

Review article

Towards Integrated Photonics: a review of femtosecond laser-written double-line waveguides in GeO₂-PbO glassesThiago Vecchi Fernandes^{a,*}, Niklaus Ursus Wetter^b, Wagner de Rossi^b,
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ABSTRACT

This review focuses on the fabrication and characterization of optical waveguides inscribed in GeO₂-PbO glasses using femtosecond (fs) laser irradiation. Fs laser writing offers key advantages, such as three-dimensional structuring, high precision, and minimal thermal effects to the surrounding material, enabling the production of complex photonic devices within transparent substrates. The discussion covers different cases, each from a distinct sample and reported in separate works: a straight waveguide doped with Yb³⁺/Er³⁺, operating as an optical amplifier in the third telecommunications window, straight waveguides doped with Nd³⁺, with and without Ag nanoparticles and the role of the plasmonic effects on the optical properties at 1064 nm. The results of S-bend and Y-shaped configurations containing Ag nanoparticles are also reviewed due to their relevance for resonant ring and beam splitters, respectively. The role of larger radius is discussed as well as the best Y configuration with respect to the opening angle and separation between the arms. The quality factor (M^2) of the proposed architecture is used to evaluate the symmetry between the x and y axes that is relevant to indicate comparable light guidance. The review highlights different configurations as well as their optical properties and the potential applications for integrated photonics.

1. Introduction

The telecommunications landscape has experienced significant expansion in recent years, primarily driven by the escalating global demand for internet connectivity. The continuous advancements in data processing speeds, coupled with the widespread adoption of wireless internet-enabled devices, have created an imperative for substantial bandwidth growth. This surge in demand has compelled telecommunications companies to actively investigate and implement more efficient and advanced data transmission technologies. Within this context, optical telecommunications have emerged as a key field, with waveguide technology playing a central role in meeting both fundamental and advanced application requirements.

The innovative integration of monolithic laser sources based on waveguide structures into compact photonic devices featuring small resonant cavities has unlocked a lot of novel opportunities and possibilities within the realm of integrated optics [1]. This progress has

enabled a wide range of developments, including Q-switched waveguide lasers [2] enabling pulsed light emission, compact solid-state waveguide lasers [3] offering stable and efficient light sources, and dual-doped waveguides, fabricated using precise fs laser writing techniques [4], among other cutting-edge advancements. Functionally, waveguides act as essential photonic components by confining light within well-defined spatial regions. This confinement mechanism leads to a significant increase in the intensity of the light within the waveguide's resonant cavity relative to the surrounding material [1,5], a crucial aspect for various optical processes and device functionalities.

In this scenario, heavy metal oxide glasses have emerged as promising alternatives, exhibiting attributes that rival, or even surpass, those of conventional silica-based optical fibers. Notably, glasses containing germanium dioxide stand out in this context. For instance, these glassy materials exhibit a lower melting temperature compared to silicate glasses and good capacity to dissolve rare earth ions (REs) [6,7]. This host has proven to be an efficient material for optical signal amplifiers

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utilizing silicon-based technology [8], overlayers to enhance the performance of silicon photovoltaic cells [9], and for sources capable of generating white light and emitting tunable visible light [10], among others. Furthermore, GeO_2 - PbO glasses present advantageous features, including a broad transmission window from visible to mid infrared region, and a high refractive index arising from the substantial atomic mass and high polarizability of their constituent elements. The lower phonon energy with respect to silicate glasses reduces the low non-radiative losses and favors the upconversion processes. Although silicate glasses exhibit a narrower transmission window, limited to the near-infrared region, and a lower refractive index, they present superior mechanical and chemical resistance as well as higher thermal stability, with a reduced tendency toward crystallization, enabling their widespread application in optical fibers with low losses over long transmission distances. Table 1 presents a comparison between the GeO_2 - PbO and other glass systems.

Germanium dioxide-lead oxide glasses enriched with REs ions have displayed enhanced optical characteristics, attributable to the plasmonic effects of metallic nanoparticles (NPs) [21]. Moreover, these glasses incorporating metallic NPs hold considerable promise for photonic technologies due to their extremely rapid response times and substantial third-order nonlinear optical properties [22]. Spurred by the increasing demands within optical telecommunications and the pivotal role of light-guiding laser sources [1], the present investigations focus on heavy metal oxide glasses, particularly GeO_2 - PbO with waveguides produced by fs laser irradiation.

The use of fs laser pulses for direct writing in transparent materials emerged in the mid-1990s as a powerful alternative to conventional planar fabrication techniques. The first demonstration of fs-laser-written optical waveguides in glass was reported by Davis et al., in 1996 [23], showing that tightly focused ultrashort pulses can induce permanent refractive-index modifications inside bulk fused silica through nonlinear absorption. So fs laser direct writing emerged as a versatile platform for three-dimensional photonic integration. Subsequent developments extended the technique to a broad range of multicomponent and rare-earth-doped glasses [24–31] enabling the fabrication of fs-laser-written active waveguides. Moreover, the implementation of complex guiding geometries, combined with optimized writing strategies, has proven essential to achieve low-loss propagation. Over the past two decades, miniaturization and integration of fs lasers with compact pump systems and mode-locking techniques have allowed portable, highly precise devices, expanding their use in ultrafast optics, 3D microstructuring, medicine, and advanced scientific research.

The recent review reported by Mamoon Khalid et al. [32] presents an extensive overview of the state of the art of fs laser-inscribed waveguides fabricated in different germanate glasses, with particular emphasis on laser applications operating around the 2.1 μm spectral region [32]. The review analyzes different writing strategies, in single-line and double-line geometries [32]. For fluorogermanate (GPGN) glasses, several writing regimes were explored. In one of them, fs laser pulses with a repetition rate of 500 kHz and pulse duration of approximately 350 fs resulted in propagation losses of about 0.7 dB/cm,

at 1550 nm [33]. Higher repetition rates, typically around 1 MHz, with pulse durations near 250 fs at 524 nm demonstrated the fabrication of low-loss waveguides with propagation losses of approximately 0.63 dB/cm at 1550 nm in single-line configurations [34–36]. When a double-line geometry with an inter-track separation of about 5 μm written was adopted under similar laser conditions, the propagation losses measured at 1550 nm were reduced to 0.22 dB/cm [37]. Additional GPGN waveguides written at repetition rates of 5 MHz and 100 kHz, using 250 fs pulses at 524 nm, exhibited propagation losses in the range of 0.58–0.80 dB/cm, respectively, at 1550 nm [37]. *Type I waveguides* inscribed in $(\text{BaO}-\text{GeO}_2-\text{Ga}_2\text{O}_3)$ BGG glass were fabricated with fs laser pulses at repetition rates around 250 kHz, pulse durations of approximately 70 fs, at 795 nm. Propagation losses as low as 0.5 dB/cm were achieved [38].

The present review intends to complement and update that recent review by focusing specifically on double-line fs laser-inscribed waveguides in doped and undoped GeO_2 - PbO glass. The discussion encompasses results already reported for straight, S-bend, and Y-shaped waveguide configurations, with particular emphasis on double-line structures fabricated by repeatedly writing overlapping lines at the same spatial location. In addition, this review highlights studies that investigate the effect of Ag NPs on the relative gain, beam quality factor, and related optical properties of fs-laser-written waveguides. By concentrating on these aspects, the present work addresses a notable gap in the literature concerning fs laser writing in GeO_2 -based glasses, providing a focused and in-depth perspective on a material system and waveguide geometry that have not been extensively explored in previous reviews.

