TeO_2–20ZnO–5Na_2O–5BaO$	900 °C	320 °C
TZNB1	$73.5TeO_2–19.6ZnO–4.9Na_2O–2BaO$	950 °C	310 °C
TZNB2	$71.25TeO_2–19ZnO–4.75Na_2O–5BaO$	975 °C	325 °C
TZNB3	$67.5TeO_2–18ZnO–4.5Na_2O–10BaO$	1075 °C	340 °C
TZNB4	$63.75TeO_2–17ZnO–4.25Na_2O–15BaO$	1175 °C	350 °C
TZKGe	$42TeO_2–18ZnO–20K_2O–20GeO_2$	950 °C	–
TZKGeSi1	$49TeO_2–21ZnO–15K_2O–10GeO_2–5SiO_2$	1100 °C	300 °C
TZKGeSi2	$42TeO_2–18ZnO–15K_2O–20Ge_2O–5SiO_2$	1000 °C	300 °C
TZNKGeSi1	$41.25TeO_2–11ZnO–2.75Na_2O–20K_2O–10GeO_2–15SiO_2$	1350 °C	–
TZNKGeSi2	$48.75TeO_2–13ZnO–3.25Na_2O–20K_2O–10GeO_2–5SiO_2$	1050 °C	–
TZNKGeSi3	$37.5TeO_2–10ZnO–2.5Na2O–20K_2O–20GeO_2–10SiO_2$	1200 °C	–
TZNKGe1	$52.5TeO_2–14ZnO–3.5Na_2O–20K_2O–10GeO_2$	1000 °C	–
TZNKGe2	$45TeO_2–12ZnO–3Na_2O–20K_2O–20GeO_2$	1050 °C	–
TZNNb	$70TeO_2–20ZnO–5Na_2O–5Nb_2O_5$	875 °C	300 °C
TZNNbLa1	$70TeO_2–15ZnO–5Na_2O–5Nb_2O_5–5LaO$	875 °C	300 °C
TZNNbLa2	$70TeO_2–18ZnO–5Na_2O–5Nb_2O_5–2LaO$	875 °C	300 °C