Fs laser writing in Nd3+ doped GeO2-PbO glasses for the production of a new double line waveguide architectures for photonic applications

Bordon, Camila D., Wetter, Niklaus, de Rossi, Wagner, Kassab, Luciana R.

Camila D. S. Bordon, Niklaus U. Wetter, Wagner de Rossi, Luciana R. P. Kassab, "Fs laser writing in Nd3+ doped GeO2-PbO glasses for the production of a new double line waveguide architectures for photonic applications," Proc. SPIE 12004, Integrated Optics: Devices, Materials, and Technologies XXVI, 120040Y (5 March 2022); doi: 10.1117/12.2610155

Event: SPIE OPTO, 2022, San Francisco, California, United States

Fs laser writing in Nd^{3+} doped GeO_2-PbO glasses for the production of a new double line waveguide architecture for photonic applications

Camila D. S. Bordon [a], Niklaus U. Wetter[b], Wagner de Rossi [b], Luciana R. P. Kassab[c]
[a]Departamento de Engenharia de Sistemas Eletrônicos, Escola Politécnica da USP, São Paulo, Brazil; [b] Centro de Lasers e Aplicações, Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN, São Paulo, Brazil; [c]Departamento de Ensino Geral, Faculdade de Tecnologia de São Paulo, São Paulo, Brazil.

ABSTRACT

A new double line waveguide architecture produced in Nd^{3+} doped GeO_2-PbO glasses is presented for photonic applications. These glasses produced with the melt quenching technique have interesting characteristics that make them attractive for photonic applications: large transmission window (400–5000 nm), large polarizability, low melting temperature (1200° C) with respect to silicates, low cut-off phonon energy (~800 cm^{-1}), large mechanical resistance, high chemical durability and high refractive index (~2.0). The double line waveguides are written directly into Nd^{3+} doped GeO_2-PbO glasses using a Ti:Sapphire femtosecond (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 collinearly overlapping lines. Results of the output mode profile, the M^2 beam quality factor at 632 and 1064 nm and refractive index change are presented, as well as the parameters used for laser writing. Double waveguides written with 4 and 8 overlapping lines, writing speed of 0.5 mm/s and pulse energy of 30 µJ demonstrated to be adequate parameters for writing; refractive index changes of ~10^{-3} were found at 632 nm for all the cases. The present results demonstrated that Nd^{3+} doped GeO_2-PbO glasses with the new double line waveguide architecture are promising materials for the fabrication of passive and active components for photonic applications. Further investigation will focus on the influence of the writing parameters on the optical performance of the different waveguides, and evaluate the potential of the materials as optical amplifiers at 1064 nm.

Keywords: Optical materials, laser processing, double line waveguides, germanate glasses

1. 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 GeO_2-PbO glasses using a Ti:Sapphire femtosecond (fs) laser operating at 800 nm, delivering 30 fs pulses at 10 kHz repetition rate. Glass formers like silicates, borates, and phosphates were initially used as hosts for rare earth ions [1-2] followed by fluoride glasses, [3-4] because of their low phonon energy (500–600 cm^{-1}), capability to incorporate large amount of rare earth ions as dopants and large transparency (near-UV to the mid-IR region) [5]. However, the difficulty in their preparation because of the need of a glove-box environment and their mechanical weakness lead researches to look for other alternatives. Then, heavy metal oxide glasses appeared as another possible host [6-8] as they exhibit better thermal, mechanical and chemical durability, can be melted in ambient atmosphere, have lower phonon energy (700-800cm^{-1}) and higher refractive index (~2.0). In particular, rare-earth doped GeO_2-PbO glasses were extensively explored, mainly with metallic nanoparticles, and showed potential applications for photonics due to their enhanced linear and nonlinear optical properties such as waveguides, cover layers to enhance Si solar cell efficiency, white light generation and tunable visible light emission [5], among others. Motivated by these results. A new configuration of double line waveguides produced directly into Nd^{3+} doped GeO_2-PbO glasses by femtosecond (fs) laser (Ti:Sapphire) operating at 800 nm, delivering 30 fs pulses at 10 kHz repetition rate) is presented for photonic applications. As the absorption of the Nd^{3+} doped GeO_2-PbO material at 800 nm is in resonance with the fs laser, the heating of the material makes writing difficult. Increase of the writing velocity avoids heating and was used as an alternative to avoid cracking of the material. We demonstrate that the use of several overlapping lines overcomes this problem and compensates for the decrease of induced index change given the necessity to increase the writing velocity (0.5 mm/s), when compared to

