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Structural and properties of heavy metal oxide Faraday glass for optical current transducer

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ABSTRACT

The influences of PbO, Bi_2O_3 and GeO_2 contents on mechanical, thermal, magneto-optical and structural properties of PbO–Bi_2O_3–GeO_2–B_2O_3 glass system were investigated. A magneto-optical current transducer MOCT prototype with sensitivity of 7.56 nW/A was constructed based on selected glass with good properties.

1. Introduction

Magneto-optical current transducer (MOCT) based on the Faraday Effect have been developed worldwide as alternative to conventional current transducer [1] because MOCT is compact and lightweight, immune to electromagnetic noise, and they offer a wide measurement range and long distance signal transmission [2].

According to the principle of Faraday Effect, high Verdet constant material is fundamental for getting a high sensitivity. Currently used high Verdet constant material for MOCTs is based on crystals (YIG, etc.), or garnets which have high rotation property, however, these materials are very expensive and have limited sensitivity probably due to saturation effects at high voltage [3–5].

As alternates to crystals, diamagnetic glasses are appealing for MOCT construction due to their low cost, easy to be processed and temperature-independent Faraday Effect [6]. Heavy metal oxide (HMO) glasses such as Bi_2O_3 and PbO, due to their mass and high polarizability of ions Pb^{2+} and Bi^{3+}, posses interesting properties in infrared optics and nonlinear optics [7]. Particularly their proprieties in the range of magneto-optics phenomena are interesting for optoelectronics. Glasses containing PbO show high refractive indices with low crystallization tendency, as well as low melting point and glass transition temperatures [8]. Germanate glasses are of interest for optoelectronic applications because they combine high mechanical strength, high chemical durability and high refractive index [9]. The low phonon energy (around 700 cm^{-1}) of PbO–GeO_2 glass, compared to borates (around 1400 cm^{-1}) and phosphates (around 1200 cm^{-1}) [2], is helpful getting good magneto-optical effect. Although these oxides do not form glass on their own, they modify a vitreous network to form glass when they were combined with B_2O_3 [10–11] which is a good absolute glass forming oxide for technological applications.

Most studies on PbO–Bi_2O_3–GeO_2–B_2O_3 (PBGB) glass system are applied for laser [12], luminescence [3,13] and elastic property [14] by doping rare earth elements. Recently the magneto-optical properties of this glass system were studied for optical sensing application [15]. However, besides magnetic property, the mechanical and thermal properties of this system were not yet investigated. Good thermal, optical and mechanical properties of glasses are important as well when they are used in real device prototype, especially in glass fiber form.

Based on a previous study [16–18] on magneto-optical glasses, in this paper, a highly doped HMO PBGB glass system was fabricated; structural and physical properties of glasses have been studied for MOCT application. A MOCT prototype was constructed and (the sensitivity) was evaluated under different currents. The sensitivity of MOCT is defined as the ratio of output signal intensity to the change of input current [19]. Good Faraday rotation of PBGB glass can ensure a high MOCT sensitivity.

2. Experiments

Glasses of nominal compositions were fabricated by melt-quenching method. Considering getting a good MO properties and thermal stability, the glass composition is based on three Bi_2O_3–PbO content groups: 60% (PBGB1), 70% (PBGB2, PBGB3 and PBGB4) and 80% (PBGB5, PBGB6 and PBGB7) (in mol%).

Optical grade reagents (Aldrich, purity 99.9%) PbO, B_2O_3, GeO_2 and Bi_2O_3 were weighted and mixed in Al_2O_3 crucibles at melting

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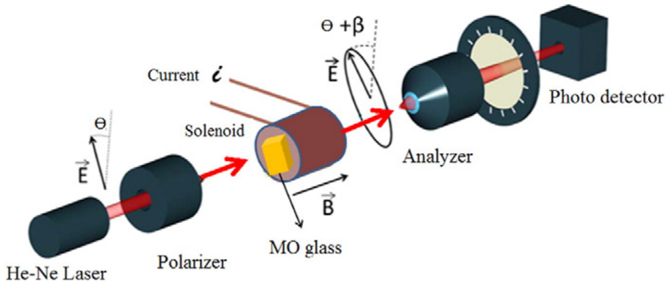

Fig. 1. Schematical setup for Verdet constant measurement of PBGB MO glass.

temperatures ranging from 900 °C to 1100 °C for 1 h and were cast on a 200 °C preheated brass plate. The casted bulk glasses were annealed for 2 h at temperature ranging from 350 °C to 400 °C at 1 °C/min heating/cooling rate. The fabricated glasses had high homogeneity, were bubble free and transparent with a yellow color. The sample with the optimum composition, assuring the best glass forming and physical properties, was chosen as sensing element for MOCT. The annealed glasses were cut into parallel slabs with a thickness of 2.5 mm and optically polished using a polishing instrument (λ—Logitech PM5).

