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Research Article

Amplification Properties of Femtosecond Laser-Written Er^{3+}/Yb^{3+} Doped Waveguides in a Tellurium-Zinc Glass

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We report on the fabrication and characterization of active waveguides in a TeO_2-ZnO glass sample doped with Er^{3+}/Yb^{3+} fabricated by direct laser writing with a femtosecond laser delivering 150 fs pulses at 1 kHz repetition rate. The waveguides exhibit an internal gain of 0.6 dB/cm at 1535 nm, thus demonstrating the feasibility of active photonics lightwave circuits and lossless components in such a glass composition.

1. Introduction

In the recent years, direct laser writing of waveguides and photonic lightwave circuits in glass and crystals has become a potential alternative to conventional fabrication methods such as ion exchange and lithography [1, 2]. The most prominent demonstrations of integrated optical devices for telecom applications have been realized by means of direct ultraviolet (UV) writing, exploiting UV coherent radiation to induce a permanent refractive index change into a glass substrate [3, 4]. This method has proved to be reliable and capable of competing with clean room processing in terms of waveguide loss, with the inherent advantage that laser writing enables fast prototyping and requires much lower ownership costs of fabrication. However, its widespread application has been hampered by the complexity of the writing procedure that requires plasma enhanced chemical vapor deposition (PECVD) glass substrates and hydrogen loading to enhance the photosensitivity. Furthermore, UV writing in bulk glass has been cumbersome and limited to two-dimensional structures.

An extensive study of femtosecond (fs) laser pulses to locally modify the structure and refractive properties of optical glasses and other dielectrics via nonlinear absorption has been conducted in the recent years [5]. The mechanism undergoing this optically induced change is still a hot research topic, though it is believed that the process is triggered by a rapid absorption of the pulse energy through nonlinear excitation mechanisms [6]. Direct laser writing of optical waveguides and photonic lightwave circuits is currently one of the most widely studied applications of femtosecond (fs) laser micromachining in transparent dielectrics. Moreover, direct laser writing opens up new routes in fabrication of three-dimensional (3D) waveguides inside transparent glass substrates, which is otherwise impossible by conventional ion exchange and photolithographic processes [7].

Channel waveguides written using ultrafast lasers in erbium (Er) doped glasses and ytterbium/erbium (Yb/Er)-codoped glasses for integrated amplifiers and lasers operating in the C-band (1530–1565 nm) have been demonstrated in a number of hosts [8, 9], including heavy metal oxide doped glasses.

Heavy metal oxide glasses are interesting materials for photonic applications due to some properties as their high linear refractive index (~2), which leads to a high nonlinear refractive index, and their transmission window from visible to near infrared, which is related to their lower cutoff phonon energy (<700 cm) compared to silicate, borate, and phosphate glasses.

The aim of this work is to study for the first time the feasibility of direct waveguide writing in a TeO_2-ZnO-Er_2O_3-Yb_2O_3 (TZEY) heavy metal oxide glass using fs laser pulses and investigate the optical amplification around 1550 nm under 980 nm excitation.

Although the optical gain at infrared wavelengths is provided by the Er ions that behave as a three-level system under the optical pumping with higher-energy photons, here, the possibility of codoping with Yb is explored, in order to exploit the energy transfer between Er and Yb, thus increasing the inverted population and enhancing the amplification of the glass.

The present work corroborates the possibility of producing optical amplifiers in the C-band fabricated by direct fs laser writing, but a number of applications such as optical sensing with planar lightwave circuits might be devised. This research represents an advance to previous studies since this is, to the best of the authors' knowledge, the first demonstration of Er/Yb doped waveguides exhibiting optical gain that have been inscribed into a glass of such a composition and, though presenting preliminary results, it paves the way to a new class of photo-writeable, active glasses.

