Femtosecond Laser-written Waveguides in a Thulium-doped Fluoroindate Glass for S-band Amplification

F. Elan, M. Olivero, E. L. Falcão-Filho, C. B. de Araújo, Y. Messaddeq and A. S. L. Gomes

Channel waveguides were written in a fluoroindate bulk glass containing thulium, with a femtosecond laser operating at 800 nm, 100 fs pulses and repetition rate 1 kHz. Formation of waveguides occurred for average powers from 1 to 8 mW (corresponding to energies of 1 to 8 μJ) and scan velocities in the range 0.1 to 4 mm/s. Passive optical characterization included visual inspection by optical microscope, insertion loss and mode profile. Active characterization was performed by co-propagating pumping in a dual-pump scheme that included a 808 nm and a 1054 nm laser diode for an efficient inversion of the $^3H_4$ level which is responsible for stimulated emission in the 1460-1530 nm spectral range. Preliminary tests show a net gain of 2.5 dB at 1487 nm, for straight waveguides 1 cm long. Applications include the fabrication of lossless components working in the S-band region of the optical communication spectrum.

Introduction: The availability of lasers operating in the femtosecond (FS) regime has contributed to a substantial improvement in the fabrication of novel integrated optical devices in areas such as telecommunications and medical physics. The fabrication of optical waveguides buried in transparent solids by direct FS laser exposure is attracting wide interest because of the simplicity of the technique and cost reduction in comparison with chemical methods and lithography processes. The FS laser-based method exploits the optically-induced local structure modification of a solid that changes its refractive index in the region where the light is focused. A number of integrated optical devices were experimentally demonstrated with this technique [1]. Great interest in lossless components has drawn the research community to the fabrication of integrated optical devices such as splitters and couplers where the waveguides are doped with rare earths and can be optically pumped to get loss compensation at the wavelengths of interest. There are a number of demonstrations of active photo-written waveguides doped with Erbium/Ytterbium to achieve gain in the C-L optical communication bands using alternative hosts [2][3], whereas no investigations have been performed to fabricate thulium-doped active waveguides for use in the S band around 1480 nm. Fluorindate glass is a potential candidate for this application because it allows for large doping with Thulium [4]. Moreover it is very stable against moisture and exhibits low optical attenuation from UV to middle infrared. Planar waveguides [5] as well as optical fibres [6] were fabricated in this host. Recently, observation of optical amplification [7] and upconverted random lasing [8] in fluoroindate glass were also reported.

In the present work direct FS laser writing was used to fabricate channel waveguides in a fluoroindate substrate for the first time. A set of parameters was found to obtain the formation of waveguides, that were then characterized in terms of mode profile, loss and active behaviour.

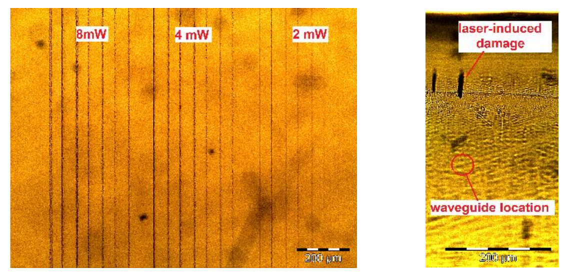
Experimental:

The glass sample had the composition (in mol.%) $37InF_3$ - $20ZnF_2$ - $16BaF_2$ - $20SrF_2$ - $2GdF_2$ - $2NaF$ - $1GaF_3$ - $2TmF_3$ and it was prepared by powder melting through double heat treatment, casting and annealing in a dry argon atmosphere as described in [4]. The sample was cut and polished and had final dimensions of 1 cm × 1 cm × 0.3 cm. The refractive index of the bulk sample was measured by m-line technique and resulted 1.487±0.001, which is in line with that found in the literature.

The sample was positioned on an XYZ motorized translation stage and aligned perpendicular to the laser beam with an accuracy better than 2 μm to guarantee the inscription of straight and smooth waveguides. The waveguides were written using a Ti:sapphire laser system operating at 800 nm and emitting 100 fs pulses with repetition rate 1 kHz. The laser beam was focused 300 μm beneath the surface of the sample using a 20× microscope objective with a focal length of 2 cm and a numerical aperture of 0.3. Waveguide formation occurred for average powers in the range 1.0 to 8.0 mW (corresponding to pulse energies of 1.0 to 8.0 μJ) and writing speeds from 0.1 to 4.0 mm/s. The sample could not be subsequently polished due to its reduced dimensions, resulting in an increased coupling loss. In order to get reliable results with good reproducibility, several waveguides were written for each parameter and the numbers presented are the results of an average over 3 to 10 measures. Passive optical characterization of the waveguides included visual inspection by optical microscope, measurement of the insertion loss and visualization of the near-field profile of the guided modes.