Within this framework, several studies have explored dual-line waveguides in different host materials. The literature reported dual line waveguides for glasses [39,40] and crystals [41–43]. We reported the first results of dual line waveguides in undoped glasses based on TeO_2 and GeO_2 [44] that motivated the continuation of the investigation whose results are reviewed in this work.

The present report reviews recent advances in double-line waveguides fabricated in doped and undoped GeO_2 - PbO glasses. The production of active double-line waveguides in $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped glasses by direct fs laser writing is discussed, achieving relative gains of up to 7.5 dB/cm at 1550 nm, demonstrating their suitability for optical amplification [45]. Novel double-line architectures in Nd^{3+} -doped GeO_2 - PbO glasses, based on repeated collinear overlays, as well as the incorporation of Ag NPs to enhance optical performance, are also reviewed [20] as well as the incorporation of Ag NPs to enhance optical performance [46]. In addition, the fabrication and characterization of different waveguide configurations, including S-bend and Y-shaped geometries, are presented, revealing improved guidance for larger curvature radii and promising potential for beam splitting in Y-shaped devices [47,48].

Studies on the fabrication and characterization of straight and S-bend channel waveguides in crystalline hosts [1] via direct fs laser writing have also been reported as optical waveguides with curved and straight configurations in a crystalline silicon wafer and in

Table 1
Optical properties of different glass matrices.

Glass System	Transmission Window (nm)	Phonon Energy (cm^{-1})	Refractive Index	Propagation Loss	References
Silica (SiO_2)	~160–4000	~1100	~1.458 (at 589 nm)	~0.07 dB/cm in Type-I single scan waveguides	[11,12]
Fluoride (ZBLAN-type)	~220–8000	~600	~1.499 (at 589 nm)	~0.21 dB/cm in Type-I multiscan waveguides	[11,13]
Chalcogenide (e.g. As-S/Se/Te)	Sulfide: ~700–8000; Selenide: ~1000–12000; Telluride: ~2000–20000	~330–380	~2.1–3.0	~1.47 dB/cm in Type-I waveguides	[14–16]
Heavy-Metal Oxide (e.g. Tellurite)	~500–5000	~700–800	1.8–2.3	~0.15 dB/cm in tubular-like waveguides	[17,18]
GeO_2 - PbO (Lead Germanate)	~400–4500	~700	~1.9	~0.89 dB/cm in double line waveguides	[19,20]

monocrystalline silicon using a nanosecond laser irradiation [49]. In silica glasses the S-bend configuration was studied [50] and glassy hosts based on phosphates [51] and fused silica [52] have shown the possibility of producing the Y-shaped architectures. The lack of investigations on germanate glasses with the aforementioned configurations, has inspired research in this direction.

Overall, these studies contribute to the ongoing advancement of waveguide technology, particularly in germanate glass systems. By employing fs laser writing techniques and exploring the effects of rare-earth doping and metallic NPs incorporation, this research paves the way for improved photonic devices with enhanced optical properties and diverse functionalities. It is important to add that the results reviewed in the present report represent an innovation for integrated photonics as it was the first time that waveguides with straight, S-bend and Y-shaped configurations together with the double line architecture were produced in $\text{GeO}_2\text{-PbO}$ glasses using fs laser irradiation.

The present double line waveguide platform with the different configurations discussed in this review, summarizes innovative recent results, represents a relevant contribution for integrated photonics and can be extended to different doped and undoped hosts.

2. Materials and methods

2.1. Preparation of the glasses

The present review focuses on a lead-germanate glass with nominal composition $40\text{GeO}_2\text{-}60\text{PbO}$ (wt%, GP), prepared using high-purity reagents (99.999%). The investigated samples are labelled as GP:Er/Yb, GP:Nd, GP:Ag:Nd, and GP2Ag, corresponding to glasses doped with $\text{Er}^{3+}/\text{Yb}^{3+}$, Nd^{3+} , Nd^{3+} with and without Ag, respectively (concentrations presented in Table 2). All samples were fabricated by the melt-quenching technique followed by controlled annealing to relieve internal stress and, when applicable, to promote the formation of Ag NPs. After thermal treatment, the samples were polished to obtain optical-quality surfaces, as detailed in Refs. [20,45,53]. The investigated samples are summarized in Table 2.

2.2. Waveguide manufacture

Two of simplest and most widely used types of waveguides are obtained by the fs laser writing technique: single (Type I) and double line (Type II). In the first one the structural modification of the material causes a positive refractive index increase, promoting light confinement within the line [54,55]. In the second, the expansion in the track's central portion promotes a decrease in the refractive index, while the adjacent peripheral zones might exhibit a comparatively elevated index due to strain-induced phenomena [56]. Light is guided in the pristine region between two or more written lines. The double line waveguide structural modification is associated with laser-induced damage within the material, where, at higher damage levels, volumetric expansion becomes the dominant mechanism, leading to a reduction in refractive indices and material density in the focus region [57–59]. This then limits the guiding region to the pristine but stressed area close to the focal zone between the modified tracks [60]. It has advantages regarding single line waveguides, promoting a better confinement of light with positive impact on the waveguide performance mainly because the waveguide core is not located in regions that experience severe damage. This

configuration provides superior preservation of the material's properties, alongside increased stability and improved index contrast [61]. The well-preserved luminescence properties of the active ions [62,63], make double-line waveguides a promising configuration for integrated waveguide laser applications. Owing to the stress-induced refractive index distribution between the modified tracks [64], Type II modified waveguides can provide strong optical confinement and enable the creation of curved waveguides with a smaller radius than single-line configurations [61]. Furthermore, the strong thermal stability of stress-induced double-line structures makes them well-suited for high-power laser applications [65].

In the present work, a focused fs laser causes localized material modifications using the appropriate laser parameters to promote the Type II waveguide modification (double line) with several overlapped lines to create the permanent refractive index modification [5,56,66]. Fig. 1 shows the set up used for waveguide writing and the resulting end-face damage that requires polishing. Waveguide pairs are spaced by $400\text{ }\mu\text{m}$; moreover, each waveguide consists of a pair of micromachined regions, that, due to spherical aberration and autofocus effects, forming parallel walls, with $178\text{ }\mu\text{m}$ high, $3\text{ }\mu\text{m}$ width and separated by a distance of $10\text{ }\mu\text{m}$. These features, difficult to see due to minimal contrast, are observable using polarized light microscopy.

The specific parameters used for the production of the waveguides will be detailed and explained for each case and presented in subsequent tables.

The tracks were created using a fs laser system operating at 800 nm with 10 kHz repetition rate (Ti:sapphire, model PRO 400, Femtolasers GmbH), equipped with a focusing lens of 20 mm focal length and numerical aperture (N.A) of 0.23 . Initially, waveguide writing was performed at a lower laser speed without overlapping lines [45]. Table 3 presents the parameters used for laser irradiation in GP matrix doped with $\text{Yb}^{3+}/\text{Er}^{3+}$ (GP:Er/Yb).

The addition of Nd_2O_3 to the $\text{GeO}_2\text{-PbO}$ glass, however, caused cracking during machining because the laser wavelength closely matched the absorption at 800 nm of Nd^{3+} ions, which causes significant localized heating. To overcome this problem, the writing parameters (Table 4) were modified, increasing the writing speed, reducing pulse energy and including line overlap (number of times the laser would make the writing path, initially 4 and 8 times). All these changes intended to insure the structural integrity of the waveguide walls [20] and promote the adequate refractive index change. Also, a long time interval between the writing of each written line was applied to cool the affected region and to ensure the structural integrity of the waveguide walls [20]. The identical set of laser parameters, as previously established, was also employed for the preparation of the samples that incorporate Ag NPs into their composition [46].