Integrated Optics: Devices, Materials, and Technologies XXVI, edited by
Sonia M. García-Blanco, Pavel Cheben, Proc. of SPIE Vol. 12004,
120040Y · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2610155

previous reports (0.06 mm/s) in which active waveguides in Yb/Er doped GeO_2-PbO glasses were produced by direct fs laser writing operating at 800nm [9]. The two written lines that form the double waveguide in Nd^{3+} doped GeO_2-PbO glass are formed by several overlapping lines, as follows: 4 and 8 collinearly overlapping lines written with a pulse energy of 30 µJ. We report results of output mode profile, beam quality factor M^2 (at 632 and 1064 nm) and refractive index change based on these the parameters used for laser writing.

2. MATERIALS AND METHODS

2.1 Glass production

Glasses were obtained by the melt-quenching method with the addition of Nd_2O_3 (1.0 wt %). The reagents were melted in an alumina crucible for 1 h at 1200 °C, quenched in air in a preheated brass mold, and annealed at 420 °C for 1 h to avoid internal stress. The annealing is relevant to reduce the internal stress in order for the samples to become less fragile and without risk breakoff breaking during the polishing. Finally, the samples were cut and polished. Transparent samples with thickness of 2 mm were produced.

2.2 Waveguide writing

The waveguides were produced by a femtosecond laser system (Ti:sapphire, model PRO 400, Femtolasers GmbH) with emission wavelength centered at 800 nm, pulse length of 30 fs, maximum energy per pulse of 200 µJ and 10 kHz repetition rate. During the writing process the polished surface of the samples receives the laser beam that is focused perpendicular to the surface, with its linear polarization tilted 45° with respect to the movement direction and with the focal point positioned 0.75 mm below the surface. A pair of parallel lines (each written line is formed by 4-8 overlapping lines) were written spaced by 10 µm, using the parameters presented in Table 1. Figure 1 illustrates the set-up used for the waveguide writing as well as the damage at the end-faces of the sample (the distance between two pairs of waveguides is 400 um). As mentioned before, a higher writing speed of 0.5 mm/s with respect to our previous work (0.06 mm/s) based on Yb/Er doped GeO_2-PbO glass [9] was used in order to avoid the heating of the material due to the absorption of the Nd^{3+} doped GeO_2-PbO material at 800 nm, that is in resonance with the fs laser.

Table 1. Parameters used in the writing process.

PARAMETERS	**VALUES**
Writing speed (mm/s)	0.5
Wavelength (nm)	800
Repetition rate (kHz)	10
Pulse energy (µJ)	30
Number of collinear, overlapping lines	4 and 8

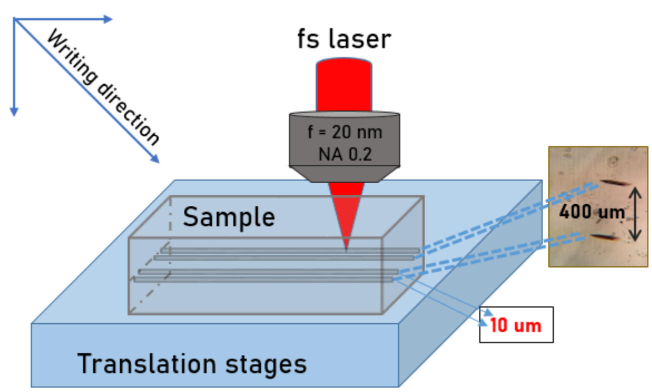


Figure 1. Set-up for waveguide writing; the end-face microscope image of waveguides written by the fs laser is also shown.

2.3 characterization of the waveguide

Because of the damage (shown in Figure 1) caused by the fs laser [10] the samples had to be polished again after the fs -writing process and the final dimensions were (5.18 x 4.0 x 2.0) mm^3. The refractive index change is estimated by the measured N.A. (numerical aperture) of the waveguide, as described in equation 1 [11]:

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

In the equation above n_1 and n_2 represents the refractive index of the core and the cladding, respectively. Figures 2a and 2b, show the experimental set-ups used to determine the mode images (using a CCD camera) and the beam quality factor (M^2) at 632 nm, respectively, using standard procedures [12]; it is important to point out that that the set-up of Fig 2b) has an additional flat-convex lens between the CCD camera and the 20x objective (located after the sample). The focal distances of these flat-convex lenses were 50 mm and 35 mm for 4 and 8 overlapping lines waveguide, respectively.

