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Er3+ doped waveguide amplifiers written with femtosecond laser in germanate glasses / Davinson Mariano da, Silva; Luciana Reyes Pires, Kassab; Olivero, Massimo; Thiago B. N., Lemos; Douglas V., da Silva; A. S. L., Gomes. - In: OPTICAL MATERIALS. - ISSN 0925-3467. - STAMPA. - 33:12(2011), pp. 1902-1906. [10.1016/j.optmat.2011.03.025]

Publisher:
Elsevier

Published
DOI:10.1016/j.optmat.2011.03.025

Er^{3+} doped waveguide amplifiers written with femtosecond laser in germanate glasses

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ABSTRACT

The authors report the fabrication and characterization of active waveguides in GeO_2–PbO–Ga_2O_3 glass samples doped with Er^{3+}, written with a femtosecond laser delivering pulses of 150 fs duration at 1 kHz repetition rate. Permanent refractive index change was obtained and waveguides were formed under different laser pulse energies and scan velocities. The passive and active optical properties of the waveguides were investigated. The minimum value of propagation loss was of 4.8 dB/cm. Optical amplification at 1.5 μm under 980 nm excitation was observed showing a maximal internal gain of 2.7 dB/cm.

1. Introduction

The use of femtosecond laser pulses to locally modify the structure and refractive properties of optical glasses and other dielectrics via nonlinear absorption has been intensively studied over the last decade [1–3]. In 1996 it was shown that fs IR laser pulses can cause a refractive index modification inside bulk materials [4–6]. The nature of this modification is still a hot research topic, but it is widely accepted that the phenomenon is initiated by rapid absorption of laser energy through nonlinear excitation mechanisms [7]. Direct fs laser writing of optical waveguides and photonic lightwave circuits is currently one of the most widely studied applications of fs laser in transparent dielectrics. Direct fs laser writing opens up new routes in fabrication of 3D waveguides inside transparent glass substrates, which is otherwise impossible by conventional ion exchange and photolithographic processes [8]. This advantage has triggered the development of several photonic devices such as waveguides [5,9], amplifier waveguides [10], gratings [11], sensors and biomedical systems [12,13]. In material science, the mechanism of fs laser-induced localized microstructures in glasses has demonstrated the possibility of space selective control of valence state of rare earth and transition metal ions, precipitation and control of metal and functional crystals, defect manipulation, etc. [14,15].

Channel waveguides written using ultrafast lasers in Er-doped phosphor-tellurite glasses and Yb/Er-codoped phosphate glasses for integrated amplifiers and lasers operating in C-band (1530–1565 nm) have been demonstrated [16,17]. A report on longitudinal writing of relatively short waveguides and positive refractive index change in niobium tellurite glasses using 130 fs pulses was published [1,18]. Up to date, the direct fs laser writing technique has been reported in the following materials only: Nd and Er doped silicate/phosphates, Er doped and Er–Yb codoped oxyfluoride silicate glasses, Er doped phospho-tellurite glasses, Er doped bismuthate, and LiF and YAG crystals [8,10,16,17,19–35] and Nd:YVO_4 crystal [36]. Concerning the latter, a number of papers have been published on direct fs laser writing of waveguides by using a “trench” approach that is, the local modification of refractive index is obtained by two subsequent scans whose separation determines the waveguide dimension. On the other hand, the first demonstration of telecom-grade active waveguides (propagation loss $\leqslant$0.2 dB/cm) manufactured by direct fs laser writing in phosphate glass and by single scan, was reported in Ref. [23]. More recently it was reported about the best performance of active waveguides written in Er–Yb phosphate glass, exhibiting an internal gain of 7 and 3 dB at 1535 and 1565 nm respectively, for a 22 mm-long sample [26].

Heavy metal oxide glasses are interesting materials for photonic applications, due to some properties as their high linear refractive index ($\sim$2), which leads to a high nonlinear refractive index, and

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their transmission window from visible to near infrared, which is related to their low 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 fs laser writing, by single scan, of waveguides in a GeO_2–PbO–Ga_2O_3 (GPG) heavy metal oxide glass doped with Er^{3+} and investigate the optical amplification around 1550 nm under 980 nm excitation.