The two S-bend architectures, one with a radius of 40 mm and the other with 80 mm and also the Y configuration [47] were produced using the same parameters presented in Table 2, but only 4 overlaps.

It is important to add that in all cases the fs laser beam was oriented perpendicularly to the polished surface of the sample, with linear polarization at an angle of 45° relative to the direction of movement [20, 45–47].

2.3. Characterization

The refractive index change was estimated from the measured numerical aperture (NA) [67,68]. Fig. 2a illustrates the setup used to obtain and measure the refractive index change at 632 nm . The beam quality factor (M^2), indicating the quality of the waveguide output beam, was measured for all configurations following standard procedures [69] and using the setup in Fig. 2b. This setup uses a horizontally translated plano-convex lens to measure the beam diameter in the near and far fields. From these measurements, M^2 was calculated at 632 nm using Equation (1) [70]. The experimental data were then adjusted using Equation (2), where the beam diameter ($d = 2w$) was recorded at

Table 2
Investigated samples and the dopants concentration.

Sample	Dopants (wt%)
GP:Er/Yb	$2.0\text{Er}_2\text{O}_3/2\text{Yb}_2\text{O}_3$
GP:Nd	$1.0\text{Nd}_2\text{O}_3$
GP:Ag:Nd	$2.0\text{AgNO}_3/1.0\text{Nd}_2\text{O}_3$
GP2Ag	2.0AgNO_3

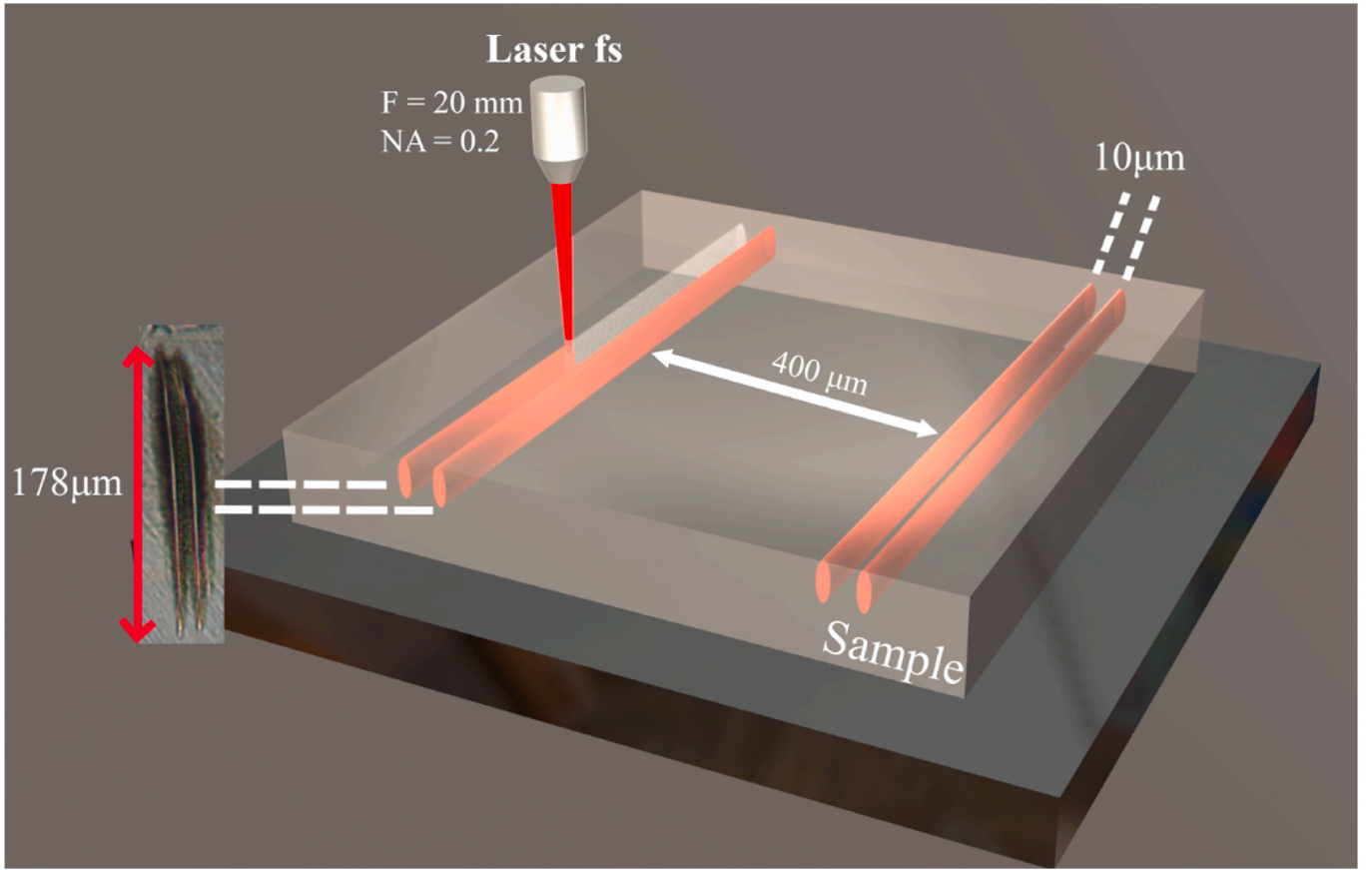


Fig. 1. The waveguide writing arrangement and microscopy images revealing laser damage on the glass sample's input and output surfaces during the writing process.

Table 3
Writing parameters of the fs laser used in the GP:Er/Yb sample [45].

Sample	GP:Er/Yb
Writing speed (mm/s)	0.06
Pulse energy (μJ)	32
Number of pulse overlaps	90
Repetition rate (kHz)	10
Temporal pulse length (fs)	30
Focal point	0.7 mm below the surface

Table 4
Writing parameters of the fs laser used in the GP:Nd and GP:Ag:Nd samples [20, 46].

Sample	GP:Nd/GP:Ag:Nd
Writing speed (mm/s)	0.5
Pulse energy (μJ)	30
Number of overlaps in the lines	4 and 8
Repetition rate (kHz)	10
Temporal pulse length (fs)	30
Focal point	0.7 mm below the surface

different distances (z) from the beam waist and these data were adjusted by equation (1) [70] to determine M^2 at 632 nm.

$$d = d_0 \sqrt{1 + \left(\frac{M^2 \lambda (z - z_0)}{\pi d_0^2} \right)^2} \quad (1)$$

In the equation above the beam diameter at the beam waist (z_0) is $d_0 = 2w_0$. To determine M^2 at 1064 nm, Equation (2) was applied to data

obtained from the setup in Fig. 2b, considering that the wavelength (λ) is significantly smaller than the beam radius (w).

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

In this context, θ represents the semi-angle of beam divergence in the far field, and w_0 stands for the waist radius at the beam focus.

The cut-back method (Equation (3)) was used to determine propagation losses at 1064 nm by measuring power (P_1 and P_2) at different sample lengths (d_1 and d_2) using the setup in Fig. 2c with 10x and 40x objective lenses [20,46,71].

$$\alpha[\text{dB} / \text{cm}] = -10 \frac{\log(P_2 - P_1)}{(d_2 - d_1)} \quad (3)$$

For S-bend and Y-shaped waveguides (where cutting is not feasible), relative losses were determined by measuring the output power distribution (Fig. 2c) of different geometries (40 and 80 mm radius S-bends, Y-shaped arms) relative to a straight waveguide using Equation (4) [72].

$$\eta = -10 \log_{10} \left(\frac{\sum P_i}{P_0} \right) \quad (4)$$

In the equation above, η indicates the magnitude of relative losses expressed in decibels (dB), P_i refers to the total output power of the waveguide under evaluation, while P_0 corresponds to the output power of the reference waveguide.