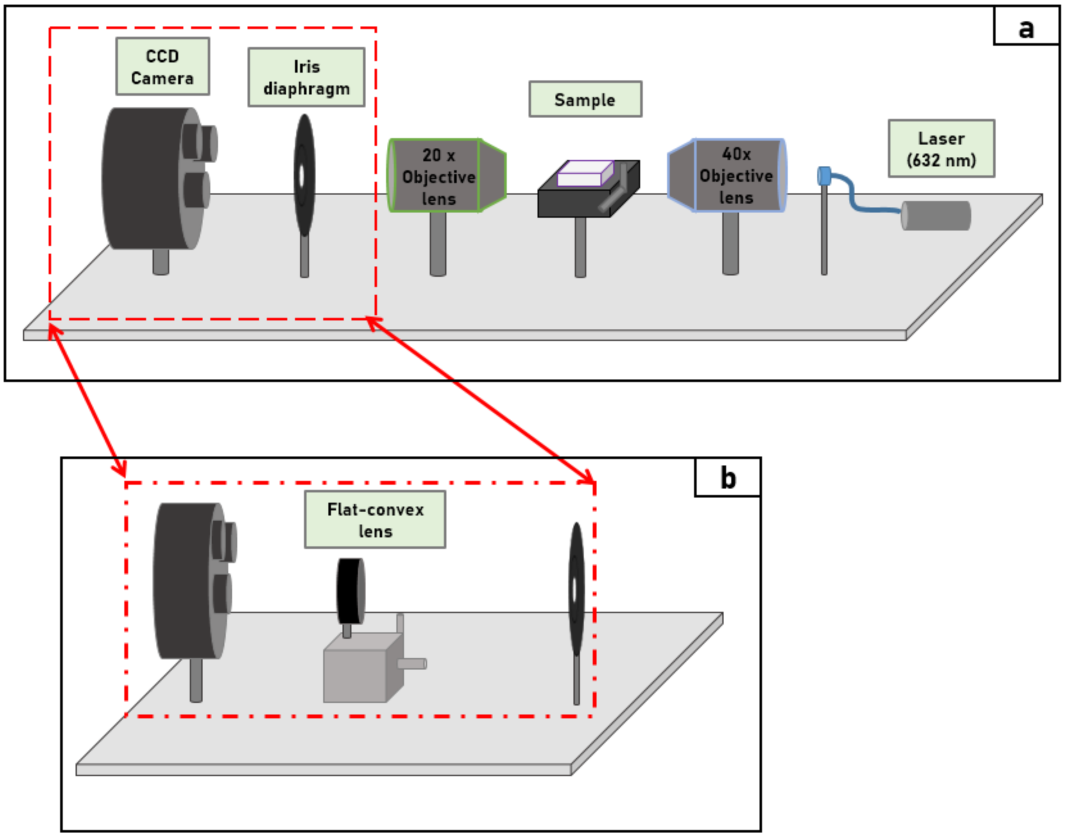


Figure 2. Experimental setup used to a) determine the mode images and the numerical aperture; and b) the beam quality (with flat-convex lens).

M^2 at 1064 is determined by using the equation bellow:

$$M^2 = \frac{\theta_{ideal}.W0_{ideal}.\pi.}{\lambda} \qquad (2)$$

In the equation above, θ is the half-angle beam divergence obtained from M^2 and W_0 (the beam waist radius) measured at 632 nm with the experimental set-up of Figure 2b.

3. RESULTS AND DISCUSSION

The refractive index change at 632 nm determined by equation (1) was 5.7 x10^{-3} and 7.3x10^{-3} for double waveguides written with 4 and 8 overlapping lines, respectively. The beam images at the output of the waveguides, are shown for both cases (4 and 8 laser passages) in Figure 3. Figure 4 shows the results of M_x^2 and M_y^2 (at 632 nm) for the different parameters used for laser writing. M_x^2 and M_y^2 were determined at 1064 nm using equation 2, as explained above. For double waveguides written with 4 overlapping lines we obtained $M_x^2 = 16.7$ and $M_y^2 = 14.2$ at 632 nm and $M_x^2 = 9.9$ and $M_y^2 = 8.4$ at 1064 nm. Waveguides written with 8 overlapped lines presented values of $M_x^2 = 16.6$ and $M_y^2 = 15.6$ at 632 nm and $M_x^2 = 9.9$ and $M_y^2 = 9.2$ at 1064 nm, respectively. The results are similar for both writing conditions (4 and 8 overlaps). Similar values for M_x^2 and M_y^2 are achieved under all conditions showing x,y-symmetrical guiding.

