Femtosecond laser induced low propagation loss waveguides in a lead-germanate glass for efficient lasing in near to mid-IR

Mamoona Khalid,1* George Y. Chen1, Heike Ebendorff-Heidepreim2 & David G. Lancaster1

To support the growing landscape of near to mid-IR laser applications we demonstrate a range of low propagation loss femtosecond laser (FSL) written waveguides (WGs) that have achieved guided-mode laser operation in a rare earth (RE) doped lead-germanate glass. The WGs are fabricated in both the athermal and thermal FSL writing regimes using three different pulse repetition frequencies (PRF): 100 kHz (athermal); 1 MHz; and 5 MHz (thermal). The lasing capability of Yb3+ doped lead-germanate waveguides is verified in the near-IR. The refractive index contrast (∆n) for 100 kHz WGs is ~ 1 × 10⁻⁴, while for 5 MHz, ∆n increases to ~ 5 × 10⁻⁴. The WGs in the thermal regime are less effected by self-focusing and are larger in dimensions with reduced propagation losses. For the 1 MHz repetition rate thermal writing regime we report a low propagation loss WG (0.2 dB/cm) and demonstrate laser operation with slope efficiencies of up to ~ 28%.

Direct inscription of waveguides (WGs) into laser gain materials using a femtosecond laser (FSL) is a fast fabrication technique that allows complex photonic functionalities to be integrated into a single device. These WGs can realize lasers that are ideal sources for photonic networks because of their small cavity size, moderate average power (~ 100 s of mW), and long energy storage lifetimes. FSL allows for writing embedded low propagation loss symmetrical structures within the transparent materials (glasses) by tight focusing of the ultrashort laser pulses beneath the surface of the material.

Germanate glasses are fascinating hosts to achieve new laser operating regimes as this glass provides a good balance of properties required for efficient laser operation in the short to mid infrared region. This includes longer wavelength transmission of germanates into the infrared region, competitive thermal, chemical and mechanical strength, medium phonon energy (~ 800 cm⁻¹), and high refractive index compared to the widely researched silicates and fluorides (where very low propagation loss WGs have already been reported). Despite the above-mentioned properties, FSL-based WG writing in germanates for laser development has only been minimally investigated. Germanate is a good candidate for further research to identify the suitable FSL parameters that can introduce low propagation loss guiding structures and high laser slope efficiencies in near to mid-IR regions.

The reported studies of FSL written WGs in germanate cover the low and high pulse repetition frequencies (PRF) ranging from 1 kHz to 1 MHz. Early work reported a 1 kHz FSL (80 fs pulses) single line WG inscribed in Er³⁺ doped lead-germanate glass GeO₂–PbO–Ga₂O₃, however the measured propagation loss was high at 4.8 dB/cm. Operating at a higher PRF (500 kHz, 350 fs pulses) resulted in bright guiding structures in a fluorogermanate glass possessing a low propagation loss of ~ 0.7 dB/cm. In other work, single line WGs inscribed in a widely investigated Barium Gallo-Germanate (BGG) glass resulted in propagation losses of as low as 0.5 ± 0.1 dB/cm for WGs inscribed using 250 kHz, 70 fs laser pulses. Stress-induced WG writing (double line) has also been achieved in germanate by a low PRF FSL (4 kHz) in Er³⁺ doped GeO₂–PbO–Ga₂O₃ resulting in 2 dB/cm of propagation losses i.e. the propagation losses reduced by a factor of 2 with double line writing compared to single line as in. Similar stress induced (double line) WGs include a Nd³⁺ doped GeO₂–PbO waveguide amplifier exhibiting a propagation loss of ~ 1.75 dB/cm; and in the authors reported an internal gain of ~ 4.6 dB/cm for double line WGs in an Er³⁺/Yb³⁺ co-doped germanate waveguide amplifier (10 kHz PRF). Overall, it is apparent that to achieve efficient germanate laser operation reductions in WG propagation losses in germanate glasses are required.