The gain properties of the waveguides were characterized as follows: the relative gain (signal enhancement) was determined using two continuous-wave (cw) laser diodes operating at 808 nm (pump) and 1064 nm (signal). The intensities of the amplified spontaneous emission

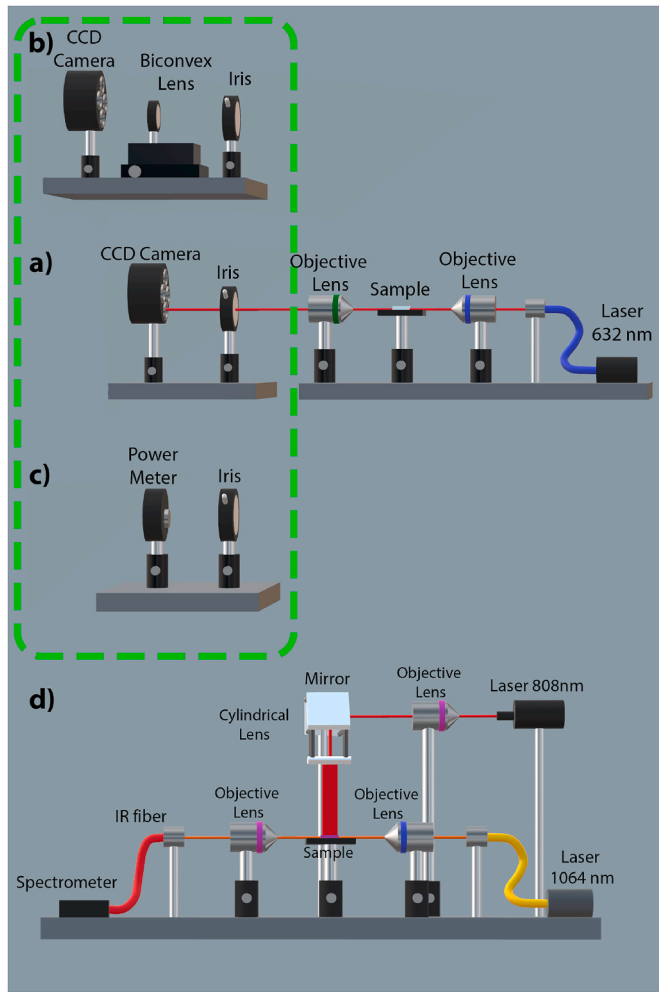


Fig. 2. Experimental setup used to determine (a) the numerical aperture, (b) the beam quality (with flat-convex lens), and (c) the propagation losses, (d) relative gain measurements at 1064 nm (excitation at 808 nm).

(ASE) and the stimulated emission (SE) at 1064 nm were measured, and the relative gain was calculated using the experimental setup shown in Fig. 2d. The relative gain measurements were performed as follows. The signal power (P_{signal}) was measured considering the signal laser on and the pump laser off and was kept constant at a very low level (400 nW) to avoid gain saturation. Then, the measurement was repeated with both lasers on ($P_{\text{signal+ASE}}$), recording the combined SE and ASE at 1064 nm.

Finally, the ASE power (P_{ASE}) was measured with the signal laser off and the pump laser on. The relative gain was then determined using equation (5), where d represents the sample length [45,71,73–75]:

$$G [\text{dB} / \text{cm}] = \frac{10 \times \log \left(\frac{(P_{\text{signal+ASE}} - P_{\text{ASE}}) / P_{\text{signal}}}{d} \right)}{d} \quad (5)$$

It is pertinent to mention that this optical gain arrangement is exclusively used for neodymium. In the case of GP:Er/Yb glass, the arrangement depicted in Fig. 3 was utilized. In this configuration, the pumping occurs along the optical axis of the waveguide, contrasting with the other setup (Fig. 2c) where the rare-earth ions are excited through the sample's top surface.

The waveguide region was analyzed using optical microscopy (Leica DMLP polarizing light microscope with MC170 HD camera).

The nucleation of Ag NPs was investigated using a 200 kV transmission electron microscope (TEM) (Thermo Fisher/FEI Titan Cubed Themis). Elemental distribution in the samples was analyzed via scanning transmission electron microscopy (STEM). TEM sample preparation involved grinding, mixing with distilled water, and partial decantation, followed by the deposition of isolated suspended particles onto ultrafine copper grids coated with a carbon film.

Photoluminescence measurements were conducted by exciting samples with an 808 nm continuous-wave diode laser. The emitted photoluminescence signal, collected orthogonally to the excitation beam, was spectrally resolved by a monochromator. A germanium (Ge) photodetector, whose output was interfaced with a lock-in amplifier and a computer, was used for signal detection.

3. Results

3.1. Waveguides produced with GP:Er/Yb glass

In this section we review the results of the double waveguides produced in GP:Er/Yb using the parameters shown in Table 1 for the fs irradiation [45]. The refractive index change at 632 nm was determined, as explained above (Fig. 2a), and the result was: $\Delta n = -7.3 \times 10^{-3}$. Propagation losses of (0.9 ± 0.3) dB/cm were obtained at 1300 nm by the cut-back method.

The variation of the relative gain at 1550 nm as a function of the pump power for 700 nW of input signal power, determined using equation (5), is shown in Fig. 4. The relative gain at 1550 nm reached 7.5 dB/cm for 980 nm excitation at 105 mW. It can be seen that the gain did not saturate; a second and lower slope efficiency can be observed for pump powers beyond 65 mW.

By compensating for both propagation and absorption losses, the relative gain (G_r) [45] was determined considering propagation (0.9 ± 0.3) dB/cm and absorption losses (2.0 ± 0.1) dB/cm; then a maximum positive internal gain (G_{int}) of 4.6 dB/cm was achieved at

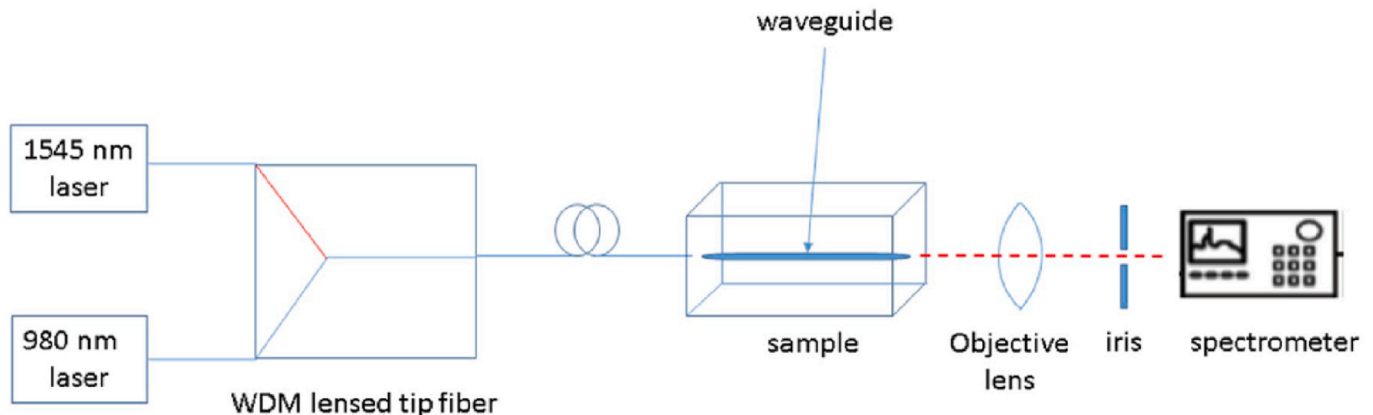


Fig. 3. Experimental setup used for relative gain measurements of the GP:Er/Yb waveguide [45].