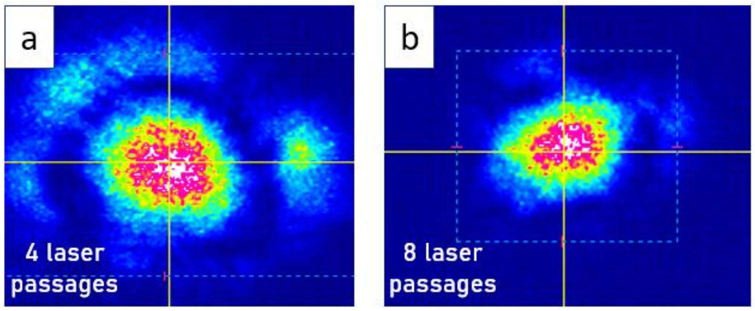
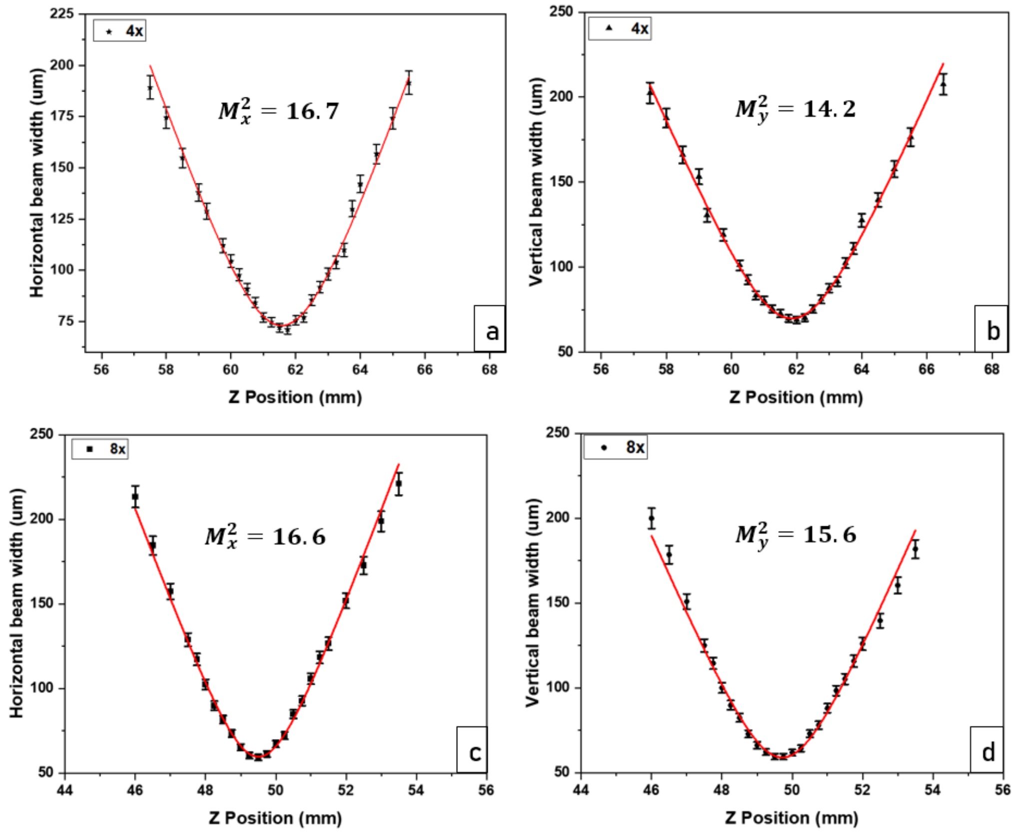


Figure 3. Beam images for the different parameters used for the writing: 4 and 8 overlapping lines (30µJ).



4. FIGURE 4. RESULTS OF M_X^2 AND M_Y^2 AT 632 NM FOR THE DIFFERENT PARAMETERS USED FOR THE WAVEGUIDES WITH 4 AND 8 OVERLAPPING LINES (30µJ). CONCLUSIONS

In the present investigation we show a new strategy for the double line configuration 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 [13]). The lines, separated by a distance of 10 µm and positioned 0.7 mm beneath the surface using writing speed of 0.5mm/s and pulse energy of 30 µJ were composed by 4 and 8 collinearly overlapping lines. The refractive index changes at 632 nm were 10^{-3}, for both horizontal and vertical directions. Regarding the beam quality factor (M^2), we highlight that the M^2 values indicate a x,y-symmetrical guiding for both waveguides. This new architecture can be extended to different hosts and represents an alternative for suitable materials for integrated optics. In the near future the relative gain will be investigated to study the influence of the double line configuration based on different repeated overlays of lines written at high speed on optical amplification. Moreover, it will be possible to identify the best condition for the fabrication of passive and active components for photonic applications at 1064 and 1300 nm.