2. Experimental

2.1. Preparation of Glasses. The basic glass composition, consisting of 17.0 mass fraction (wt%) of TeO_2 and 72.8 wt% of ZnO, was supplemented with 2.0 wt% of Er_2O_3 and 0.5 wt% of Yb_2O_3. The glass was prepared by a conventional melting and quenching method: batches of 7.0 g of high purity (99.999%) compounds were fully mixed in a platinum crucible and melted at 1200°C for 1 h. The melts were then poured into preheated brass molds, in air, and annealed at 392°C for 1 h to avoid internal stress. Finally the glasses were cooled to room temperature inside the furnace. After cooling, samples were polished to acquire an optical quality surface for absorption and emission measurements. Transparent and homogeneous glasses, stable against crystallization, were produced. The linear absorption spectra of the doped TZEY glass are shown in Figure 1. The pattern highlights the typical absorption spectrum of Er/Yb doped glass and demonstrates the presence of the rare-earth ions in trivalent form, which are responsible for the active behavior. In particular, the peaks at 980 nm and 1550 nm, related to the Er^{3+} transitions $^4I_{11/2}$ and $^4I_{13/2}$, indicate the feasibility of optically pumped waveguides that can exhibit gain in the third window of optical communications.

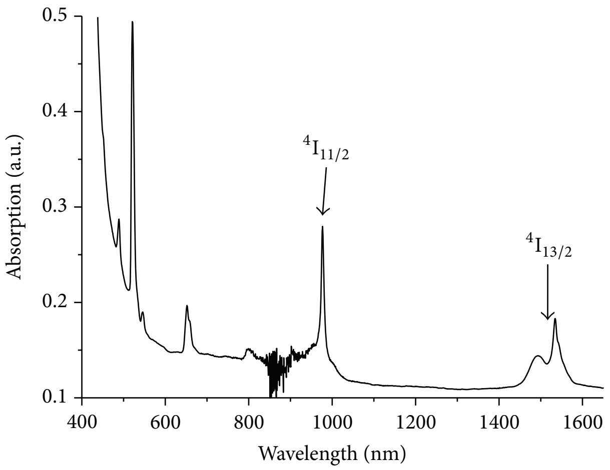

Figure 1: Absorption spectra of the doped (TZEY) glass. The labels indicate the atomic transitions of interest for the direct fs laser patterning and the active behavior of the photo-written waveguides.

2.2. Waveguides Writing. The setup to inscribe the waveguides into the glass consists of a Ti:Sapphire laser system, steering mirrors and lenses, and a translation stage to slide the sample under the beam, as sketched in Figure 2. The laser delivers 800 nm pulses with 1.0 mJ maximum energy at 1 kHz repetition rate and pulse duration down to 80 fs in a linearly horizontal polarized beam. The pulse energy is trimmed with a half-wave plate and a polarizer: by rotating the axis of the half-wave plate, the direction of the linear polarization of the incoming beam can be arbitrarily shifted and the polarizer is used to transmit the amount of power contained in the horizontal axis. Fine-tuning of the pulse energy, from 5 μJ to 10 μJ, is then performed by trimming a variable optical filter. The collimated beam is focused into the sample by a 20x microscope objective with NA = 0.3 into a spot of ~3 μm. The sample is mounted on a 3D translation stages system, perpendicular to the laser beam propagation direction. The sample is moved at scan speeds of 10 to 2000 μm/s with an overall accuracy in the positioning better than 0.5 μm. Two imaging lenses equipped with a CCD camera, mounted on top and aside the sample, are used to align the beam and to ensure straight and flat scans. In our experiments, the laser beam was focused at 200 μm below the sample's surface in order to avoid damage on the top of the glass, while the glass underwent scans from 50 to 500 μm/s. After waveguide writing, the TZEY glasses were polished to acquire optical quality at both facets and the final length of the obtained waveguides was 0.9 cm.

2.3. Waveguides Characterization. The photo-written waveguides were characterized in terms of near field pattern and optical gain.

The setup for waveguide characterization, mounted on a vibration-damped optical table, is depicted in Figure 3.