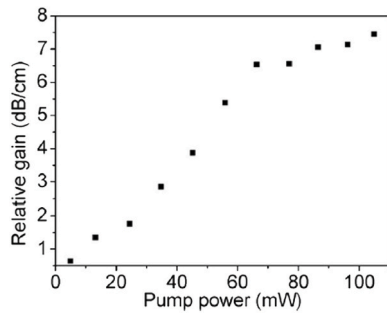


Fig. 4. Relative gain at 1550 nm of the GP:Er/Yb waveguide as a function of pump power for 700 nW of signal input power.

1550 nm under 105 mW of pump power.

3.2. Waveguides produced with GP:Nd and GAg:Nd glasses

This section intends to review the results of double line waveguides inscribed in Nd^{3+} doped GP matrix, with and without Ag NPs (GP:Nd and GAg:Nd glasses) [20,46]. As explained before, due to the addition of Nd_2O_3 the writing parameters had to be changed with respect to the writing speed used before for GP:Er/Yb, and the 4 and 8 lines overlaps were also included in the production of the waveguides; this configuration overcomes the problem of heat accumulation and fracture because neodymium absorption (at 800 nm) is in resonance with the fs laser's emitting wavelength. The increase of the writing speed promotes the decrease of pulse number that compromises the necessary accumulation of induced damage and consequently the adequate resultant refractive index change that is relevant for light guidance. So, the higher speed together with several superimposed lines produce the necessary damage and guarantee the aforementioned necessary refractive index change.

After fs laser irradiation, an increase in absorption below 550 nm is observed, attributed to the formation of color centers and photoreduction of Ag^+ ions [76,77]. Fs laser interaction induces nonlinear optical effects—photoionization and impact ionization—producing free electrons. These electrons can be trapped forming color centers or reduce

Ag^+ ions, promoting NP nucleation [76,77]. NP growth is further driven by localized heating at the laser focus, enhancing atomic mobility [76].

Fig. 5 shows the photoluminescence (PL) spectra of bulk samples with and without Ag NPs, featuring emissions at 900, 1064, and 1340 nm. These emissions correspond to the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{9/2}$, $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$, $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{13/2}$ transitions, respectively. A PL enhancement of approximately 47% was observed in samples containing Ag NPs compared to those without as shown in Fig. 5. This increase is attributed to the enhanced local electromagnetic field generated by the Ag NPs, which boosts the excitation efficiency of nearby Nd^{3+} ions [78–80]. This increase is attributed to the enhanced local electromagnetic field generated by the Ag NPs, which boosts the excitation efficiency of nearby Nd^{3+} ions [78–80]. The light absorption by metallic NPs is described as coherent oscillation of the electrons which is induced by the interaction with the electromagnetic field resulting in surface plasmon waves. In the case of the NPs, the plasmon oscillations are localized and referred as localized surface plasmon (LSP) whose frequency depends on the dielectric functions of the host matrix, the NPs nature as well as on the NPs shape and size [81]. So, the local electric field in the vicinities of the NPs, that is increased [82,83] in the vicinities of the NPs (due to the mismatch between the dielectric function of the NPs and the host) improves the density of excited Nd^{3+} ions and, consequently, the photoluminescence.

The dependence of relative gain at 1064 nm on 808 nm pump power for double waveguides with 8 overlaps is depicted in Fig. 6(a and b). These results were obtained using Equation (5) with an input signal power of 400 nW. Specifically, Fig. 6a shows the relative gain for a waveguide in an Ag-free sample, while Fig. 6b presents the relative gain measurement for a waveguide with Ag NPs. This allows for a direct comparison of the impact of the metallic NPs on the waveguide gain.

The beam quality parameters, M_x^2 and M_y^2 , were determined at 1064 nm using Equation (2). A significant finding is that the utilization of eight line overlaps resulted in more similar values between the horizontal and vertical directions at 632 and 1064 nm. These results underscore superior x,y-symmetrical light guiding in comparison to the four line overlaps configuration. These data, presented in Table 3, are contrasted with the values of double line waveguides fabricated with four and eight line overlaps in GP:Nd glass. The comparative analysis in Table 5 reveals an enhancement in the M^2 values for the double line

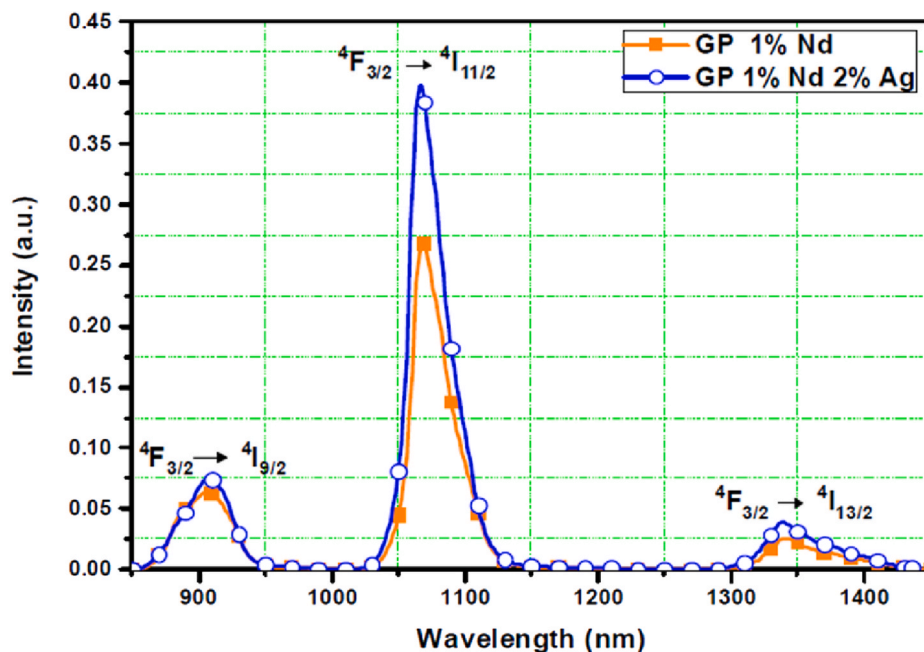


Fig. 5. PL spectra for GP:Nd (square) and GAg:Nd (open circles).