Fig. 1 depicts a top view and a cross-section view of the sample surface.

The area above the waveguides exhibited some damage which may be attributed to material evaporation.



a *b*

Fig. 1 *Microscope images of waveguides written at 8, 4 and 2 mW: a) top view and b) cross-section view. The artefact in b) indicates the location of a waveguide, 300 μm below the surface. Close to the surface, the damages produced by the FS laser are visible as dark vertical lines.*

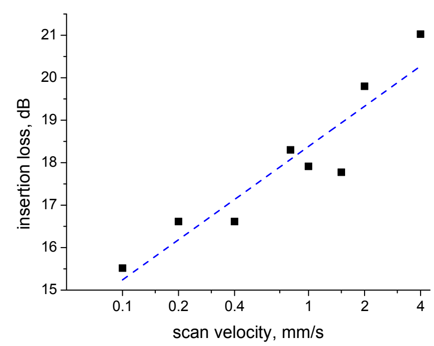
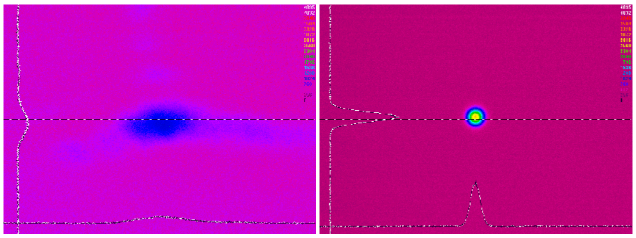


Fig. 2 *Insertion loss vs scan speed for waveguides written at 2mW. Note the log scale representation on the horizontal axis.*

The waveguide loss was measured at 633 nm by butt-coupling through a standard single-mode fibre in which care was taken to excite only the fundamental mode. The output power from the waveguide was collected through a 20× microscope objective, filtered by an iris to limit the stray light and finally measured by a photodetector.

The smallest loss at 633 nm (15.5 dB) was obtained from waveguides written with an average power of 2 mW (2 μJ) and writing speed of 0.1 mm/s. The loss increased exponentially with the writing speed as depicted in Fig. 2, suggesting that mode confinement decreases as the scan velocity rises. On the other hand, scan velocities below 0.1 mm/s induced severe damages into the glass and prevented the waveguide formation. In any case, a low scan velocity would make unpractical and time-consuming the realization of complex photonics circuits.

The near field profiles of the waveguides were taken at 633 nm, 808 nm, 1054 nm and 1479 nm. Fig. 3 depicts an example of near field profile at 1479 nm compared to that of standard single-mode fibre. The waveguides generally supported two guided modes in the visible spectrum, whereas they were single-mode above 1054 nm. Coupling loss to the single-mode fibre was estimated by the overlapping integral between the mode profiles and it turned out to be ~2.5 dB/facet. Hence, the coupling loss accounts for 1/3 of the total insertion loss. This value is a rough estimation since the mode profiles were affected by the poor surface of the sample. However, it yielded a quantitative evaluation of the astigmatism of the mode, as visible in Fig. 3a. Engineering of the writing may help to solve this problem, for instance by circularizing the writing beam using the slit beam shaping technique [9].



a *b*

Fig. 3 *Near field profile at 1479 nm a) of a waveguide written at 2 mW, compared to that b) of a standard G652 single mode fibre.*

Active characterization was performed by pumping the waveguides at 808 nm and 1054 and amplifying a signal in the range 1468-1543 nm. The pump at 808 nm was used to enhance the population inversion in the $^3H_4$ level, which can produce amplification around 1490 nm through stimulated decay to the $^3F_4$ level. The 1054 nm laser was used both to pump the thulium ions to the $^3H_4$ level by excited-state absorption as well as to increase the population of the $^3F_4$ level, whose decay to the ground state also produces amplification at the wavelengths of interest. This technique is explained in detail in [10], where it was proved to be effective for the realization of thulium-doped fibre amplifiers. The pumps and signal were coupled into the waveguides in a co-propagating scheme by means of three wavelength-division-multiplexers and provided a total power of 14 mW. The signal was provided by a series of narrow-linewidth lasers that could deliver up to -40 dBm output power into the sample.
The gain was evaluated as:

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

where P_{ASE} is the power measured with pump only, P_{signal} is the power of the signal and d the length of the waveguide. The gain versus the signal wavelength is depicted in Fig. 4.