A 632 nm light from a HeNe laser is delivered to the waveguides through butt coupling with a single mode silica

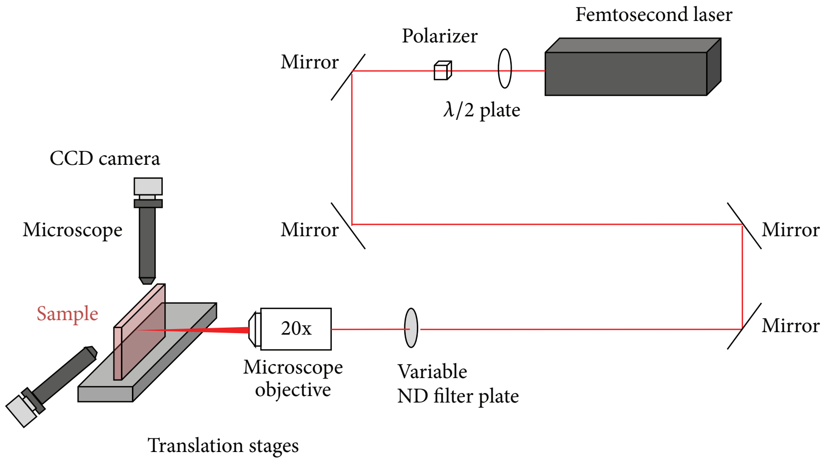

FIGURE 2: Optical setup used for femtosecond laser waveguide writing.

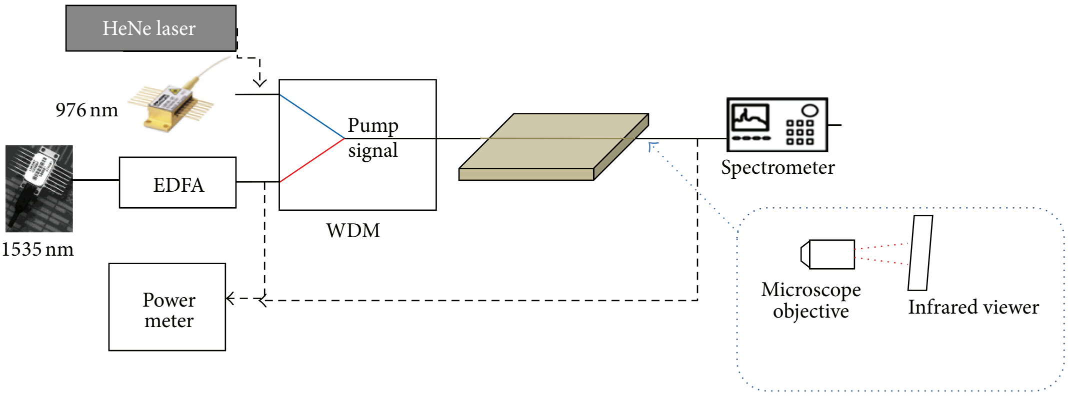

FIGURE 3: Setup for characterization of the photo-written active waveguides.

fiber for rough alignment. The waveguide propagation properties are then investigated through spectral and power measurements, by collecting the waveguide output power either with a multimode or a single mode standard telecom fiber. In the first case, some stray light from the bulk is caught, but the alignment process is made easier, whereas the second method requires the use of μm to sub-μm accuracy positioning stages, but it guarantees that no stray light propagating through the glass is received. The pump source is a laser diode emitting at 976 nm an output power up to 600 mW. The signal is provided by a standard telecom laser diode emitting at 1535 nm that can be further enhanced by a doublestage commercial erbium doped amplifier. Notice that pumping at 976 nm rather than 980 nm (typical for Er) is advantageous because the absorption peak of Yb ions is located at that wavelength. Moreover, thanks to the development of high power Yb doped fiber lasers for industrial applications, the cost of low-brightness pump diodes at 976 nm has dramatically dropped, making a point for using Yb as a sensitizer for Er doped glass compositions.