Studies related to the energy transfer in GPG glasses doped with Yb^{3+} and Er^{3+} were reported recently and demonstrated the possibility for applications such as red upconversion lasers [37]. Besides, the spectroscopic properties of Er^{3+} doped GPG glass reported in Ref. [38] showed that these glasses are more suitable hosts for short optical amplifiers than phosphate glass systems. However, no studies related to the determination of optical amplification around 1550 nm were performed.

Hence, the present work corroborates the possibility of producing optical amplifiers with Er doped GPG glasses for applications in the C-band, fabricated by direct fs laser writing. This research represents an advance to previous studies since there are no reports, to the best of authors knowledge, related to direct fs laser writing of waveguides in Er^{3+} doped GPG heavy metal oxide glasses.

2. Experimental

2.1. Preparation of glasses

To the basic glass composition (GPG) $17.0GeO_2$–$72.8PbO$–$10.2Ga_2O_3$ (in wt.%) it was added 2.0 wt.% of Er_2O_3 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 pre-heated 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, the 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 undoped (GPG) and doped (GPG 2Er) glasses are shown in Fig. 1.

2.2. Waveguides writing

The waveguides were written inside the glass with a Ti:Sapphire laser system capable of delivering 800 nm pulses with 1.0 mJ maximum energy at 1.0 kHz repetition rate. The setup is sketched in Fig. 2. The laser pulse energy was varied from 5 μJ to 10 μJ with half-wave plate, a polarizer and a variable optical filter. A 0.3 NA lens focused the laser beam to a few micrometers in diameter and ~10.0 μm depth of focus at a position ~200.0 μm below the surface of the GPG glass. Such a value was chosen to be above the threshold depth that avoids the damage of the surface of the sample [23].

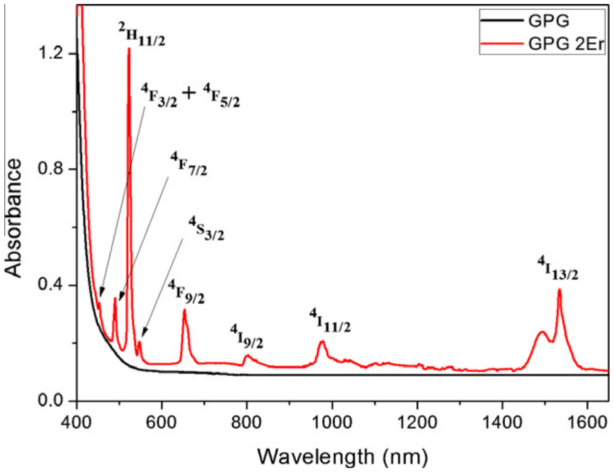

Fig. 1. Absorption spectra of the undoped (GPG) and doped (GPG 2Er) glasses.

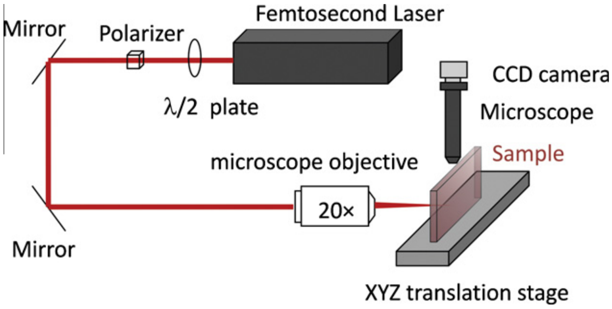

Fig. 2. Optical setup used for femtosecond laser waveguide writing.

The GPG glass was mounted on 3D motion stages and scanned perpendicular to the laser beam direction, with velocities in the range of 0.05–0.5 mm/s. A microscope and a CCD camera, mounted on top of the sample, were used to align the beam and to guarantee parallel and straight scans. After waveguide writing, the GPG glasses were polished at both facets and the final length of the obtained waveguides was 0.9 cm.

2.3. Waveguides characterization

For the alignment and preliminary characterization, a 632 nm light from a HeNe laser was butt coupled into the waveguides. Waveguide losses were investigated by measuring the beam output power with a 20× microscope objective, an iris and a power meter. The mode distribution was magnified by a 20× microscope objective and displayed on a CCD camera.

The same steps were used to characterize the waveguides at 1530 nm, being the wavelength of interest, at which the waveguides resulted to be single mode. The insertion loss measurement at 1530 nm was repeated a number of times in order to get little statistics and to validate the results.

