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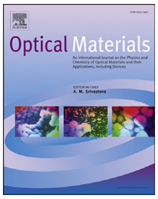

Production and characterization of femtosecond laser-written double line waveguides in heavy metal oxide glasses

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ABSTRACT

We report the fabrication and characterization of double line waveguides directly written in tellurite and germanate glasses using a femtosecond laser delivering 30 μJ, 80 fs pulses at 4 kHz repetition rate. The double line waveguides produced presented internal losses inferior to 2.0 dB/cm. The output mode profile and the M^2 measurements indicate multimodal guiding behavior. A better beam quality for the $GeO_2 - PbO$ waveguide was observed when compared with $TeO_2 - ZnO$ glass. Raman spectroscopy of the waveguides showed structural modification of the glassy network and indicates that a negative refractive index modification occurs at the focus of the laser beam, therefore allowing for light guiding in between two closely spaced laser written lines. The refractive index change at 632 nm is around 10^{-4}, and the structural changes in the laser focal region of the writing, evaluated by Raman spectroscopy, corroborated our findings that these materials are potential candidates for optical waveguides and passive components. To the best of our knowledge, the two double line configuration demonstrated in the present work was not reported before for germanate or tellurite glasses.

1. Introduction

A considerable research effort in the area of femtosecond (fs) laser pulses used to locally modify the structure and refractive properties of optical glasses and other dielectrics via nonlinear absorption, has been conducted in recent years [1]. Because the pulse length of this type of laser is shorter than the electron phonon interaction, one can obtain a process without thermal effects and produce tiny structures, such as waveguides, in transparent materials [2]. Depending on the material properties, as well as on the characteristics of the laser used for inscribing, two types of waveguides can be obtained: the first type consists of a single line, where the modification of the material causes a refractive index increase, leading to light confinement [3]. The second type consists of stress-induced positive refractive index changes in the region adjacent to the writing [4], or negative refractive index changes in the laser focal region [5]. In the latter case, the light is guided in between two or more written lines. The methodology used in this work is based on the second type of writing, where double line waveguides demonstrated good results, after previous experiments testing both types of writing. Double line waveguides have been demonstrated in a number of hosts, including crystals [4,6–10]. Single line waveguides have the advantage of simpler and faster processing and have also been demonstrated in a variety of glasses including fused silica, borosilicate [11], chalcogenides [12] and BK7 [13]. Double line waveguides are an alternative technique for materials whose properties do not permit the confinement and propagation of light by a single written line and, in principle, permit guiding in an almost unperturbed and pristine region of the bulk material once laser writing occurs at the border of the guiding region.

The fs laser writing methodology has proven to be reliable and is able to compete with clean room processing in terms of waveguide loss, with the advantage that laser writing enables fast prototyping and requires much lower cost of ownership and complexity of fabrication.

Heavy metal oxide glasses, like germanates and tellurites, are interesting materials for photonic applications due to properties such as their high linear refractive index (~2) that is responsible for a high nonlinear refractive index, their extensive transmission window from visible to near infrared and lower cutoff phonon

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energy (<700 cm^{-1}) when compared to silicate, borate, and phosphate glasses. Previously we reported on the fabrication and characterization of active waveguides in GeO_2–PbO–Ga_3O_3 glass samples doped with Er^{3+}, written by a femtosecond laser delivering pulses of 80 fs duration at 1 kHz repetition rate. Single line waveguides were formed under different laser pulse energies and scan velocities and the passive and active optical properties of the waveguides were investigated [14].

This work presents, to the best of our knowledge, the first demonstration of waveguiding by the double-line technology using the fs laser writing process in germanate and tellurite glasses.

2. Experimental

2.1. Preparation of glasses

Conventional melting and quenching method was used for the preparation of the glasses. High purity starting oxide powers (99.999%) were melted in platinum (TeO_2 –ZnO) or aluminum (GeO_2-PbO) crucibles, then poured into heated brass molds (preheated at annealing temperature), annealed to reduce the internal stress and then cooled to room temperature inside the furnace. The temperature and time duration for melting and annealing are presented in Table 1, for each glass composition.