1Laser Physics and Photonics Devices Laboratory (LPPDL), University of South Australia, Mawson Lakes, SA 5095, Australia.
2Institute for Photonics and Advanced Sensing and School of Physical Sciences, University of Adelaide, Adelaide, SA 5000, Australia.
*email: khamy062@mymail.unisa.edu.au
One of the challenges of FSL writing in germanate glass is its high 1st order (n) and 2nd order refractive index (i.e., nonlinear index, n2). The high linear refractive index of the germanate glass (1.8–2) is not matched with standard (n ~ 1.5) index matching liquid (e.g., oil) and oil immersive objective lenses which are designed to compensate spherical aberrations in the focal region. Furthermore, irradiating FSL pulses can exceed the self-focusing critical power limit of the glass which can occur even at low average laser power in conjunction with other FSL parameters. This combination typically results in non-spherical and elongated structures. Currently, there are no commercially available high-index matching oils and objective lenses; thus limiting the parameter space that can be explored.

In this paper, we investigate a range of FSL inscribed low propagation loss single line and double line induced WGs in a rare earth doped lead-germanate glass GeO2-PbO-Ga2O3-Na2O (hereafter referred to as GPGN glass) and verify their near-IR lasing capability. The selection of this composition of GPGN glass is based on the fact that its low loss fabrication has extensively been researched for mid-IR fibers. Employing GPGN glass for this study extends its utilization to inscribe low loss waveguides for laser applications.

The aim of the study is to optimize the FSL parameters in such a way that low propagation loss guiding structures are induced in the GPGN glass. Yb3+ is doped in the glass to evaluate the lasing performance of the fabricated WGs. We believe that this study will provide a roadmap towards the fabrication of low loss WGs for efficient lasing in the mid-IR. The study is conducted for both the athermal (low PRF) and thermal (high PRF) regimes. The effect of nonlinear interaction of FSL with GPGN glass and the resulting modified index region in athermal (100 kHz) and thermal (1 MHz and 5 MHz) regimes of FSL are discussed, and the parameters to achieve lowest propagation loss in GPGN glass are presented. A high slope efficiency of ~28% is achieved for 1 MHz double line inscribed WG which is ~5 times higher than achieved with FSL parameters presented in our previous study.

Experimental methods
Glass fabrication and waveguide writing. Yb3+ doped GPGN glass ingots are fabricated by a conventional melt quench technique. The ion density of Yb3+ selected for small cavity WG laser operation is ~7 × 1020 ions/cm3. The 15 × 12 × 4 mm3 glass sample is cut to have parallel surfaces. The sample is polished to optical grade for WG writing, characterization, and laser demonstration.

The parameters to achieve controlled and symmetric refractive index modifications in glasses depends on the careful tuning of the FSL parameters such as pulse energy, translation speed, PRF, and the laser spot size. These parameters need to be balanced with glass properties (e.g., thermal conductivity) to produce modifications that are unique to each glass composition. For writing WGs in GPGN glass a ~250 fs pulse width Yb3+ fiber laser (IMRA FCPA-µJewel) operating at 1047 nm (Pavg. = 2.4 W) and externally frequency doubled to λ = 524 nm is used. The WG writing setup is demonstrated in Fig. 1a.

The glass sample is translated in three dimensions using an air-bearing x–y–z translation stage. An initial translation speed of 0.5 mm/s is selected for these experiments based on the value around which a minimum propagation loss in BGG germanate glass was achieved (~0.5 dB/cm). Moving the sample transversely with respect to the focus of the FSL produces tracks (also known as lines) of respective index modifications at the focus point all the way through the sample (the dashed line in Fig. 1a represents single line writing at the FSL focus). Multiple parallel tracks (e.g., double lines, triple lines etc.) with a defined spacing between the lines are inscribed in the sample. The cross-section of the single line FSL modified region presented in the sample is the heat accumulated region (thermal writing regime).