Pump and signal are multiplexed by a 980 nm/1550 nm WDM and coupled into waveguides. During the measurements, the power of the signal was kept constant at about −20 dBm (100 μW) to avoid gain saturation. The output signal is sent into an optical spectrum analyzer for gain measurements or, alternatively, to a power meter for output power checking.

The measurement procedure for the gain is performed in three steps.

(1) Both pump and probe are switched on and the output power at signal wavelength is measured on the spectrum analyzer, later denoted by $P_{\mathrm{ASE+signal}}$.

(2) The pump is turned off and a new value of the output power (P_{signal}) is recorded.

(3) The pump is turned on and the signal is shut down, in order to measure the amplified spontaneous emission P_{ASE}.

The internal gain of the active waveguides was determined using the following expression:

$$G\,[\mathrm{dB/cm}] = \frac{10 \times \log\left(\left(P_{\mathrm{ASE+signal}} - P_{\mathrm{ASE}}\right)/P_{\mathrm{signal}}\right)}{d}, \quad (1)$$

where d is the length of the waveguide, P_{ASE} represents the amplified stimulated emission (ASE) power (when only the

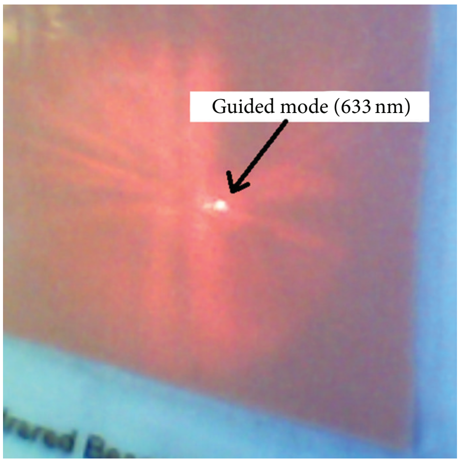

Figure 4: Near field pattern of a photo-written waveguide at 1535 nm displayed by the aid of an infrared-sensitive card.

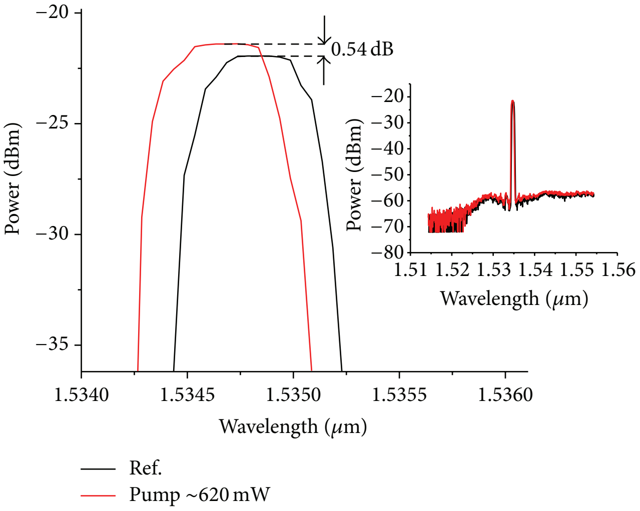

Figure 5: Optical gain of a waveguide, measured through the optical spectrum analyzer.

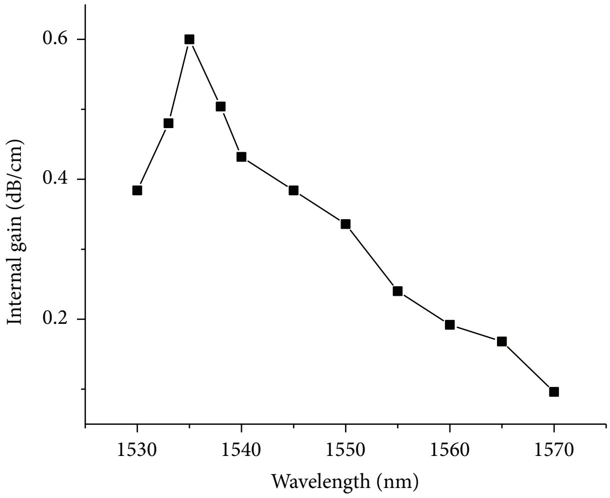

Figure 6: Internal gain as a function of wavelength, measured with a tunable laser.

pump laser is coupled into the waveguide), and $P_{\mathrm{ASE+signal}}$ represents the output signal when both signal and pump are coupled into the waveguide.

