New double line architecture produced by fs laser irradiation in Nd^{3+} doped TeO_2-ZnO glass for photonic applications

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***Abstract*—We report the fabrication and passive characterization of Nd^{3+} doped TeO_2-ZnO glass with a new configuration of double waveguides, written with fs laser operating at 800 nm, delivering 30 fs pulses at 10 kHz repetition rate. The two written lines that form the double waveguide are formed by several overlapping lines. Results of output mode profile, beam quality factor M^2 and refractive index change are presented as well as the parameters used for laser writing. Writing speed of 0.5 mm/s and pulse energy of 15 µJ demonstrated to be adequate parameters for writing. Refractive index changes of $\Delta n = 1x10^{-5}$ and $\Delta n = 1x10^{-4}$ were found at 632 nm for double waveguides written with 4 and 8 overlapping lines, respectively. The mode image results at the output of the waveguides showed a confined beam in agreement with multi transverse order mode. Beam quality factor results were the following: $M_y = 24\pm3$ and $M_x = 14\pm3$ at 632 nm. The glasses are produced with the melt quenching technique and the preliminary results demonstrated that they are promising materials for the fabrication of passive and active components for photonic applications.**

Keywords*—laser processing, double line waveguide, passive optical component, glasses

I. INTRODUCTION

In recent years, many efforts have been made to find suitable materials for integrated optics using different methods for waveguides fabrication. We report the fabrication and passive characterization of double line waveguides written directly into Nd^{3+} doped TeO_2-ZnO glasses using a femtosecond (fs) laser, Ti:Sapphire operating at 800 nm, delivering 30 fs pulses at 10 kHz repetition rate. These glasses have interesting characteristics that make them attractive for photonic applications [1-7]: large transmission window (400–5000 nm), large polarizability, low melting temperature (around 800°C), low cut-off phonon energy (~800 cm^{-1}), large mechanical resistance, high chemical durability and high refractive index (~2.0) that is important for ultrafast optical switching. Localized structural changes can be produced in a transparent material when ultra-short laser pulses are tightly focused inside it. A very complex distribution, of the refractive index around the irradiated region is created as a result of the strain left in the material, [8] and several types of waveguides can be produced, among which the single- and double-line waveguides are the most frequently used. When a single line is written using the appropriate laser parameters, a refractive-index profile inside the transparent material can be generated acting as a waveguide. In this case, a positive refractive index change is necessary for light confinement to occur. On the other hand, when double line waveguides are produced, the light can be guided in between the two lines if a negative refractive index change is produced around the fs laser's focus. In the case of lead oxide silicate, phosphate and heavy metal oxide glasses, [8] the main structural modifications caused by the laser consist of an expansion of the material volume at the focus, accompanied by a lower local density and refractive index in these regions. Regions of higher refractive index and density take place in the surroundings where light guiding occurs, as a result of the compression induced by the mentioned volume expansion. Our previous report [9] demonstrated, for the first time, promising results for the fabrication of passive devices based on undoped TeO_2-ZnO glasses using fs laser written double line waveguides and motivated the present investigation. However, in the present investigation we utilize a different procedure for writing the two lines in which each line is produced by several, separate cumulative passages of the fs laser on top of each other instead of one single, continuous line (each written line is formed by 4 and 8 overlapping lines). Moreover, unlike in our previous works, this different double line architecture performed in Nd^{3+} doped TeO_2-ZnO glasses had to be done due to the absorption of the material at 800 nm ($^4I_{9/2} \rightarrow {}^4F_{5/2} + {}^2H_{9/2}$ transition of Nd^{3+}) that is in resonance with the fs laser used for the writing. This matching between absorption and the laser's wavelengths made writing difficult, cracking the sample due to heating; so new parameters for laser writing had to be found, as the velocity increase to reduce heating. On the other hand, the velocity growth reduced the structural changes caused in the material, compromising the refractive index change caused by the written lines and, consequently, light guiding performance. The presence of several overlapping lines demonstrated to be a suitable alternative to compensate the mentioned decrease of induced damage and optimize light confinement. We show preliminary results in view of future fabrication of passive and active devices for integrated photonic applications. Output mode images, beam quality factor M^2 and refractive index change

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results are presented as well as the parameters used for laser writing.