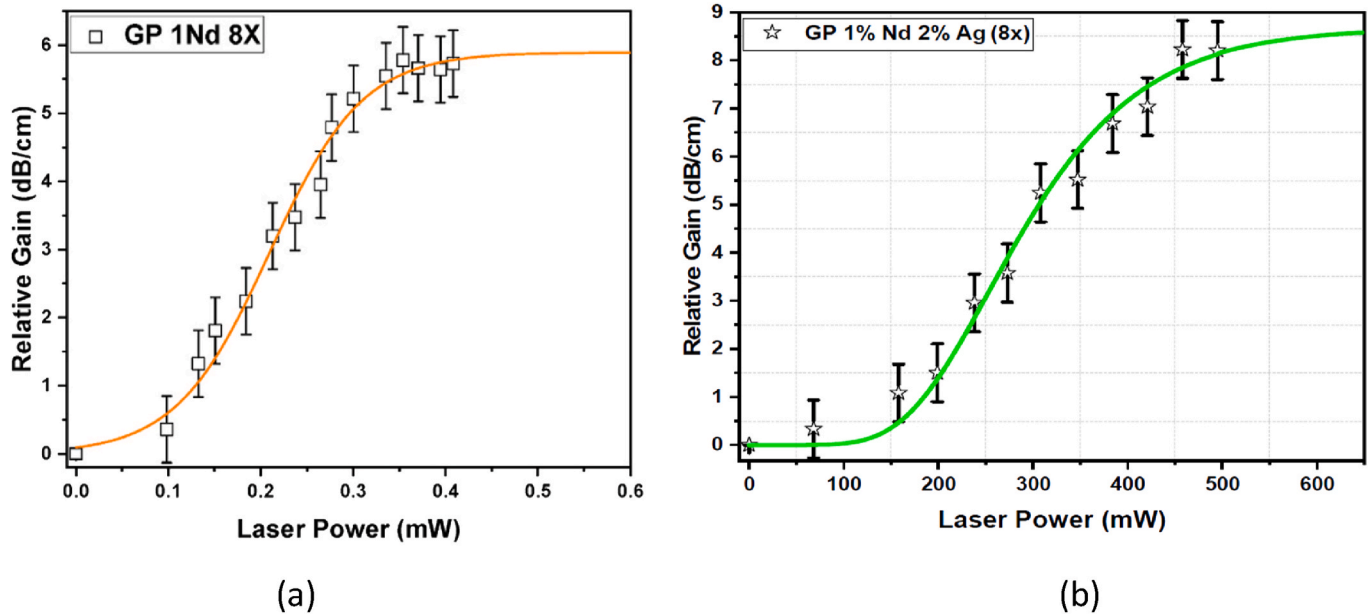


Fig. 6. Relative gain for double waveguide with 8 overlaps in: (a) GP:Nd sample and (b) GPAg:Nd glasses [46].

Table 5
Results of GP:Nd and GPAg:Nd [20,46].

Parameters	GP:Nd		GPAg:Nd	
	4 lines overlaps	8 lines overlaps	4 lines overlaps	8 lines overlaps
M_x^2 (at 632 nm)	16.7	16.6	5.12	5.22
M_y^2 (at 632 nm)	14.2	15.6	3.66	5.82
M_x^2 (at 1064 nm)	9.9	9.9	3.0	3.1
M_y^2 (at 1064 nm)	8.4	9.2	2.2	3.5
Δn_x	-5.7×10^{-3}	-7.3×10^{-3}	-5.5×10^{-3}	-8.1×10^{-3}
Δn_y	-5.4×10^{-3}	-5.3×10^{-3}	-4.3×10^{-3}	-4.2×10^{-3}
G_{INT} (dB/cm)	3.61 dB/cm	5.56 dB/cm	5.11 dB/cm	7.2 dB/cm

waveguides, with both four and eight line overlaps, when the AgNO_3 dopant is present. The most probable explanation for this improvement is the facilitated nucleation of Ag NPs that allows the refractive index improvement. This was observed in silicate glass which had an increase in the refractive index by 4.6% [84]. In this case the presence of NPs are responsible for the increase of the refractive index change [85], as the fs laser irradiation improves the nucleation of the NPs [86]. The color centers induced by the fs laser implied that localized heat accumulation was highly beneficial for the single-step precipitation of Ag-NPs in glass [84].

3.3. Different waveguides architectures: S bend and Y configurations in GP2Ag glass

In this section, recent results are reviewed related to double line waveguides with four overlaps, prepared with Straight (Fig. 7a), S-bend (Fig. 7b) and Y configurations (Fig. 7c) in GP2Ag glass [47]. The straight waveguides consisted of two parallel lines with a 10 μm separation, 4 overlaps, and was used as reference to determine the relative propagation loss. The S-bend waveguides, also separated by 10 μm as reported previously [20,46], featured bending radii of 40 and 80 mm. This selection radius was based on prior findings [48], which indicated that S-bends with 5 and 10 mm radii did not exhibit light guidance. On the other hand, S-bend waveguides with 20 mm radii and distance between

the guide walls of 10 and 25 μm showed light guidance. However, the relative propagation loss obtained for the S bend waveguide with a 25 μm distance between the guide walls presented higher loss of 2.19 dB/cm, when compared to the smaller distance of the guide walls of 10 μm (1.33 dB/cm) [48].

The results of the Y-shaped waveguides are also reviewed, and this configuration presents 5° opening angle and a 300 μm separation between their arms, maintaining a 10 μm distance between the guide walls (Fig. 7c). These parameters were used based on previous results in which the Y configuration with opening angle of 5° and distance of 620 μm between the two arms (with distance between the guide walls of 10 μm), presented an output power ratio between the left and right arms of 53.9/46.1 and propagation loss of 0.55 dB/cm.

It is worth highlighting the previous results for the beam quality index (M^2) that showed the S-bend waveguides exhibit significantly higher M^2 values, indicating more pronounced beam distortion [48]. The S bend waveguide with 25 μm distance between the guide walls, in particular, showed the highest values with $M_x^2 = 23.5$ and $M_y^2 = 28.8$, suggesting a strong degradation in beam quality due to tighter curvature. The S-bend waveguide with 10 μm distance between the guide walls also presented lower values than the 25 μm version. In contrast, the straight waveguides displayed much lower M^2 values, indicating a much better beam quality, as expected. In this case, for 10 and 25 μm distances between the walls, it was reached M_x^2 values of 5.23 and 6.30, and M_y^2 values of 4.16 and 5.31, respectively.

For the Y-branch structure (with 620 μm distance between the arms), the first arm exhibited $M_x^2 = 5.03$ and $M_y^2 = 6.99$, while the second one showed $M_x^2 = 5.84$ and $M_y^2 = 5.46$. These values indicated a moderate level of beam quality compared to straight waveguides but better than the S-bend configuration [48].

The M^2 values at 1064 nm, calculated using Equation (3), are presented in Table 6 alongside those obtained at 632 nm for all waveguide architectures. The setup depicted in Fig. 2a enabled the measurement of relative propagation losses, the results of which are also detailed in Table 4. Relative propagation loss at 632 nm was determined by comparing the losses in the S-bend and Y configurations to that of the straight waveguide, as explained in section 2.3, which exhibited the lowest loss due to its minimal path length. The experimental setup in Fig. 2c was employed to measure the output power ratio between the left and right arms of the Y configuration whose result was 50.47/49.53. This excellent division ratio with respect to the Y configuration with