Samples were subjected to different characterizations. The glass transition temperature (T_g) and crystallization temperature (T_x) were determined by differential scanning calorimetry (Perkin-Elmer DSC7), under N_2 atmosphere at a heating rate of 10 °C/min. The density was calculated at room temperature following the Archimedes' principle using water as immersion liquid. The refractive index (n) was measured under different wavelengths by the prism coupling method using Metricon 2010. The UV absorption spectra were recorded in the wavelength range of 200 nm to 800 nm by means of a UV–VIS spectrophotometer (Varian Cary 500) using optically polished samples with a thickness of 2.5 mm. Using the thickness of samples, the absorption coefficient can be calculated by equation: $\alpha = \log(^{I_0}/_{I})/z = A/z$, where α is the absorption coefficient, A is the absorbance obtained from UV spectra, z is the thickness of sample, in this study, z = 2.5 mm. The cutoff is defined as the wavelength at which light ceases to propagate in the medium, it is normally calculated as the one at which the transmission decreases to 50% of its maximum. Fourier transform infrared spectra (FT-IR) measurements from 1500 to 4000 cm^{-1} wave number were carried out using a Varian Cary 500 spectrophotometer. Raman spectra were recorded by a Raman spectrometer (RSI 2001 B, Raman system, INC) equipped with a 532 nm solid-state diode green laser. The mechanical property in terms of Vicker's hardness was tested using a 136° pyramidal diamond indenter applies to the glass at a weight load of 150 g. According to the square indent formed on the glass, the Vicker's hardness can be calculated through the formula: HV = $0.1891F/d^2$, where F is the applied load, and d is the diagonal of the indentation.

The Verdet constants of glasses were measured using a home-made optical bench as shown in Fig. 1. A He-Ne laser, emitting 1.8 mW in a linearly polarized laser beam about 1 mm in diameter, 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∶5000. Glass samples were mounted in a solenoid which wrapped with a copper electrical wire, 2 mm in diameter, coiled into 220 turns around a 19 cm long a polymeric 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), where the x stands for different positions along the solenoid from the center ($x = 0$), l is the length of solenoid, r_1 is the solenoid radius, r_2 is the electrical coil radius.

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

As highlighted in Fig. 1, the polarized beam propagates through the glass and then passes through an analyzer, which was mounted on a rotational stage graduated with a precision of 3×10^{-4} rad. 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.

A MOCT prototype was constructed as shown in Fig. 2. It consists of two linear polarizers, the PBGB glass, the conductor, laser and photodiode detector. The Faraday rotation angle β can be calculated using the output light intensity difference with/without magnetic field from Eqs. (2) to (5); where:

I_{trans}	is the output laser intensity after the light goes through the sample without magnetic field,
I_{field}	is the output laser intensity after the light goes through the sample in magnetic field,
ΔI_{int}	is difference of I_{trans} and I_{field},
θ	is the angle between two polarizers,
B	is the magnetic flux,
dL	is the integral thickness of sensing glass along the light path,
μ_0	is a constant (1.26×10^{-6} B m^{-1}),

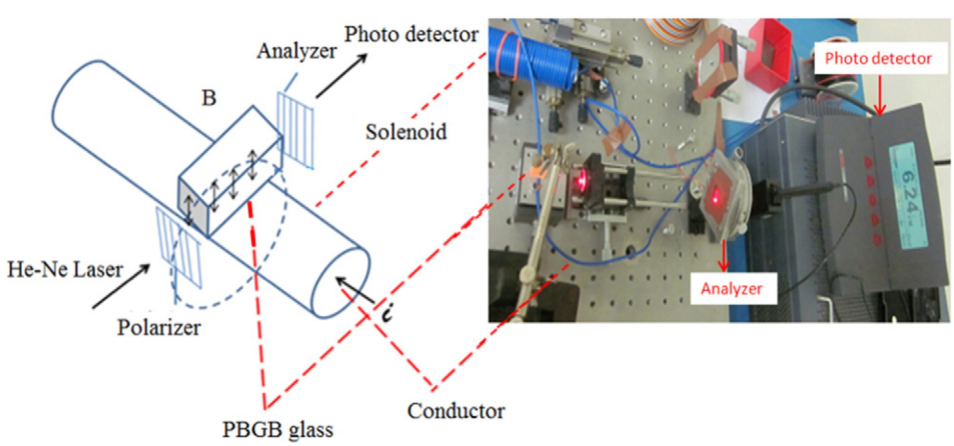

Fig. 2. Schematic and real setup for the MOCT based on PGBG glass.