II. MATERIALS AND METHODS

A. Preparation of the glasses

Glasses were produced by the melt-quenching method adding 1.0 wt.% of Nd_2O_3 to the following composition (in wt.%): $85TeO_2$-15ZnO (TZ) High purity reagents (99.999%) from Sigma Aldrich were used. The melting of the reagents was performed at 835°C for 30 minutes, using a high purity platinum crucible (99.99%); the melting was followed by the quenching in preheated brass mold. The annealing was the last step: performed at 325°C for 120 minutes in order to reduce the internal stress. We highlight that this step is important because large internal stress lets the samples become fragile that may even break during the polishing. Finally, the samples were cut and polished; transparent samples with thickness of 2 mm were then produced.

B. Writing and characterization of the waveguide

The femtosecond laser system (Ti:sapphire, model PRO 400, Femtolasers GmbH) with emission wavelength centered at 800 nm had a pulse length of 30 fs, maximum energy per pulse of 200 µJ and 10 kHz repetition rate. The system uses a stationary focal point in which the sample is positioned in a three-axis translation stage with accuracy of ± 5 nm. A focal point with diameter of 3.6 µm in air was produced by a doublet lens with focal length of 20 mm and numerical aperture NA=0.2. The beam was focused perpendicular to the polished surface with its linear polarization tilted 45° (this is the natural emission polarization of the laser beam guidance and focusing system), with respect to the movement direction and positioning the focal point 0.75mm below the surface. This process was repeated 4-8 times and a pair of parallel lines (each written line is formed by 4-8 overlapped lines) were written spaced by 10 µm, 0.7mm beneath the surface of the sample, using the parameters presented in Table 1, whose energy is based on previous report [9]. In order to avoid the fracture of the sample, the number of overlaps and the writing speed were determined experimentally; Fig. 1 illustrates the set-up used for the waveguide writing and Fig. 2 shows the resulting pair of parallel lines separated by 10 µm.

TABLE I. PARAMETERS USED IN THE WRITING PROCESS

Writing speed (mm/s)	0.5
Walength (nm)	800
Repetition rate (kHz)	10
Pulse energy (µJ)	15
Number of Overlapped lines	4 and 8

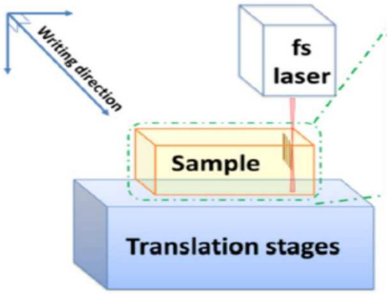

Fig. 1. Set-up used for the waveguiding writing

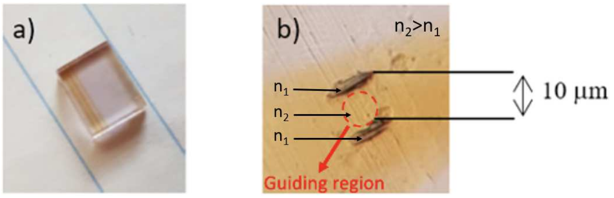

Fig. 2. Pair of two parallel, double line waveguides in Nd^{3+} doped TZ glass: a) photo, b) microscope image at the sample's exit face of a single double line before polishing.

After the writing process the samples were polished again due to the damage caused by the fs laser [8]; the final dimensions of the sample were (6.9 x 5.2 x 2.8) mm^3. To estimate the refractive index change, the waveguide output beam diameter 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 is estimated by the measured N.A. of the waveguide, as described in equation 1 [10] where n_1 and n_2 represents the refractive index of the core and the cladding, respectively:

$$N.A. = \sqrt{n_1^2 - n_2^2} \approx \sqrt{2n_2\Delta n} \qquad (1)$$

Fig. 3a) shows the experimental set-up used to determine the mode images (using a CCD camera). Using the same set up with an additional flat-convex lens (with focal distance of 75mm) between the CCD camera and the 20x objective (located after the sample), it was possible to determine the beam quality factor (M^2) using a standard procedure [11] and the set-up shown in Fig. 3b).