Figure 1. (a) FSL material processing setup for WG writing. The sample is moved transversely with respect to the FSL focus to inscribe tracks/lines of index modifications. The cross-section of the single line FSL modified region presented in the sample is the heat accumulated region (thermal writing regime). Reproduced with permission from 20. (b) Ray schematic showing the estimated change in writing depth [from d = 150 μm to d’ = 234 μm (FSL estimated focus)] through a low refractive index n = 1.51 index matching oil to a high refractive index sample (n’ = 1.82). θ and θ’ are the angle of refraction of the focusing beams (for actually set and estimated writing depths) with respect to incidence normal.
also inscribed with the aim to increase the cross-section of the resulting WGs. If assuming \( n = 1.5 \) (the design wavelength for the \( 100 \times, \text{NA} = 1.25 \), oil immersive microscope objective), the linearly polarized laser beam would be focused \( 150 \mu m \) beneath the surface of the sample with a predicted FSL spot radius of \( \omega_0 \sim 0.13 \mu m \) \((\omega_0 = \lambda / \pi \text{NA})\) (Fig. 1).

Selected writing depth into this \( n = 1.82 \) glass is a balance between shallow writing depths resulting in thermally induced cracking, while deeper focusing increases the spherical aberration. An externally set writing depth of \( 150 \mu m \) is chosen which results in an estimated writing depth of \( \sim 234 \mu m \) (Fig. 1b) predicted using Snell's law. After WG writing, the end faces of the sample are polished back by \( 1 \text{ mm} \) each to reveal the cross-section of the WGs.

**Waveguide characterization.** WG characterization focuses on the investigation of (i) structural features of the modified region; and measurement of (ii) coupling loss (CL) into the WG; (iii) propagation loss (PL) through the WG determined from the measured transmission loss (TL); and (iv) numerical aperture (NA) of the WG. For the structural characterization, the cross-sectional details of the modified region are collected via rear illuminated brightfield microscopy. To characterize the WG losses (CL, TL etc.) a flexible probe beam technique is developed that can simultaneously measure CL and TL. The alignment error is estimated by taking 4 measurements of each WG. Figure 2 shows the complete setup employed for the loss measurements.

A single transverse mode, linearly polarized 1550 nm fiber coupled LD is used to probe the WGs. 1550 nm is chosen as the Yb\(^{3+}\) doped glass does not have ground state absorption at this wavelength. A polarized beam splitter cube (PBS-104) followed by a quarter waveplate (\( \lambda/4 \)) is used to separate the probe beam going-to and traveling-back from the glass sample (Fig. 2). A red He–Ne laser counterpropagating to the probe light ensured the optical components are orthogonal to the direction of the probe beam. The probe beam is a \( \sim 0.8 \text{ mm} \) diameter (\( D_4\sigma \)) collimated beam focused into the WGs using a 10 mm focal-length lens to produce (\( D_4\sigma \)) a \( \sim 16 \mu m \) beam spot.

With reference to Fig. 2, the total probe beam loss \( (L) \), in units of dB, in the optical path from ‘a’ to ‘e’ includes the following loss contributions:

(i) Optical loss (OL) through the PBS and the \( \lambda/4 \) waveplate.
(ii) Mirror M2 loss (ML) while retroreflecting the probe beam to ‘b’.
(iii) Coupling loss (CL) which arises due to the mode mismatch between the probe beam and the WG dimensions and WG NA. A reasonable mode-match is selected based on a \( f = 10 \text{ mm} \) focusing lens.
(iv) Fresnel reflection loss (FL) due to the surface reflections at the air/glass/air interfaces of the glass sample.
(v) Transmission loss (TL) due to the scattering, impurities, and defects in the WG.

