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# The influence of the different parameters used for the production of double line waveguides in $Nd^{3+}$ doped $TeO_2$-ZnO glasses by fs laser writing

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## ABSTRACT

$Nd^{3+}$ doped $TeO_2$-ZnO glasses with double line waveguides produced by femtosecond (fs) laser writing technique are presented. The waveguides are written directly into these glasses using a femtosecond (fs) Ti:Sapphire laser, operating at 800 nm, delivering 30 fs pulses at 10 kHz repetition rate. Each written line is formed by several collinearly overlapping lines. When double line waveguides are produced, the light is guided in between the two lines and a negative refractive index change is produced in the region of the fs laser's focus. However, as the absorption of the material at 800 nm ($^4I_{9/2} \rightarrow {}^4F_{5/2} + {}^2H_{9/2}$ transition of $Nd^{3+}$) is in resonance with the fs laser, the heating of the material makes writing difficult. In this context, the use of several overlapping lines represents a good alternative as the velocity of the writing can be increased to avoid, heating. We report results of output mode profile, beam quality factor $M^2$ and refractive index change for, different parameters used for the fs laser writing. Pulse energies were 15µJ for 4 and 8 overlapping lines and 30 µJ for 2, 4 and 8 overlapping lines and the writing speed was 0.5 mm/s. The present investigation evaluates the best condition for the waveguides inscription, studying the influence of different parameters used in the writing process aiming at future photonic applications.

**Keywords:** glasses, double line waveguides, fs laser writing, photonics.

## 1. INTRODUCTION

Glasses based on $TeO_2$ are known to present good chemical and mechanical stabilities, large transparence window (from visible to mid-infrared), high values of linear and nonlinear refractive indexes[1-3] and have been investigated for a large range of applications. Laser action at 1064 nm for different concentration of $Nd^{3+}$ ions[4] was reported. Memory devices due to gold nanoparticles[4], is another application that was reported. Regarding luminescence increase due to metallic nanoparticles, different compositions based on $TeO_2$ were investigated with silver and gold nanoparticles[4] and efficient infrared-to-visible light conversion and applications regarding displays in the blue-red region were demonstrated. Solar cell efficiency increase was reported using cover layer glasses based on $TeO_2$ doped with rare earth ions, with and without silver nanoparticles. In these cases, enhanced Si solar cell performance can be mediated by plasmonic effects[4]. More recently, nuclear shielding applications of glasses based on tellurium oxide were reported, too[5]. In this work, a new configuration of double line waveguides produced directly into $Nd^{3+}$ doped $TeO_2$-ZnO glasses is presented for photonic applications. The double line waveguides are 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). As the absorption of the material at 800 nm is in resonance with the fs laser, the heating of the material makes writing difficult. This problem was overcome by increasing the writing velocity. However, the lower spatial density of laser pulses reduces the structural changes and consequently the refractive index change. We demonstrate that the use of several collinearly overlapping lines represents a good alternative to compensate the mentioned decrease of induced index change caused by the increase in writing velocity. The two written lines that form the double waveguide are formed by several lines that overlap collinearly, using different energies as follows: 4 and 8 overlapping lines using 15 µJ and 2, 4 and 8 overlapping lines

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using 30 µJ. 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.

## 2. METHODOLOGY

### 2.1 Preparation of the glasses

The 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. Melting of the reagents was performed at 835°C for 30 minutes in a high purity platinum crucible (99.99%) followed by quenching in a preheated brass mold and annealing. We highlight that the annealing process, performed at 325°C for 120 minutes, plays an important role to reduce the internal stress, letting the samples less fragile. Finally, the samples were cut and polished and transparent samples with thickness of 3 mm were produced.