5. ACKNOWLEDGMENTS

We acknowledge the financial support from Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP, 2013-26113-6), from National Institute of Photonics, supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (INFO/CNPq, 465763/2014-6) and from Sisfoton-MCTI (-CNPq 440228/2021-2); we also thank the support from Coordenação de Aperfeiçoamento de Pessoal de Ensino Superior (CAPES).

REFERENCES

[1] Lin, H., Pun, E. Y. B., Wang, X., Liu, X., "Intense visible fluorescence and energy transfer in Dy^{3+}, Tb^{3+}, Sm^{3+} and Eu^{3+} doped rare-earth borate glasses," J. Alloys Compd. 390(1-2), 197-201 (2005).

[2] Nageno, Y., Takebe, H., Morinaga, K., "Correlation between radiative transition probabilities of Nd^{3+} and composition in silicate, borate, and phosphate glasses," J. Am. Ceram. Soc. 76(12), 3081-3086 (1993).

[3] Nishibu, S., Yonezawa, S., Takashima, M., "Preparation and optical properties of HoF_3–BaF_2–AlF_3–GeO_2 glasses," J. Non-Cryst. Solids, 351(14-15), 1239-1245 (2005).

[4] Florez, A., Ulloa, E. M., Cabanzo, R., "Optical properties of Nd^{3+} and Er^{3+} ions in fluoro-phosphate glasses: Effects of P_2O_5 concentration and laser applications," J. Alloys Compd. 488(2), 606-611 (2009).

[5] De Araújo, C. B., Kassab, L. R. P., "Enhanced photoluminescence and planar waveguides of rare-earth doped germanium oxide glasses with metallic nanoparticles, in Glass Nanocomposites: Preparation, Properties, and Applications, Elsevier, 131-144 (2016).

[6] Uma, V., Vijayakumar, M., Marimuthu, K., Muralidharan, G., "Luminescence and energy transfer studies on Sm^{3+}/Tb^{3+} codoped telluroborate glasses for WLED applications," J. Mol. Struct. 1151, 266 - 276 (2018).

[7] Alvarez-Ramos, M. E., Alvarado-Rivera, J., Zayas, M. E., Caldiño, U., & Hernández-Paredes, J., "Yellow to orange-reddish glass phosphors: Sm^{3+}, Tb^{3+} and Sm^{3+}/Tb^{3+} in zinc tellurite-germanate glasses," Opt. Mater. 75, 88 - 93 (2018).

[8] Liao, M., Gao, W., Duan, Z., Yan, X., Suzuki, T., & Ohishi, Y., "Supercontinuum generation in short tellurite microstructured fibers pumped by a quasi-cw laser," Opt. Lett. 37(11), 2127-2129 (2012).

[9] Da Silva, D. S., Wetter, N. U., Kassab, L. R. P., De Rossi, W., De Araujo, M. S., "Double line waveguide amplifiers written by femtosecond laser irradiation in rare-earth doped germanate glasses," J. Lumin. 217, 116789 (2020).

[10] Borca, C. N., Apostolopoulos, V., Gardillou, F., Limberger, H. G., Pollnau, M., Salathé, R. P., "Buried channel waveguides in Yb-doped KY (WO_4) 2 crystals fabricated by femtosecond laser irradiation," Appl. Surf. Sci. 253(19), 8300-8303 (2007).

[11] Gattass, R. R., Mazur, E., "Femtosecond laser micromachining in transparent materials," Nat. Photonics 2(4), 219-225 (2008).

[12] Feise, D., Blume, G., Dittrich, H., Kaspari, C., Paschke, K., Erbert, G., "High-brightness 635nm tapered diode lasers with optimized index guiding. Proc. SPIE 7583, 75830V-1-75830V-12 (2010)

[13] Da Silva, D. S., Wetter, N. U., De Rossi, W., Kassab, L. R. P., Samad, R. E., "Production and characterization of femtosecond laser-written double line waveguides in heavy metal oxide glasses," Opt. Mater. 75, 267-273 (2018).