The probe beam is then retroreflected back to ‘b’ from ‘e’ to allow determination of TL, independent of CL (based on the assumption that the light that propagates in the waveguide to ‘e’ is already mode matched). The probe beam is retroreflected at ‘e’ via butting a \( R = 97\% \) mirror to the end of the glass sample. The 3% leakage from the butted mirror has the advantage of allowing the launched mode to be monitored at ‘e’. A phosphor-coated CCD camera beam profiler (Ophir SP503U, factory calibrated to be linear at 1550 nm) is used to measure the beam intensity of the WG fundamental mode by selecting it using the built-in aperture of the beam profiler software (pixel values integrated over the circular aperture). CL and TL are calculated based on measured beam intensities at selected locations in the experimental layout using the derived loss equations given in detail in the supplement 1. The PL of a WG is then extracted from the measured TL using \( \text{PL} = \text{TL} / d \), where \( d \) is the length of a WG in cm. The final set of equations through which TL and CL are calculated are given below

\[
\text{TL (dB)} = L_4 - L_3 - L_2 - L_1 \\
\text{CL(dB)} = 2L_3 + L_1 - L_4
\]

where \( L_1 = \text{OL + ML} \), \( L_2 = \text{FL} \), \( L_3 = \text{CL + TL + FL} \), and \( L_4 = 2\text{TL} + 2\text{FL} + \text{CL + OL + ML} \).

Figure 2. Experimental configuration to measure CL and TL (and thus PL) through a WG. A 1550 nm LD is used as the probe beam. \( \lambda/4 \) is the quarter waveplate, PBS is the polarized beam splitter. \( M_1 \) and \( M_2 \) are the 97% reflecting mirror @ 1550 nm, placed at point ‘c’ and ‘e’ without and with sample respectively. Probe beam loss in the forward beam path (‘a’ to ‘e’) is measured at point ‘e’ (details in supplement 1) and the beam loss in the reflecting path (from ‘e’ to ‘b’) is measured at point ‘b’. 
The NA of a WG is estimated by the 1550 nm probe beam divergence angle (θ) out of the WG. Using this estimated NA of the WG, and the refractive index of GPGN glass, the refractive index modification is estimated using $\Delta n = \left( n_{\text{core}}^2 - n_{\text{cladding}}^2 \right) / 2n_{\text{core}}^2$.

**Waveguide laser setup.** Figure 3 shows the experimental configuration for demonstrating the WG laser. A 900 mW, 976 nm fiber coupled LD pump beam is launched into the laser cavity using a pair of achromatic lenses configured for mode matching to the targeted WGs. The WG laser cavity consists of a highly transmitting (HT) input coupler (IC) at 976 nm and a 90% reflecting output coupler (OC) @ ~1 μm butt ended to the end facet of a WG giving a laser cavity length of d = 10.5 mm. The diverging laser beam from the WG is collimated using a 30 mm aspheric lens to monitor the mode profile using the camera-based beam profiler (SP503U).

**Results and discussion**

**Fresnel reflection-based loss (FL) and optical loss (OL) in Yb3+: GPGN glass.** With reference to Fig. 2, OL from ‘a’ to ‘c’, is measured under conditions where the focusing lens and glass sample is removed. OL is measured to be ~0.43 dB which includes 0.13 dB of $M^2$ loss.

The GPGN glass sample is then inserted into the setup (without the focusing lens) to determine FL. The probe beam is passed through the GPGN bulk glass (i.e. the portion of the sample without WGs). The FL due to the air/glass/air interfaces of the sample is measured to be 0.73 ± 0.05 dB. The experimentally determined FL is in close approximation to the theoretical value of FL = 0.74 dB which is calculated from the refractive index of GPGN glass (n = 1.82) using FL = 10 × log ((n^2 + 1)/2n). The value of n is taken from4.