### 2.2 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 beam was incident perpendicular to the polished surface, with its linear polarization tilted 45° (the polarization of the laser beam guidance and focusing system) with respect to the movement direction, and the focal point was positioned 0.75 mm below the surface. This process was repeated 2, 4 and 8 times for each line. The process was repeated for the second, parallel line which was 10 µm apart, using the parameters presented in Table 1. Number of overlaps and writing speed were determined experimentally with the goal to avoid fracture of the samples. Figure 1 illustrates the set-up used for the waveguide writing and Figure 2 the resulting pair of parallel lines separated by 10 µm.

Table 1. Parameters used in the writing process.

| | |
|---|---|
| Writing speed (mm/s) | 0.5 |
| Wavelength (nm) | 800 |
| Repetition rate (kHz) | 10 |
| Pulse energy (µJ) | 15, 30 |
| Number of Overlapped lines | 2, 4 and 8 |

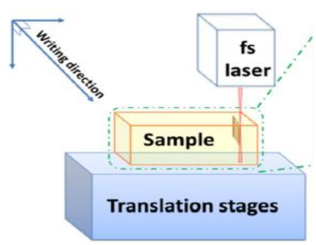



Figure 1. Set-up used for the waveguide writing.

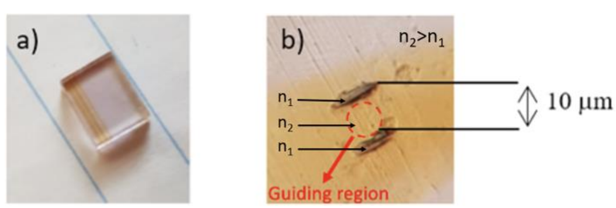



Figure 2. Two parallel, double line waveguides in Nd3+ doped TZ glass: a) photo, b) microscope image at the sample's exit face before polishing.

After the writing process the samples were polished again due to the damage caused by the fs laser[6], shown in Figure 2b. The final dimensions of the sample were 6.9 x 4.0 x 2.9 $mm^3$. The refractive index change is estimated by the measured

N.A. of the waveguide, as described in equation 1[7], where $n_1$ and $n_2$ represent the refractive index of the core and the cladding, respectively:

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

The experimental set-ups used to determine the mode images (using a CCD camera) and the beam quality factor ($M^2$) at 632 nm, using standard procedures[8], are exhibited in Figures 3a) and 3b), respectively. We point out that the set-up of fig 3b) is almost the same of Fig. 3a) with an additional flat-convex lens (with focal distance of 75 mm) between the CCD camera and the 20x objective (located after the sample).