The induced refractive-index changes were estimated by the method presented in Refs. [11,39].

The gain properties of the waveguides were characterized in a standard optical amplifier configuration. The sources consisted of a laser diode at 980 nm providing up to 250 mW of pump power and a small signal probe, generated by a tunable laser source. Pump and signal were multiplexed by a 980 nm/1550 nm WDM and coupled into the waveguides. The probe power was kept constant at about −20 dBm to avoid gain saturation. The output signal was collected with a multimode optical fiber and sent into an optical spectrum analyzer for evaluation of the gain.

3. Results

3.1. Passive characterization

By retrieving the intensity distribution from near-field pattern (Fig. 3) and using it in the inverted scalar wave equation, as described in Ref. [11], it was obtained the refractive index change Δn is about 6×10^{-3}.

The minimum propagation loss obtained at 1530 nm was about 4.8 dB/cm for the waveguide written with 5 μJ and 0.05 mm/s.

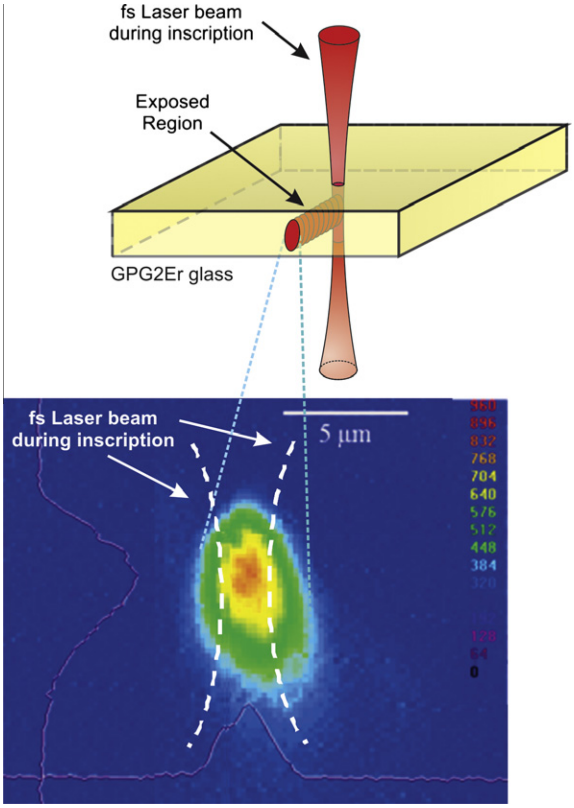

Fig. 3. Near-field mode profile of waveguides at 633 nm; white-dashed lines represent the laser beam during inscription, and the side-picture depicts the GPG glass during waveguide writing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Active properties of the waveguides

The optical gain was analyzed by varying the input signal wavelength from 1520 to 1575 nm, under 980 nm pumping. The measurement procedure consisted of three steps:

(1) both pump and probe are on; the output power at signal wavelength is measured on the spectrum analyzer, later denoted as $P_{ASE+signal}$;
(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}.

Attention must be paid on the optical spectrum analyzer's settings: the resolution bandwidth of the instrument must be kept constant all over the three measurements, in order to get reliable data.

The highest gain was obtained for an input signal around 1535 nm, as shown in Fig. 4. Subsequent measurements were then performed at that wavelength to evaluate the dependence of the internal gain with scan velocity and the outcome of such analysis is summarized in Fig. 5. The variation of the internal gain as a function of the pump power (Fig. 6) was also measured in order to determine the best condition for the laser writing.

4. Discussion

A typical near-field pattern obtained by coupling 633 nm laser light into waveguides is presented in the Fig. 3. It can be observed that the bread-cut profile of the mode guided into the waveguides, 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 [40] or cylindrical lenses [41] technique might be employed in future experiments, to avoid the asymmetric mode profiles. As mentioned before, from the near-field pattern it was calculated a refractive index change (Δn) of about 6×10^{-3} at 633 nm. Such a value is very close to that of a standard single mode fiber (5.5×10^{-3}), paving the way to realization of integrated optical devices that can be pigtailed with reduced coupling loss. Similar values for the refractive index change were also reported in Ref. [42], demonstrating that the photo-induced index step relies on the same physical mechanism. It can also be observed the photo-induced refractive index change, related to the near-field pattern shown in Fig. 3, extends the same area as the writing spot, indicating the absence of thermal diffusion [26]. Such a speculation is also supported by the low repetition rate (1 kHz) used during the experiment [26,35], pointing out a non-thermal inscription regime. Last but not least, the direct fs laser writing of waveguides in the presented GPG composition proves to be very efficient in fabrication and rapid prototyping of photonic structures because, contrary to other frameworks (cfr. [34–36]), it requires only one scan, thus halving the processing time.