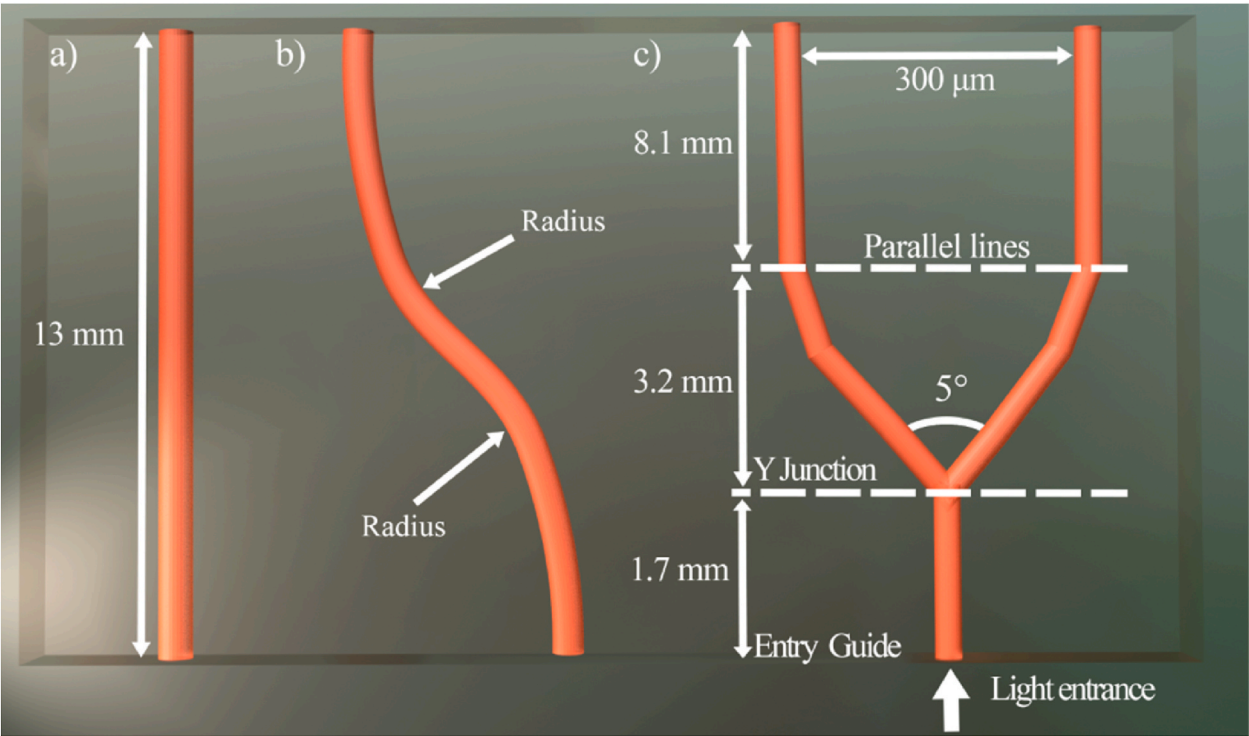


Fig. 7. Illustration of waveguide architectures in GP2Ag glass irradiated with a fs laser: (a) straight, (b) S-bend with 40 mm and 80 mm radius, and (c) Y-shaped.

Table 6
Results of M^2 , relative propagation losses, and vertical polarization for straight, S-bend and Y configurations.

Waveguide	M_x^2 (632 nm)	M_y^2 (632 nm)	M_x^2 (1064 nm)	M_y^2 (1064 nm)
Straight	3.8	3.1	2.3	1.9
S-bend 40 mm	6.4	5.0	3.8	3.0
S-bend 80 mm	5.4	5.2	3.2	3.1
Y first arm	6.1	4.1	3.7	2.5
Y second arm	5.6	4.3	3.3	2.5

620 μm distance between the arms, leads to enhanced outcomes for

photonics applications.
Fig. 8a presents a TEM image of the sample, revealing an isolated Ag NPs and an interplanar distance of 0.236 nm, which corresponds to the (1,1,1) crystalline plane of face-centered cubic Ag [87–89]. The size distribution of the Ag NPs is displayed in Fig. 8b.

4. Discussions and perspectives for the near future

Specifically, this review focuses on double-line fs laser-inscribed waveguides in both Nd^{3+} doped and undoped $\text{GeO}_2\text{--PbO}$ glasses with particular emphasis on double-line structures fabricated through repeated writing of overlapping lines. The results presented in the

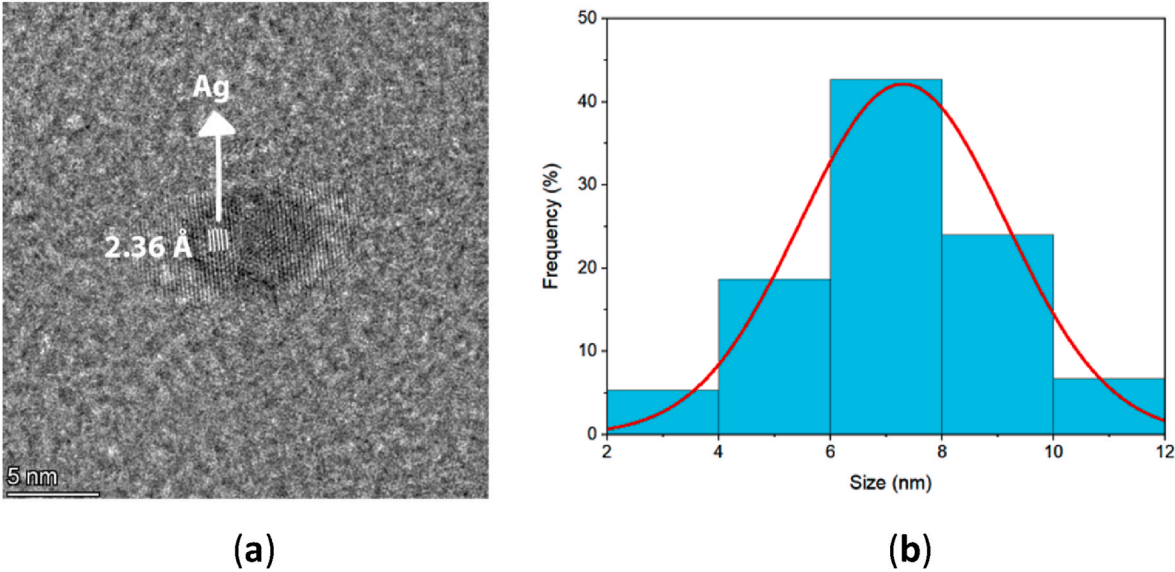


Fig. 8. (a) TEM image of an isolated Ag NPs with the interplanar distance corresponding to the crystalline plane (1,1,1) of a face centered cubic Ag. (b) Size distribution of Ag NPs.

previous sections enable a systematic comparison among different architectures and glass compositions, that are presented in Table 7. Among straight waveguides, a clear dependence of the optical performance on both writing parameters and glass composition is observed. The comparison between four- and eight-line overlap configurations shows that increasing the number of overlaps generally improves modal confinement, leading to reduced propagation losses and beam quality improvement. This effect is especially evident in GP:Nd and GPAg:Nd waveguides, for which the eight-overlap configuration exhibits lower losses and higher internal gain results. The same applies to the beam quality parameters, M_x^2 and M_y^2 . The role of Ag NPs also deserves to be highlighted. The incorporation of Ag in the glass matrix improves the beam quality, as lower M^2 values are observed with respect to equivalent Ag-free waveguides, particularly at 1064 nm. These results suggest that the presence of Ag promotes a more homogeneous refractive-index profile and more efficient modal confinement, thereby reducing spatial distortions of the guided mode. The PL improvement is attributed to the electric local field growth around the Ag NPs, which enhances the population that is in the excited state favoring the relative gain. The importance of the Nd^{3+} concentration on waveguide performance is evident when comparing the present results (relative gain of up to 7 dB/cm at 1064 nm) with those assisted by Au NPs used as a cover layer and having half the Nd^{3+} concentration [90]. The different configuration used with respect to GP:Er/Yb samples, overlapped waveguides and higher writing speeds enabled the incorporation of Nd^{3+} ions without inducing cracking in the sample, by mitigating the heating effects arising from the overlap between the absorption wavelength of these ions and the fs laser.

In particular, it should be emphasized that, for S-bend and Y-shaped architectures (GP2Ag sample) the reported losses correspond to relative losses with respect to the straight reference waveguide, thus directly quantifying the additional contribution introduced by bending or splitting, rather than absolute propagation losses. The Y configuration exhibits smaller relative propagation losses when compared to the S-bend one (Table 7). In general, straight waveguides consistently exhibit the lowest M^2 values, indicating superior modal preservation when compared with S-bend and Y architectures (Table 6). In contrast, S-bend and Y-shaped architectures exhibit a progressive increase in both M^2 and relative losses (Table 7) as the bending radius decreases or as the separation between walls and arms increases, confirming that geometric effects dominate the performance in these configurations. Nevertheless, the Y-shaped structure with a 300 μm separation between its arms

maintains excellent functional behavior in terms of power splitting when compared to the structure with 620 μm separation.