2.2. Waveguide writing

The femtosecond laser setup consists of a Ti:Sapphire laser system operating at $\lambda = 800$ nm, able to deliver up to 800 μJ of energy in a pulse with duration ranging from 25 to 200 fs, in a 4 kHz repetition rate pulse train (Femtopower Compact Pro HR/HP, from Femtolasers). Sample translation stages with 300 nm precision were controlled via an integrated CadCam system. The parameters used for writing the waveguides are shown in Table 2. Several pairs of closely spaced, parallel waveguides were written using a 20X objective lens with N.A = 0.4, focal length = 10 mm and depth of focus = 200 μm, separated by a distance of 10 μm, using laser energies of 3 μJ and 30 μJ. The waveguides were written 0.7 mm beneath the sample's surface. After waveguide writing, the glasses were re-polished at the input and output facets that were damaged during the femtosecond writing process. The final length of the obtained waveguides was 1.0 cm.

2.3. Materials and waveguide characterization

The absorbance of the samples was measured with a spectrometer (Cary 5000) to analyze the composition of the samples at the laser focus. For this measurement, a sample with a large number of closely spaced waveguides was prepared. Optical transmission microscopy was used to capture the images of the laser written structures. Fig. 1 shows the setup used to determine the near field profile (using a CCD camera), optical losses (using a Powermeter) and beam quality factor M^2 (using a measurement system formed by a CMOS controlled by a LabVIEW™ program) of a coupled HeNe beam. The optical losses were determined using equation (1), where P_2 represents the output power measured for a sample of length Z_2, and P_1 the output power of a sample with reduced length Z_1 [15],

$$\text{Optical losses} = -\frac{10\log\left(\frac{P_2}{P_1}\right)}{Z_2 - Z_1} \tag{1}$$

Table 2
Parameters used in the writing process.

Writing speed (mm/min)	1.0
Laser spot size (μm)	5.0
Pulse duration (fs)	80
Wavelength (nm)	800
Polarization to writing direction	parallel
Repetition rate (kHz)	4
Depth of focus (μm)	200

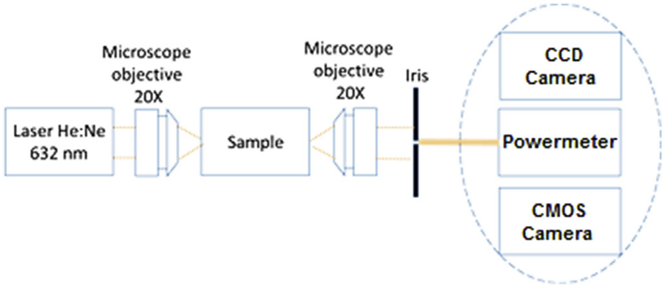

Fig. 1. Basic schematic diagram used to determine the near field profile, optical losses and M^2 factor.

To estimate the refractive index change of the waveguides, the output diameter at $1/e^2$ width was measured at a distance of several centimeters, and the numerical aperture (N.A.) of the waveguides was calculated from the ratio between the distance and the mode radius. The refractive index change can be estimated by the measured N.A. of the waveguide, as described in Ref. [15] by the basic equation $N.A. = \sqrt{n_1^2 - n_2^2} \approx \sqrt{2n_2\Delta n}$, where n_1 and n_2 represent the refractive index of the core and the cladding, respectively. Raman spectroscopic measurements were made in the focal region of the writing and in the bulk glass using a confocal Raman Microscope (WITEC, model: Alpha300) at $\lambda = 532$ nm, power of 45 mW, wavenumber within the range of 0–3793 cm^{-1}, 50X objective and resolution of 0.464 μm.

3. Results and discussions

Fig. 2 shows the absorption spectra of TeO_2 –ZnO and GeO_2-PbO glasses taken from the bulk and also from the waveguides written by 30 μJ pulses. Comparing both results we observe a change in the transmittance window mainly for GeO_2-PbO glasses. These defects may be attributed to nonlinear absorption of the fs laser beam that generates defects such as oxygen deficient centers and non-bridging oxygen hole centers [16,17].

Fig. 3a shows an image of the waveguide's exit facet,

Table 1
Parameters of the fabrication of the bulk glasses.

Glass	Composition (wt%)	Melting/annealing temperature (C°)	Melting/annealing time (min)
TeO_2 –ZnO	TeO_2: 18.0 ZnO: 72.0	800/325	20/120
GeO_2 –PbO	GeO_2: 40.3 PbO: 59.7	1200/420	60/60