The internal gain of the active waveguides, presented in Figs. 4–6, was determined using the following expression:

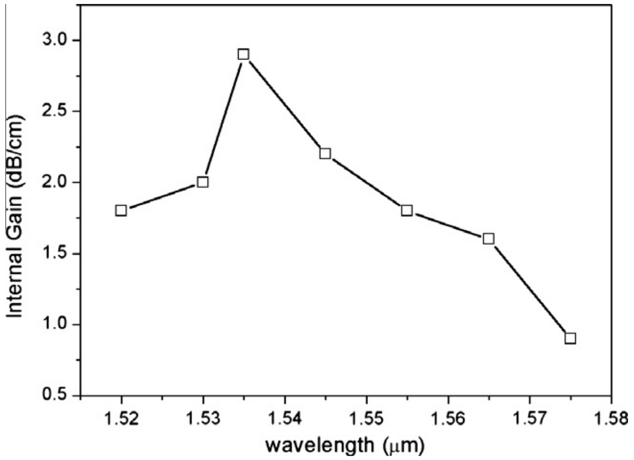

Fig. 4. Internal gain as a function of the signal wavelength for 5 μJ laser energy, using 0.05 mm/s as the scan velocity.

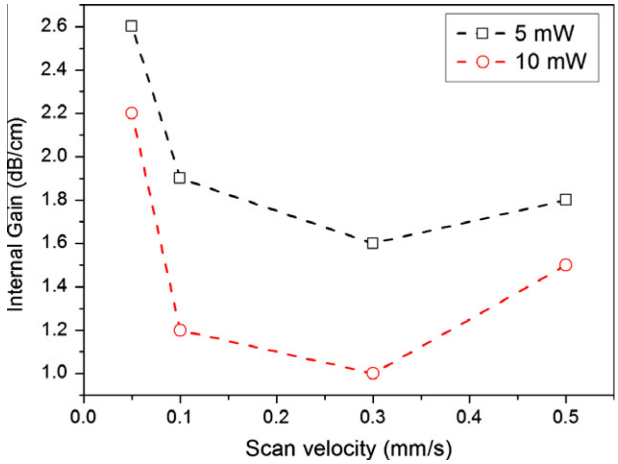

Fig. 5. Internal gain at 1535 nm as a function of the scan velocity.

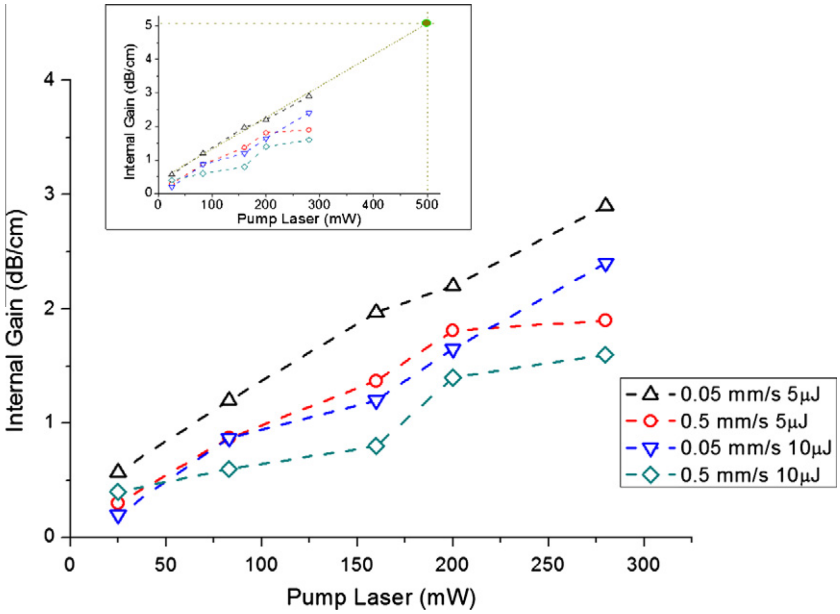

Fig. 6. Internal gain at 1535 nm as a function of pump power for different values of the scan velocity pulse energy. Inset: gain forecast for bi-directional pumping up to 500 mA.