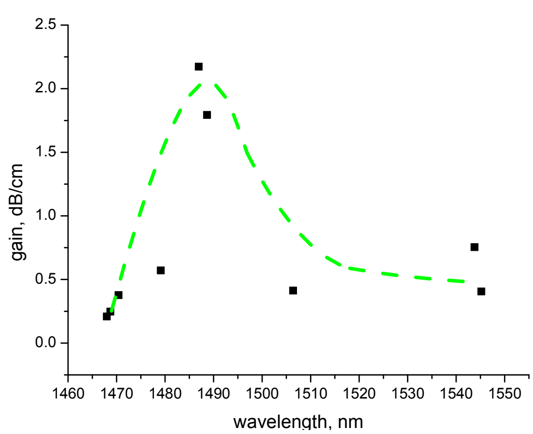


Fig. 4 *Optical gain as a function of wavelength in the S band (1460-1530 nm). The gain exhibits a peak at 1486 nm, where it reaches 2.2 dB/cm.*

The largest gain of 2.2 dB/cm was measured at 1486 nm. This value is not sufficient to compensate for the high loss, but the residual pump level at the waveguide output suggests that an optimized length of the waveguide can improve the gain. The net gain per length unit is comparable or even higher than that achieved in in other realizations for the C-band [3]. It is believed that an appropriate optimization of the glass preparation [6] and writing process may significantly reduce the propagation and coupling loss, opening the way for the realization of truly lossless waveguides in the S-band.

Conclusion: For the first time optical waveguides were fabricated by direct FS laser writing in a thulium-doped fluoroindate glass. A range of powers and scan speeds for the waveguide formation were experimentally determined. Passive characterization yielded propagation losses of ~ 10dB/cm and coupling loss of 2.5 dB/facet, that can be lowered by optimization of the writing process. Active characterization was made by dual pumping at 808 nm and 1054 nm and a net gain of 2.2 dB was measured at 1486 nm. Although the loss performances of the fabricated devices need improvement, this work paves the way to the realization of a new class of integrated optical devices that could extend the telecommunication band and open up new possibilities for rapid prototyping of thulium-doped photonic lightwave circuits that work around 1490 nm.

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References

1. Della Valle G., Osellame R., Laporta P.: 'Micromachining of photonic devices by femtosecond laser pulses', *J. of Opt. A*, 2009, **11**, 013001
2. Olivero M., Mariano da Silva D., Kassab L., Gomes A. S. L.: 'Amplification Properties of Femtosecond Laser-Written Er^{3+}/Yb^{3+} Doped Waveguides in a Tellurium-Zinc Glass', *Adv. in Opt. Tech.*, 2013, **2013**, pp. 1–5
3. Osellame R. et. al:'Optical gain in Er-Yb doped waveguides fabricated by femtosecond laser pulses', *IEE Electron. Lett.*, 2002, **38**, (17), pp. 964–965
4. de Araujo C. B. et al.: 'Frequency upconversion in rare-earth doped fluoroindate glasses', *C. R. Chimie*, 2002, **5**, pp. 885–898
5. Melo Jr R. P. et al.: 'Novel fabrication process of planar waveguides in rare-earth doped fluoroindate glasses', *Appl. Phys. Lett.*,1995, **67**, (7), pp. 886–887
6. Bei J. et al.: 'Reduction of scattering loss in fluoroindate glass fibers', Opt. Mat. 2013, **3**, (9), pp. 1285–1301
7. Haro-Gonzáles P., et al.: 'Optical amplification by upconversion in Tm-Yb fluoroindate glass', *Opt. Mater.*, 2010, **32**, (10), pp. 1349–1351
8. de Oliveira M. A. S. et al.: 'Upconversion ultraviolet random lasing in Nd^{3+} doped fluoroindate glass powder', *Opt. Express*, 2011, **19**, (6) pp. 5620–5626
9. Ams M., Marshall G., Spence D., Withford M.: 'Slit beam shaping method for femtosecond laser direct-write fabrication of symmetric waveguides in bulk glasses', *Opt. Express*, 2005, **13**, pp. 5676–5681
10. Gomes, A. S. L. et al.: 'Characterization of efficient dual-wavelength (1050+ 800 nm) pumping scheme for thulium-doped fiber amplifiers', *IEEE Photon. Technol. Lett., 2003,* **15**, (2), pp. 200–202