

# Curved Waveguide Irradiated by Femtosecond Laser in Ag-doped GeO<sub>2</sub>–PbO glasses for photonic applications

Thiago Vecchi Fernandes<sup>a</sup>, Camila D. S. Bordon<sup>a</sup>, Niklaus U. Wetter<sup>b</sup>, Wagner de Rossi<sup>b</sup>, Luciana R. P. Kassab<sup>c</sup>

<sup>a</sup>Departamento de Engenharia de Sistemas Eletrônicos, Escola Politécnica da USP, São Paulo, Brazil; <sup>b</sup>Centro de Lasers e Aplicações, Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN, São Paulo, Brazil; <sup>c</sup>Departamento de Ensino Geral, Faculdade de Tecnologia de São Paulo, São Paulo, Brazil

Author e-mail address: thiago.vecchi.f@hotmail.com

**Abstract:** We demonstrate the fabrication of straight and curved dual waveguides in GeO<sub>2</sub>-PbO glasses embedded with silver nanoparticles using femtosecond laser inscription. This research includes evaluating beam quality, propagation loss, and polarization of the double-wall waveguides.

## 1. Introduction

GeO<sub>2</sub>-PbO glasses exhibit several properties that make them promising candidates for numerous photonic applications, including a wide transparency range (400-5000 nm), high polarizability, a low phonon cutoff energy (approximately 800 cm<sup>-1</sup>), robust glass stability, excellent chemical durability, and a high refractive index (around 2.0). Metallic nanoparticle-doped glasses offer great potential for photonic applications due to their high third-order nonlinearities and ultrafast response times [1]. In a recent study, we demonstrated a new configuration of double-wall curved waveguides that were directly produced in GeO<sub>2</sub>-PbO glass doped with silver (Ag) nanoparticles (NPs) using femtosecond (fs) laser writing [2]; this configuration had different inter-wall distances (10 and 25 μm) and a curvature radius of 20 mm. Motivated by these results, the design of the curved waveguides was modified in order to optimize the results; the new configuration presented only 10 μm of inter-wall distance (the best result reported in the previous study) and an increase in the curvature radius to 40 mm in order to evaluate influence on the beam quality factor (M<sup>2</sup>), propagation losses and polarization. This new configuration was directly inscribed by fs laser in GeO<sub>2</sub>-PbO glasses containing Ag nanoparticles.

## 2. Experimental Method

The glass fabrication process employed a base composition of 40 wt% of GeO<sub>2</sub> and 60 wt% of PbO (designated as GP), incorporating 2.0 wt% of AgNO<sub>3</sub>, and the melt quenching method was used to prepare the sample. The sample was then polished in order to obtain better optical quality. The waveguides have a double-walled structure, where each wall consists of four superimposed tracks created by overlapping laser pulses. Due to spherical aberration and nonlinear autofocusing effects, the focusing energy extends along a long line, forming a thin, tall wall, about 10 μm thick and 180 μm high, and it is between these two walls of modified material that the light is guided. The tracks were produced using a femtosecond laser system (Ti:sapphire, model PRO 400, Femtolasers GmbH) and a 20 mm focal length focusing lens whose focus was positioned 0.75 mm below the surface. The laser beam has its linear polarization tilted 45° with respect to the direction of motion. It is incident perpendicularly on the polished sample

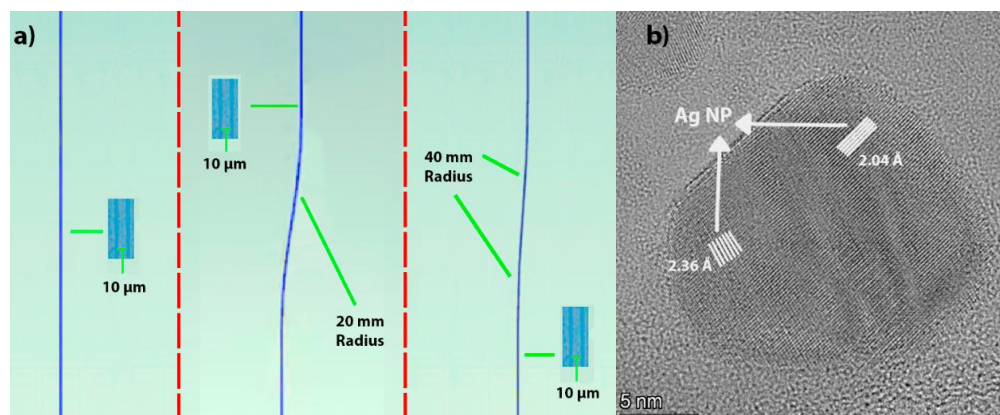


Fig. 1. a) Design of the waveguides produced with fs laser in GeO<sub>2</sub>-PbO glass b) TEM image of an isolated silver nanoparticle with the interplanar distance corresponding to the crystalline plane (1,1,1) of a face centered cubic silver crystal.