This calculation does not take into account the background propagation loss of the waveguides, which can be separately measured by cut-back method. Because of the short length of the sample, we did not implement such a technique and we just probed the transmission out of the gain band (1500 nm), measuring a total loss of 6.7 dB. Accounting for a 1 dB/facet of coupling loss, the propagation loss of the waveguides is estimated around 4.7 dB, corresponding to 5.2 dB/cm.

The visual check that optical waveguiding occurs within the photo-written waveguides was made by observing the near field pattern. This was done by substituting the collecting fiber with a properly aligned microscope objective that magnifies the illuminated glass facet onto an infrared viewer, as depicted in the inset of Figure 4.

3. Results

A typical near field pattern obtained by coupling 633 nm laser light into waveguides is presented in Figure 4. From a peer observation, it can be observed that the mode profile guided into the waveguide exhibits a degree of ellipticity. This is due to the inherent astigmatism of the fs beam and its extended Rayleigh length at the focal point. However, slit beam shaping [10] or cylindrical lenses [11] technique might be employed in future experiments, to avoid the asymmetric mode profiles.

An internal gain of 0.54 dB (correspondent to 0.6 dB/cm) was observed for 5 mW average laser power, for the waveguide written at 0.05 mm/s. This is shown in Figure 5, in which the spectrum at the waveguide output is reported in the case of simple/amplified signal (the inset depicts a broadband measurement of the spectrum). In addition to the measurement at 1535 nm, by substituting the signal source with a tunable laser, it was also observed an internal gain in the whole 1530–1570 nm band. Figure 6, depicting the internal gain as a function of wavelength, shows that it resembles quite well the gain profile of erbium ions in the C-band of optical communications. It is believed that a net gain could be measured down to 1510 nm, but at the time of this work, instruments limitations do not allow to verify such a prediction. No gain saturation was observed, indicating that higher internal gain is achievable, provided the pump power is further increased. The gain measurements so far performed do not indicate a tight dependence between the gain and the writing speed, since a maximum deviation of −0.1 dB from the result of Figure 5 was observed. This is at the limit of the inherent measurement accuracy, so it might be inferred that the waveguides exhibit nearly the same refractive index profile. Hence, further experiments shall include a broader range of writing velocities to investigate the confinement mechanism and the possibility to tune the photo-induced refractive index for optimum waveguide geometry and active behavior.

4. Conclusions

This work has addressed for the first time the feasibility of active waveguides in a Te/Zn heavy metal oxide glass doped with Er^{3+} and Yb^{3+} by direct fs laser writing.

Samples were prepared using a standard melting/quenching procedure and optical-quality glass was obtained, which was later characterized from a spectroscopic viewpoint.

Active waveguides were written by 150 fs laser pulses at 800 nm, using different energies and scan speeds. Waveguide characterization was performed at 633 nm and 1.5 μm and included near field, loss, and gain measurements. The near field pattern highlighted the typical ellipticity of fs-written waveguides. A net gain of 0.6 dB/cm was obtained at 1535 nm, which did not show a strong dependence on the writing conditions. The results obtained in the present work, though preliminary and requiring further investigations such as refractive index profiling and waveguides reproducibility are promising for the fabrication of Er/Yb doped integrated amplifiers and lasers based on tellurite-zinc glasses and increased performances are expected both from a further optimization of the glass composition and from improvements in the writing setup.

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