**FSL interaction and self-focusing in GPGN glass.** FSL-based WG writing involves tightly focused FSL pulses that produce extremely high peak powers $P_{\text{FSL}}$ ($P_{\text{FSL}} = E/T_{\text{FSL}}$, $E$ = FSL pulse energy and $T_{\text{FSL}}$ = FSL pulse duration) in the focal volume of a glass sample that eventually leads to permanent local modification of the refractive index23. Due to these peak powers at the focal volume, a non-linear multiphoton absorption takes place resulting in the release of an electron. Once a bounded electron is free through the initial ionization process, it then undergoes avalanche ionization where the free electron linearly absorbs the remaining laser pulse, gets excited and transfers its energy to the neighboring atom which then releases another electron once it has attained sufficient energy. The avalanche ionization process, therefore, results in exponential growth of free electrons, which generates a plasma and melts the localized volume of the sample. Due to the very short lifetime of free electrons (of the order of ps23), the electrons decay to the valence band almost immediately. This rapid cool down of the melted glass (fast quenching) thus freezes the structural modification and can lead to a change in the refractive index of the focal volume.

The high peak-power of the FSL pulses also induce nonlinear self-focusing into the material at the FSL exposed area. The self-focusing effect increases with increasing pulse energy until a critical self-focusing power ($P_{\text{critical}}$) is reached, where it counters the diffraction and produces an elongated structure as the beam continues propagating deeper into the glass24. The critical self-focusing power is given by Eq. (3)

$$P_{\text{critical}} = \frac{3.77 \lambda^2}{8\pi n_2}$$

where λ is the operating wavelength of the FSL, n and n_2 are the linear and nonlinear refractive indices of the material, respectively. The self-focusing critical limit in germanate glass is reached at low pulse energies due to its high n_2 value compared to fluoride and silica15. To estimate the $P_{\text{critical}}$ in GPGN glass the nonlinear refractive index ($n_2 \approx 56 \times 10^{-20} \text{ m}^2 \text{ W}^{-1}$) of a related lead-germanate glass (GPNL) from25 is considered. Applying $n_2 = 56 \times 10^{-20} \text{ m}^2 \text{ W}^{-1}$, n = 1.82, and λ = 524 nm in Eq. (3) gives $P_{\text{critical}} \approx 40 \text{ kW}$ for lead-germanate. For comparison with silica where $n = 1.45$ and $n_2 = 2.4 \times 10^{-20} \text{ m}^2 \text{ W}^{-1}$, $P_{\text{critical}}$ is considerably higher ~1183 kW.

**Athermal regime (100 kHz repetition rate).** For WG writing in the athermal regime, the PRF of the FSL is set to 100 kHz. The time between the successive 100 kHz laser pulses $T_{\text{athermal}}$ is 10 μs, which we assume is longer than the thermal diffusion time, $\tau$, of this glass. $\tau$ can roughly be estimated from the thermal diffusivity of the glass given by $\alpha$ (in m^2/s) = $k/\rho C_p$ where $k$ is the thermal conductivity, $\rho$ is the glass density and $C_p$ is the specific heat capacity. To evaluate $\alpha$ for GPGN glass we consider $k = 0.7 \text{ W m}^{-1} \text{ K}^{-1}$ (for a lead-germanate glass in23), $\rho = 5.61 \text{ g/cm}^3$ and $C_p = 500 \text{ J/(kg K)}$ (for another germanate glass in16). The focusing conditions for the FSL used in this study (focusing radius ~0.2 μm for λ = 524 nm and NA = 1.25) leads to $\tau \approx 0.8 \mu$s for GPGN glass which is comparable to the thermal diffusion time of glass mentioned in26 ($\tau \approx 1 \mu$s, for λ = 800 nm and

![Figure 3. Laser setup to demonstrate the near-IR WG laser operation. The laser cavity consists of a HT @ 976 nm IC mirror and a 90% reflecting OC mirror @ ~ 1 μm. Cavity length is d = 10.5 mm.](image-url)
NA = 1.4). As $t_{\text{thermal}} > \tau$, the time between the pulses is sufficiently long to carry the heat away from the focal volume before the arrival of the next pulse.