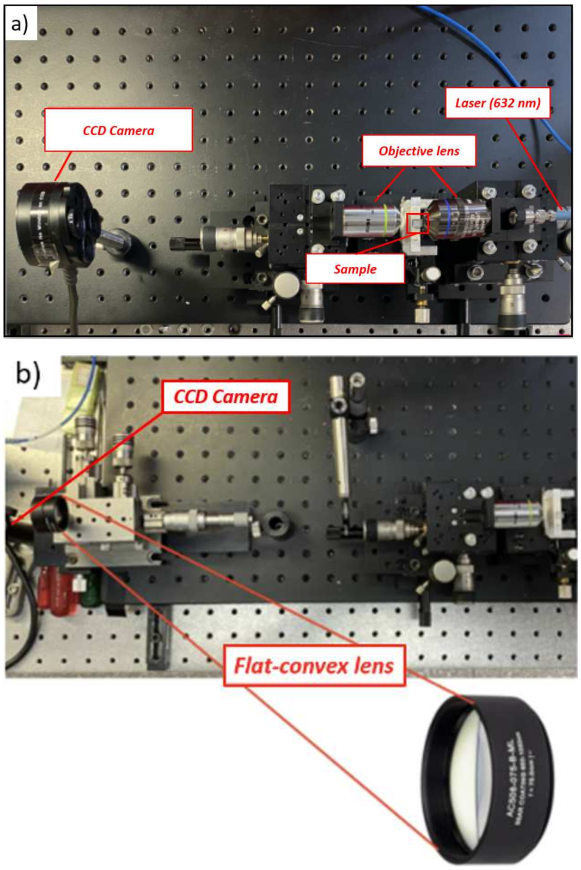

Fig. 3. Set-up used to a) determine the mode images and b) the beam quality factor (flat-convex lens with focal distance of 75mm).

III. RESULTS

The refractive index change at 632 nm determined by equation (1) was $\Delta n = 1\mathrm{x}10^{-5}$ and $\Delta n = 1\mathrm{x}10^{-4}$ for the double waveguides written with 4 and 8 laser passages, respectively. The beam images at the output of the waveguides, shown for both cases (4 and 8 passages), can be seen in Fig. 4 that shows confinement of the beams in agreement with multi transverse order mode. By focusing a collimated beam by means of the flat convex lens (Fig. 3b) the beam waist was measured at different positions around the focus, in the near field and in the far field. The M^2 values (8 laser passages) for the different directions were $M_y = 24 \pm 3$ and $M_x = 14 \pm 3$ at 632 nm.

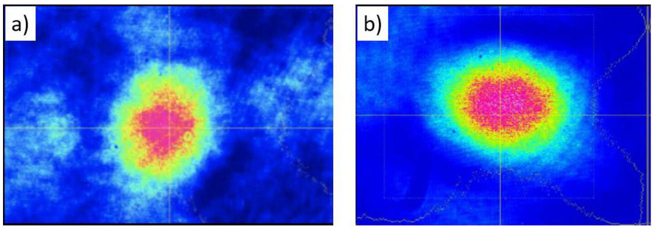

Fig. 4. Beam images for different laser passages: a) 4 and b) 8

IV. CONCLUSION

The present study shows a strategy to fabricate double line waveguides written directly in Nd $^{3+}$ doped TeO_2-ZnO glasses using 30 fs laser pulses at 800 nm. The absorption of the material at 800nm ($^4I_{9/2} \rightarrow {}^4F_{5/2} + {}^2H_{9/2}$ transition) is in resonance with the fs laser wavelength, used for the writing, and, as a consequence, heating of the materials takes places, resulting in cracking of the material. A workaround to this problem is to increase writing speed, however, this decreases the amount of structural damage caused in the material and, consequently, the negative index change caused by the laser. Here, a new strategy for the double line configuration is demonstrated based on repeated overlays of lines written at high speed when compared to the traditional single continuous line written at much lower speed (0.02 mm/s [9]). The lines, separated by a distance of 10 µm and positioned 0.7 mm beneath the surface, were composed by 4 and 8 overlapping lines, therefore, writing speed of 0.5mm/s and pulse energy of 15 µJ demonstrated to be adequate parameters in order to optimize light confinement. The refractive index changes at 632 nm were of $\Delta n = 1\ \mathrm{x}10^{-5}$ and $\Delta n = 1\ \mathrm{x}10^{-4}$ for double waveguides written with 4 and 8 laser passages, respectively. The beam images at the output of the waveguides showed confinement beam in agreement with multi transverse order mode. Regarding the beam quality factor (M^2), the results obtained were $M_y = 24 \pm 3$ and $M_x = 14 \pm 3$ at 632 nm (8 laser passages). The present results are promising for the fabrication of passive and active components based on Nd^{3+} doped TeO_2-ZnO glasses for photonic applications. Further investigation will be done to measure the relative gain at 1064 and 1300nm in order to evaluate the influence of the parameters used in the writing process on the optical performance of the different waveguides fabricated with 4 and 8 overlapping lines.

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