As a natural continuation of this study, several research directions can be pursued to further expand the understanding and performance of fs laser written photonic structures. First, future efforts could focus on investigating optical gain by using different rare-earth-ions and also Au NPs instead of Ag NPs, for example. These new dopants would enable a detailed assessment of emission efficiency, excitation dynamics, and energy-transfer mechanisms, contributing to the development of other optical amplifiers.

Additionally, the architectures currently explored in passive waveguides can be reproduced in doped hosts, allowing the quantification of optical gain in more complex configurations to compensate the losses. This approach will make it possible to evaluate propagation losses, coupling behavior, and uniformity in elaborate geometries, providing experimental validation for theoretical propagation models.

On the other hand, the Y configuration could be used to separate or recombine optical paths while minimizing radiation loss. In a more advanced stage, it would be possible to develop increasingly sophisticated photonic architectures, including the implementation of a fs-laser-written Mach-Zehnder interferometer and even integrating it the straight waveguide. This will not only assess the feasibility of fully integrated optical circuits but also support the optimization of existing architectures.

Regarding the S-bend configuration, the results presented for 40 and 80 nm radii are adequate, for example, to connect straight waveguides as they exhibit higher propagations losses when connected perpendicularly. However, it would be necessary to join efforts to improve the parameters used for fs laser irradiation to produce smaller radius for compact on chip applications.

Collectively, these future developments aim to establish a stronger foundation for more efficient integrated optical devices, with improved control over gain, lower losses, and overall functionality, thus contributing to advancements in rare-earth-doped glass photonics.

Finally it is important to add that the micromachine of waveguides by fs laser overcomes some issues of the Si based technology [91] that is more complex and demands several steps based on photolithography and etching procedures. Although different alternatives exist to produce the core (sputtering, ion implantation among others), in the fs laser writing method, the waveguides are inscribed into the glasses fabricated with the well-known and cheap procedure, the melt quenching technique. Of course, the choice of the method depends on the facilities of the laboratory in which the experiments are performed as well as on the applications that are being pursued.

5. Conclusion

The present article encompasses the combination of several aspects previously reported separately and now presented and discussed together: the $\text{GeO}_2\text{-PbO}$ material system, the fabrication of double waveguides with overlaps, different configurations (straight, S bend and Y), relative gain, propagation losses and M^2 results, and the impact of Ag NPs on the optical waveguide performance.

The optical waveguides were inscribed in Nd^{3+} doped and undoped $\text{GeO}_2\text{-PbO}$ glasses by using fs laser irradiation at 800 nm with repetition rate of 10 KHz. The double line architecture was fabricated based on repeated writing of overlapping lines. The glass samples were produced using a standard melt-quenching method. Initially, waveguide writing was performed at a lower laser speed (0.06 mm/s) without overlapping lines in GP:Er/Yb sample. Optimal amplification performance was achieved with relative gain of 7.5 dB/cm under 105 mW pump power at 980 nm. When propagation losses were taken into account, a positive internal gain of 4.6 dB/cm was obtained. The double-line waveguide architecture in Nd^{3+} doped $\text{GeO}_2\text{-PbO}$ glasses was also reviewed; in this case, repeated collinear overlays of fs laser-written lines were produced (eight and four overlaps in each written line) at higher writing speed

Table 7

Summary of the main experimental results of the investigated samples with different architectures: measured propagation losses and internal gain (G_{int}); GP:Er/Yb, GP:Nd, and GPAg:Nd with the straight configuration, S bend and Y configurations with 4 overlaps.

Sample	Waveguide configuration	Propagation losses (dB/cm)	G_{int} (dB/cm)
GP:Er/Yb	Without Overlaps	0.9	4.6 at 1550 nm
GP:Nd	4 Overlaps	0.89	3.61 at 1064 nm
	8 Overlaps	0.44	5.56 at 1064 nm
GPAg:Nd	4 Overlaps	1.89	5.11 at 1064 nm
	8 Overlaps	1.30	7.12 at 1064 nm
GP2Ag	Straight 4 Overlaps	Reference	-
	S-bend ($r = 20$ mm)	1.33	-
	S-bend ($r = 40$ mm)	1.13	-
	S-bend ($r = 80$ mm)	0.84	-
	Y 300 μm arms separation	0.27	-
	Y 620 μm arms separation	0.55	-

(0.5 mm/s) to create the waveguides. The influence of Ag NPs on optical properties was also discussed. More similar values for the beam quality factors (M_x^2 and M_y^2) at 632 nm and 1064 nm were observed for eight superimposed lines, in samples with and without Ag NPs demonstrating improved x,y-symmetrical guiding compared to waveguides formed by four superimposed lines. PL enhancement of about 47% was observed at 1064 nm, compared to the sample without Ag NPs. This enhancement was attributed to the strong local electromagnetic field in the vicinities of the Ag NPs, which increases the population of excited Nd^{3+} ions. The relative gain at the signal wavelength (1064 nm) reached 7.0 and 8.5 dB/cm for waveguides written with four and eight superimposed lines, respectively, under 808 nm pump power. Compared to samples without Ag NPs these values represented gain enhancements of approximately 40% and 30%, due to the plasmonic properties of Ag NPs. Propagation losses of 1.89 and 1.30 dB/cm were measured for four and eight superimposed lines, respectively, resulting in positive internal gain values of 5.11 and 7.2 dB/cm.

Lastly, employing identical parameters but limiting to four overlaps, passive waveguide designs (S-bend and Y-branch) incorporating Ag NPs were created. Results from the S-bend waveguides demonstrated superior guiding performance for the 80 mm bending radius compared to the 40 mm radius, as evidenced by the improved x- and y-symmetry of the guided light paths. Consequently, the best values of the beam quality factor (M^2), at both 632 and 1064 nm, as well as the lowest propagation losses, were obtained for the 80 mm waveguide. The M^2 values were 5.4 (M_x^2) and 5.2 (M_y^2) at 632 nm, and 3.2 (M_x^2) and 3.1 (M_y^2) at 1064 nm, with propagation losses of 0.84 dB/cm. This aligns with reports in the literature, which state that smaller losses are typical in waveguides with less acute curvature radii, consistent with the findings herein.

Using the same double line waveguide configuration (double waveguides formed by four superimposed lines), a Y-branch was fabricated with opening angle of 5° and a 300 μm separation between the two arms. An excellent power ratio between the outputs of 50.5/49.5 was achieved, together with the lowest relative propagation loss of 0.27 dB/cm, outperforming the S-bend waveguides. The close similarity of the M^2 values at 632 nm — $M_x^2 = 6.1$ and $M_y^2 = 4.1$ for the first arm, and $M_x^2 = 5.6$ and $M_y^2 = 4.3$ for the second arm — indicates negligible differences in light guiding between them. This consistent behavior was also observed at 1064 nm.

The present review demonstrates the feasibility of producing double line waveguide architecture with repeated writing of overlapping lines in different configurations micromachined by fs laser irradiation in $\text{GeO}_2\text{-PbO}$ glasses. Given the lack of similar studies in literature, we believe that the proposed platform constitutes a relevant contribution to the field and can be extended to a wide range of doped and undoped host materials.

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CRediT authorship contribution statement

Thiago Vecchi Fernandes: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft. **Niklaus Ursus Wetter:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Wagner de Rossi:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Writing – review & editing. **Luciana Reyes Pires Kassab:** Conceptualization, Funding acquisition,

Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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