**Structural features of the FSL modified region using 100 kHz PRF.** For initial index modifications within the bulk GPGN glass, intermediate pulse energies of 80 nJ and 100 nJ are selected. 100 nJ appeared to be the approximate threshold pulse energy for producing observable modified regions in the glass. To write more prominent regions in GPGN glass the writing pulse energy is increased to 200 nJ, i.e. twice the writing threshold. Figure 4a illustrates the structural features of the single line FSL modified region with 200 nJ pulse energies. The red arrow indicates the direction of the incoming FSL pulses. The modified region in the athermal regime is composed of three structures,

(i) An elongated non-guiding dark structure at the focal volume, labelled as $A_1$ in Fig. 4a.
(ii) A bright guiding structure $A_2$ above $A_1$. $A_2$ is referred to as WG due to its strong ability to guide light, and
(iii) A weak guiding structure $A_3$ below $A_1$.

Figure 4b–e represent the FSL modified regions inscribed with (b) single lines, (c) double lines (i.e. 2 single lines inscribed 5 μm apart) (d) triple lines (i.e. 3 single lines inscribed 5 μm apart), and (e) 2 × 2 array of single lines inscribed with 5 μm spacing. The bright guiding structures formed through these inscription approaches are referred to as WG$_2$, WG$_3$, and WG$_4$, respectively.

As discussed earlier in results “Experimental methods”, the high peak power of FSLs generates a plasma in the focal volume which melts the glass. The melted glass immediately cools down as the sample moves away from the FSL beam path. A less dense glass volume leads to a lower refractive index and thus results in the formation of an anti-guiding or dark structure ($A_1$ in Fig. 4a) at the FSL irradiated area$^{23,30}$.

As the $P_{\text{FSL}}$ (results “Experimental methods”) at 100 kHz PRF (~ 800 kW) is far above the estimated $P_{\text{critical}}$ (~ 40 kW) for lead-germanate, the low self-focusing threshold is most likely the cause of elongation of $A_1$ (Fig. 4a). Similar $A_1$ structures (with varying elongation lengths depending on the strength of self-focusing) are also reported earlier in other germanate glasses and crystals such as in$^{12,15,31}$.

A positive index change is observed at both ends of $A_1$ (Fig. 4a). $A_2$ near the surface of the sample (Fig. 4a) is found to strongly guide the light and is likely attributable to the lower density of $A_1$30. As the pulse continues to propagate deeper, it is spatially degraded due to passing through the ionization that occurs at $A_1$ and results in the formation of a diffused structure $A_3$ (Fig. 4a).

WG$_1$ in Fig. 4b inscribed using 200 nJ pulse energy (100 kHz) results in a small bright guiding structure closer to the surface with an apparent diameter of ~ 4 μm (Table 1). To inscribe WGs with increased beam diameters, multiple parallel lines are inscribed; double lines inscribed 5 μm apart (Fig. 4c), triple lines with 5 μm spacing (Fig. 4d), and 2 × 2 array of single lines with 5 μm spacing (Fig. 4e). As expected, the diameter of the guiding regions increases from 4 to 10 μm while remaining single mode. The maximum NA of the largest WG (i.e. WG$_4$) written with the 100 kHz FSL (pulse energy = 200 nJ) is measured to be 0.028 with an estimated refractive index change ($\Delta n$) of $\Delta n \approx 1 \times 10^{-4}$. For 100 kHz PRF, the maximum FSL pulse energy of 200 nJ is not sufficient to induce heat accumulation in GPGN glass. However, as observed for silicate glasses in$^{8,32}$, increasing the pulse energy above 200 nJ can result in sufficient thermal diffusion to initiate weak to modest heat accumulation even at low PRF of 100 kHz (depending on the focusing conditions). This in turn can also lead to larger $\Delta n$ and WG dimensions and needs to be explored further for GPGN glass.