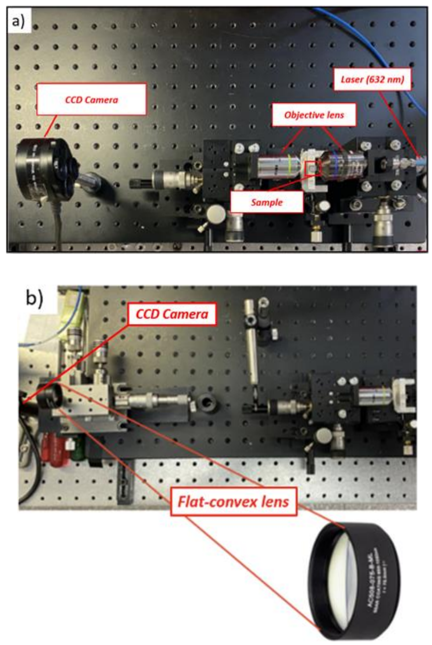


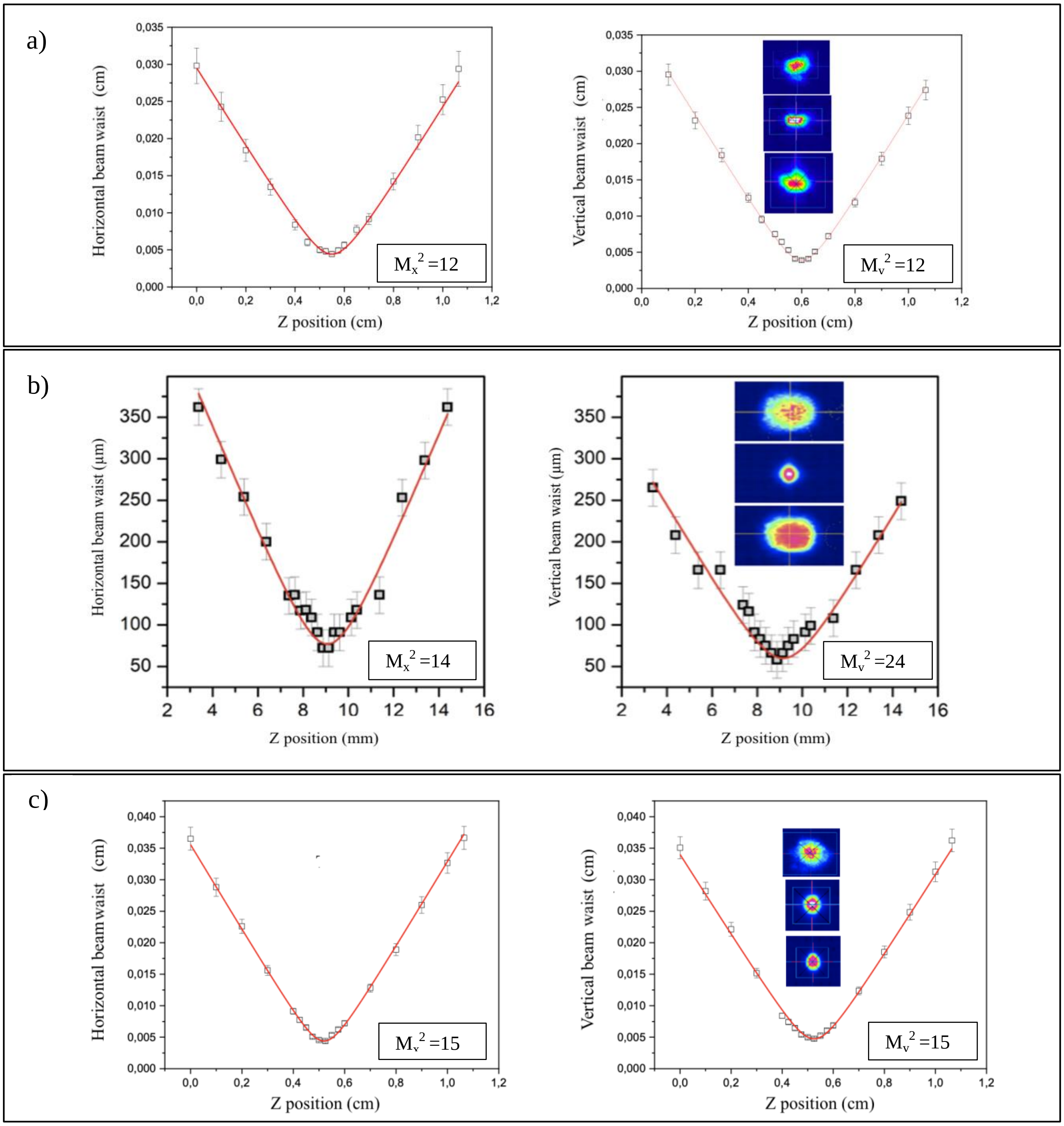

Figure 3. a) Experimental set-up used to determine the mode images (using a CCD camera) and b) Experimental set-up used to determine the beam quality factor ($M^2$)

The beam quality factor $M^2$ at $\lambda$ = 1064 nm is determined by using the equation bellow, where $\theta$ is the half-angle beam divergence at 632 nm and $w_0$ is the beam radius at the beam waist, also obtained with the experimental set-up of Figure 3b.