surface at a speed of 0.5 mm/s and a pulse energy of 30  $\mu\text{J}$ . The guides included a straight waveguide and two curved guides with radius of curvature of 20 mm and 40 mm, always using a distance of 10  $\mu\text{m}$  between the guide walls. Transmission electron microscopy was performed to evaluate the size of the Ag NP. Fig 1 (a) shows, from left to right, a straight guide with a 10  $\mu\text{m}$  distance between the walls and two curved guides also with a 10  $\mu\text{m}$  distance between the walls but with different curvature radii: the first with 20 mm and the second one with 40 mm. Fig 1 (b) shows the TEM image of the sample doped with 2 wt%  $\text{AgNO}_3$  where it is possible to observe an isolated silver NP and the interplanar distances of 0.236 nm and 0.204 nm corresponding to the crystalline plane (1,1,1). To determine the beam quality index ( $M^2$ ), the standard procedure [3] was used with the configuration illustrated in Fig. 2 (a) for all waveguide architectures written in the sample. Using the configuration shown in Figure 2 (b), the propagation losses were measured for the curved waveguides and compared, relative to the straight guide [4].

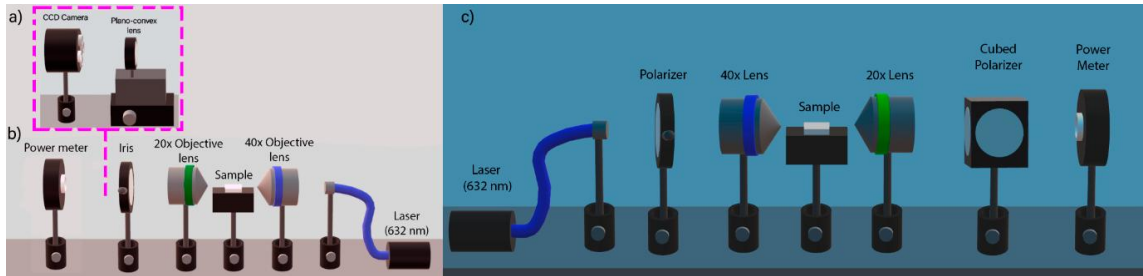


Fig. 2. Experimental setup used for measurements of a)  $M^2$ ; b) propagation loss and c) experimental arrangement used for polarization measurements of double-wall waveguides.

With the configuration in Figure 2 (c), the polarization ratio was measured, so it was possible to quantify the vertical and horizontal polarization that occurs during light guidance.

### 3. Results

Table 1 reports the results obtained for each axis of the  $M^2$  at 632 and 1064 nm and the relative propagation loss in comparison to the 10  $\mu\text{m}$  straight waveguide, which served as a reference.

Table 1.  $M^2$  values at 632 and 1064 nm (for all waveguide configurations) and propagation losses in relation to a straight waveguide with a distance between the waveguide walls of 10  $\mu\text{m}$ .

Waveguide Architecture	$M^2_x$ (632 nm)	$M^2_y$ (632 nm)	$M^2_x$ (1064 nm)	$M^2_y$ (1064 nm)	Propagation losses (dB/cm)
Straight	5.23	4.16	3.11	2.47	reference
Curve 20 mm	15.2	10.64	9.02	6.32	1.33
Curve 40 mm	6.4	5.0	3.8	3.0	1.13

Observing the data mentioned above, we observe lowest propagation loss and highest beam quality for the straight waveguide. We also observe an improvement for bigger radius of curvature when compared to smaller curvature. The straight guide and the curved guide with radius of 40 mm, when polarized horizontally at the entrance, generate 12.9% and 8.4%, respectively, in the vertical polarization at the exit of the waveguides. For vertically polarized entrance beams the polarization is maintained. The waveguide with 20 mm curvature behaved differently and did not alter horizontally polarized light whereas vertically polarized light at the entrance resulted in 12.1% horizontal polarization at the exit. This suggests that the results of the curved guide with the larger radius of 40 mm is more similar to the straight waveguide in all measured characteristics, thus demonstrating an improvement that could contribute to the production of these configurations in  $\text{GeO}_2\text{-PbO}$  glasses.

### 4. References

- [1] De Boni, E. C. Barbano, T. A. de Assumpção, L. Misoguti, L. R. P. Kassab, and S. C. Zilio, "Femtosecond third-order nonlinear spectra of lead-germanium oxide glasses containing silver nanoparticles," *Opt. Express* 20(6), 6844–6850 (2012).
- [2] Fernandes, T. V. et al. "Passive Waveguide Fabrication through Femtosecond Laser irradiation in Ag-doped  $\text{GeO}_2\text{-PbO}$  glasses for photonic applications," in *CLEO 2024*, Technical Digest Series (Optica Publishing Group, 2024), paper JTU2A.179.
- [3] Bordon, C. D. S. et al. "Effect of Silver Nanoparticles on the Optical Properties of Double Line Waveguides Written by fs Laser in Nd<sup>3+</sup>-Doped  $\text{GeO}_2\text{-PbO}$  Glasses". *Nanomaterials* 13(4), p. 743, (2023).
- [4] Aldana, J. R. V. D. et al. "Femtosecond laser direct inscription of 3D photonic devices in Er/Yb-doped oxyfluoride nano-glass ceramics." *Optical Materials Express* 10 (10), p. 2695–2704, (2020).