**Figure 4.** (a) 50 × bright field microscopy image illustrating the structural features of the single line FSL modified region (100 kHz PRF, 200 nJ pulse energy). The dark structure $A_1$ is the focal volume. $A_2$ above $A_1$ is the WG due to its strong guiding capability. $A_3$ below $A_1$ is a weaker guiding structure. The red arrow indicates the direction of the FSL incoming pulses. (b–e) are 50 × brightfield microscopy images of the modified regions (cross-sectional view in top row). (b) single line (c) double line (2 single lines inscribed 5 μm apart). (d) triple line (3 single lines 5 μm apart) (e) 2 × 2 array of single lines written 5 μm apart. The 2nd row represents the corresponding 1550 nm beam profiles of the WGs in the strong guiding structures.
MHz) which upon quenching results in larger heat accumulated regions.

B1 gradually decreases in size as the pulse energy increases (as is evidenced from the brightfield microscopic images and 1550 nm beam profile in Fig. 5b–e). In short, smooth transition from thermal diffusion at low pulse energy to near-IR WG laser operation.

Table 1. PL and CL through 100 kHz, 200 nJ written WGs at 1550 nm wavelength. FL for the Yb³⁺:GPGN glass is (0.73 ± 0.05) dB. PL is the WG PL calculated from TL using PL = TL/d where d = 1.05 cm is the length of the WGs.

| WG      | WG diameter (μm) | CL ± 0.05 (dB) | PL (dB/cm) | Laser operation |
|---------|------------------|----------------|------------|-----------------|
| WG₁     | Single line      | 4 μm × 4 μm    | 1.33       | 0.80 ± 0.07     | No              |
| WG₂     | Double lines (5 μm apart) | 6 μm × 4 μm | 1.01       | 0.91 ± 0.04     | No              |
| WG₃     | Triple lines (5 μm apart) | 8 μm × 6 μm    | 0.85       | 1.08 ± 0.06     | No              |
| WG₄     | 2 × 2 array of four single lines (5 μm apart) | 10 μm × 9 μm | 0.79       | 1.28 ± 0.07     | No              |

Structural features of FSL modified region in 1 MHz PRF. 1 MHz single and double line FSL modified regions are inscribed in GPGN glass with pulse energies varying from 50 to 200 nJ with 50 nJ interval (Fig. 5a–g). The guiding structures (WGs marked in red) formulated in the single line and double line FSL modified regions are named as WG₁-WG₁₀ for pulse energies varying from 50 to 200 nJ. Figure 5a illustrates the 1 MHz PRF structural features induced by the single line FSL modified region with 150 nJ pulse energy. A red arrow indicates the direction of incoming FSL pulses. The modified region is composed of the following three structures:

(i) An elongated dark structure (lower refractive index) at the focal volume in the middle of the modified region, labeled as B₁ in Fig. 5a. Even at a low pulse energy of 50 nJ, the peak laser power (P_PSL ~ 200 kW) exceeds the self-focusing threshold limit and results in the elongation of B₁, (described in “Experimental methods”).

(ii) A bright guiding structure (WG) labeled as B₂ below B₁.

(iii) An elliptical-shaped annulus structure B₃ with varying index layers above B₁. The heat accumulation in B₁ results in the formation of B₃.