$$\theta = \frac{M^2.\lambda}{\pi.w_0} \quad (2)$$

## 3. RESULTS

The refractive index changes at 632 nm, determined by Equation (1), was ~$10^{-4}$ for all the tested double waveguides. Figure 4 shows the results of $M_x^2$ and $M_y^2$ (at 632 nm) for the different parameters used for laser writing; The insets show images of focus, near and far field. $M_x^2$ and $M_y^2$ values at 1064 nm were determined using Equation 2 as explained above. Table 2 summarizes all the values obtained for $M_x^2$ and $M_y^2$ at 632 and 1064 nm, respectively. $M^2$ values for samples written with 2 overlapping lines, using pulse energy of 30 µJ, are 15 and 9, at 632 and 1064 nm, respectively, in both, x and y directions. For a pulse energy of 15 µJ and 4 overlapping lines the $M^2$ values are 12 and 7, at 632 and 1064 nm, respectively. Other combinations of pulse energy and number of overlapping lines resulted in worse $M^2$ values in at least one direction.


a)
Horizontal beam waist (cm)
Z position (cm)
Mx2 =12
Vertical beam waist (cm)
Z position (cm)
Mv2 =12
b)
Horizontal beam waist (µm)
Z position (mm)
Mx2 =14
Vertical beam waist (µm)
Z position (mm)
Mv2 =24
c)
Horizontal beam waist (cm)
Z position (cm)
Mx2 =15
Vertical beam waist (cm)
Z position (cm)
Mv2 =15