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

where P_{ASE} represents the amplified stimulated emission (ASE) power, when only the pump laser at 980 nm is coupled into the waveguide; P_{signal} represents the signal power, when there is only the signal laser coupled into the waveguide; $P_{ASE+signal}$ represents the sum of the amplified stimulated emission power and the signal power and d is the total length of the waveguide.

The internal gain shows its optimum value for an input signal of 1535 nm, in the middle of the C-band. In this case, an internal gain of 2.7 dB/cm was observed for 5 mW average laser power, using 0.05 mm/s as scan velocity. In addition, it was also observed an internal gain in the whole C + L band. Fig. 5 shows that the internal gain is also maximized for lower values of scan velocity and smaller values of laser power. For a laser power of 5 mW, the internal gain tends to decrease with the increase of the scan velocity; for 10 mW this trend still holds, but for a scan velocity of 0.5 mm/s there is a gradual increase. This could be attributed to possible localized inhomogeneities, like Er^{3+} ions distribution along the matrix. Another possible explanation of this behavior might be a slightly different waveguide cross-section depending on the scan velocity, which produces a different effective area. A thorough investigation shall be carried out by writing a large number of waveguides at the same speed, in order to get a reliable figure of the reproducibility of the process and, at the same time, a quantitative outline of the glass homogeneity.

The internal gain as a function of incident pump power at 1535 nm is shown in Fig. 6. The gain achieved under a 250 mW pump power was 2.7 dB/cm for 0.05 mm/s scan velocity and 5 μJ pulse energy. Additionally, no gain saturation was observed, indicating that higher internal gain is achievable if the pump power were increased. A comparison of the measured gain performance with the best ones presented in literature is not straightforward (e.g. Ref. [26], in which an internal gain of 7 dB for a 2.2 cm-long sample is claimed), since in our experiments it was not possible to arrange a bi-directional pump scheme with pump levels up to ~500 mW as presented by other authors, due to a lack of instrumentation. However, a linear fit of the data presented in the inset of Fig. 6 indicates an achievable internal gain of ~5 dB/cm, nearly approaching the results obtained in phosphate glass. Besides that, an improved performance under 980 nm pumping wavelength is expected by codoping the glass with ytterbium ions.

The waveguides that exhibited lower propagation losses and higher refractive index change are those producing the highest values of internal gain. This can be attributed to reduced micro-bending losses, induced by mechanical vibrations during the writing process. The micro-bending losses typically scale with Δn^{-3} [16]. As a consequence, waveguides presenting higher refractive index change presents lower micro-bending losses, thus exhibiting higher pumping efficiency [16,42].

5. Conclusions

This work has addressed, for the first time, the feasibility of active waveguides in (GPG) heavy metal oxide glass doped with Er^{3+} by direct fs laser writing.

Samples were prepared using a standard melting/quenching technique, producing an optical-quality glass that 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. The localized refractive index change was achieved by single scan and the waveguide dimension was defined by the laser spot size. Waveguide characterization was performed at 633 nm and 1.5 μm and included loss, near field and gain measurements. The minimum propagation loss at 1532 nm was 4.8 dB/cm. The near-field pattern, that highlighted the typical ellipticity of fs laser-written waveguides, allowed for the estimation of the photo-induced index change, which resulted to be $\sim 6 \times 10^{-3}$. The best condition for amplification was achieved by waveguides written at 0.05 mm/s, which exhibited an internal gain of 2.7 dB/cm under a 980 nm pumping at 250 mW pump level. The results obtained in present work are promising for the fabrication of Er-doped integrated amplifiers, lossless components and lasers based on germanate glasses, and increased performances are expected from improvements in the writing setup.

Acknowledgments

This work was supported by the National Institute of Photonics (INCT Project) and the Nanophotonics Network Project. Financial support by CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico, FACEPE – Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco, and CAPES/COFECUB are acknowledged.

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