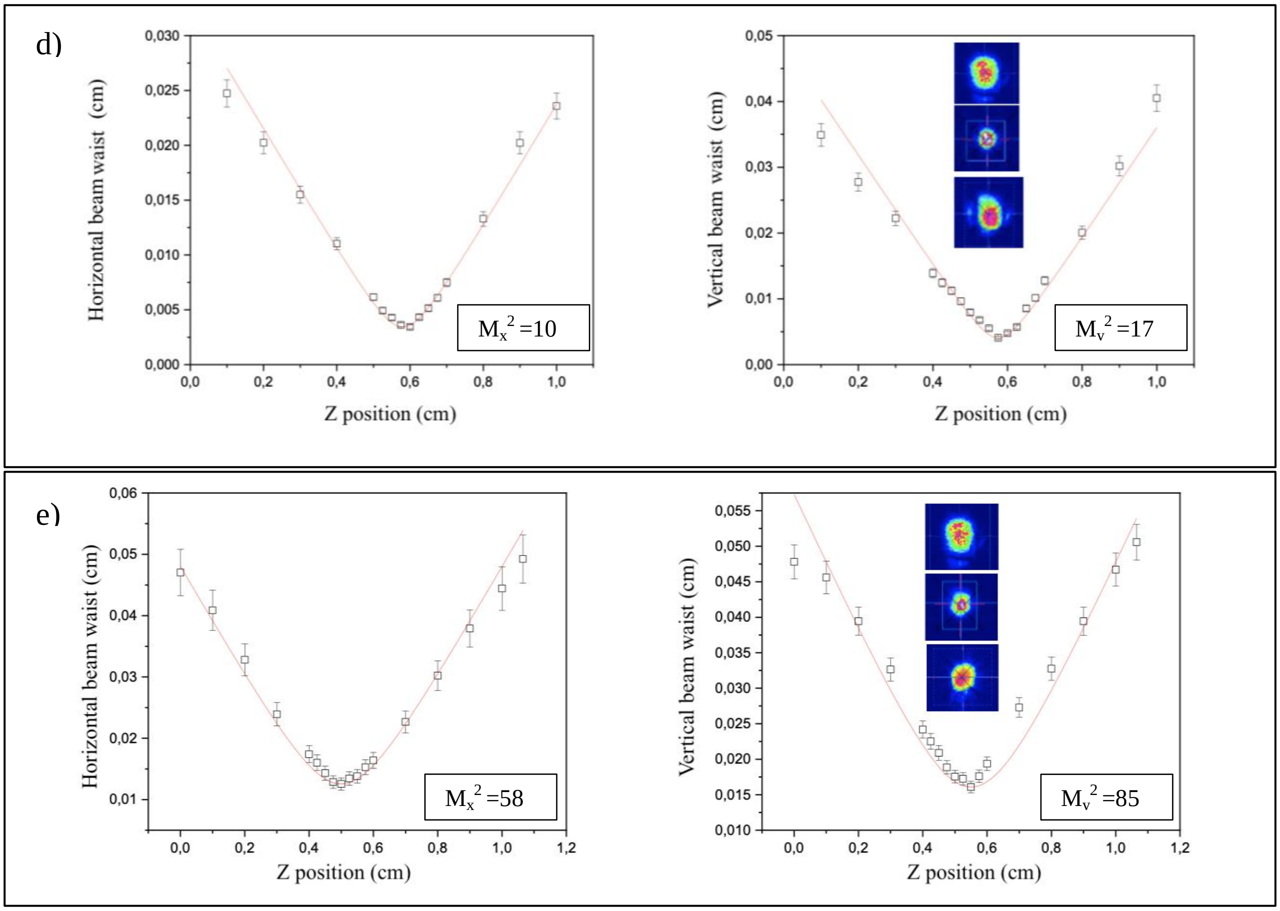



Figure 4 - Results of $M_x^2$ and $M_y^2$ (at 632 nm) for the different parameters used for the writing a) and 4 and b) 8 passages (15µJ) and c) 2, d) 4 and e) 8 passages (30 µJ). The results of $w_0$ are also shown. Insets (from top to bottom): Images of near field, focus and far field, respectively.

Table 2 Results of $M_x^2$ and $M_y^2$ at 632 and 1064 nm for different passages and energies

| **Overlapping lines** | **2** | **4** | **4** | **8** | **8** |
|---|---|---|---|---|---|
| **Energy (µJ)** | **30** | **15** | **30** | **15** | **30** |
| $M_x^2$ - 632 nm | 15 | 12 | 10 | 14 | 58 |
| $M_y^2$ - 632 nm | 15 | 12 | 17 | 24 | 85 |
| $M_x^2$ - 1064 nm | 9 | 7 | 6 | 8 | 34 |
| $M_y^2$ - 1064 nm | 9 | 7 | 10 | 14 | 47 |

## 4. CONCLUSIONS

In the present investigation we show a new strategy for the double line configuration based on repeated collinear 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 written at a speed of 0.5 mm/s, composed of either 4 and 8 overlapping lines at a pulse energy of 15 µJ or 2, 4 and 8 overlapping lines at a pulse energy of 30 µJ. The refractive index changes at 632 nm was $10^{-4}$. The images at the output of the waveguides showed confinement of the beam in agreement with multi transverse order mode. Regarding the beam quality factor ($M^2$), we highlight the best results for samples with 4 overlapping lines and pulse energy of 15 µJ ($M_x^2$ and $M_y^2$ = 12 at 632 nm and $M_x^2$ and $M_y^2$ = 7 at 1064 nm) and 2 overlapping lines with pulse energy of 30 µJ ($M_x^2$ and $M_y^2$ = 15 at 632 nm and $M_x^2$ and $M_y^2$ = 9 at 1064 nm). The present results show that the procedure of writing double lines by repeated, collinear overlays of single lines written at high speed into $Nd^{3+}$ doped $TeO_2$-ZnO glasses shows potential for the fabrication of passive and active components for photonic applications. Further investigation will be done to determine the relative gain at 1064 nm in order to evaluate the influence on the optical amplification of the different parameters used in the writing process. The present procedure can be extended to different glasses doped with $Nd^{3+}$ to operate at 1064 nm and at 1300 nm.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