The 1 MHz PRF, 50 nJ single line FSL modified region (Fig. 5b) is closer in form to the 100 kHz modified region with B₁ as WG₁. As the pulse energy increases from 50 to 100 nJ (Fig. 5c) more heat accumulates in B₁ and the characteristic heat accumulated structural features (B₁ in Fig. 5a) around B₁ start appearing along with the positive index guiding structure (WG₂) below B₁. As the pulse energy further increases (Fig. 5c–e), more heat is deposited in B₁ resulting in the formation of larger and brighter B₃. In addition to increasing B₁, B₂ below B₁ gradually decreases in size as the pulse energy increases (as is evidenced from the brightfield microscopic images and 1550 nm beam profile in Fig. 5b–e). In short, smooth transition from thermal diffusion at low pulse...
energies to heat accumulation at higher pulse energies is observed in 1 MHz PRF modified regions thus reflecting 1 MHz to be an intermediate regime. For 1 MHz PRF, 100 nJ is observed to be the threshold pulse energy to initiate heat accumulation in GPGN glass (Fig. 5b–c). Similar transition from thermal diffusion (athermal regime) to heat accumulation (thermal regime) is previously studied in silicate glasses and fused silica from 0.1 to 5 MHz.8,24,32. For silicate glasses the transition threshold is observed for PRF ~ 0.2 MHz while for fused silica the transition threshold PRF is ~ 0.5 MHz under the same focusing conditions.

To increase the WG diameter in the 1 MHz PRF we also inscribed double line FSL modified regions in GPGN glass with 5 µm spacing (Fig. 5f,g). The resulting guiding structures are referred to as WG9 and WG10 in Fig. 5f,g and are of larger diameters compared to single line induced WGs in Fig. 5a–e. The 1550 nm beam profiles for 1 MHz written structures reflect that the inscribed WGs are single mode in nature.

**PL in 1 MHz induced WGs and near-IR WG laser operation.** The measured PL and the laser slope efficiencies for the 1 MHz PRF induced WGs are listed in Table 2. Figure 6 plots the PL for the 1 MHz inscribed WGs. The data in blue (Fig. 6) is the PL for single line induced WGs using 1 MHz PRF with varying FSL pulse energies. The brown plotted data is the PL for WGs induced by writing double line regions. As shown in Table 2, PL in WG5 is greater than WG6. For WG7 and WG8 the PL starts increasing again as the guiding structure deeper into the sample decreases (in size) giving way to the formation of heat accumulated region which becomes more prominent (with no defined guiding structure) as the pulse energy increases (Fig. 5b–e).

WG9 and WG10 are written with the same pulse energies as WG6 and WG8, respectively, however, the PL measured for the double line WGs are observed to be relatively lower. This is attributed to the formation of larger and smoother WGs (∆n ~ 5.4 × 10−4 for WG10). A low PL of ~ 0.2 dB/cm is measured for WG10 which is the lowest PL observed in GPGN glass to date.

Laser operation at ~ 1 µm (using the setup in Fig. 3) is achieved in WG5, WG6, WG9, and WG10 with ~ 7%, 10%, and 28% slope efficiencies, respectively (Figs. 7 and 8). WG, and WG9 could not be operated as a laser due to higher PL. The broad spectral output from WG10 is shown in Fig. 8b and is centered at ~ 1060 nm with a full width half maximum value of ~ 5 nm.

| WG | Pulse Energy (nJ) | CL ± 0.05 (dB) | PL (dB/cm) | Laser slope efficiency (%η) |
|----|------------------|----------------|------------|-----------------------------|
| WG5 | 50               | 0.92           | 0.74 ± 0.05 | 7                           |
| WG6 | 100              | 0.68           | 0.63 ± 0.06 | 10                          |
| WG7 | 150              | 0.95           | 0.88 ± 0.05 | No lasing                   |
| WG8 | 200              | 1.24           | 1.22 ± 0.07 | No lasing                   |
| WG9 | 100              | 0.85           | 0.34 ± 0.03 | 19                          |
| WG10 | 200             | 0.63           | 0.22 ± 0.03 | 28                          |

**Table 2.** CL, PL and laser slope efficiencies in 1 MHz written WGs in Yb3+: GPGN glass at 1550 nm. FL for the Yb3+:GPGN glass is (0.73 ± 0.05) dB. PL is the WG PL calculated from TL using PL = TL/d where d = 1.05 cm is the length of the WGs.
Structural features of FSL modified region in 5 MHz PRF. 5 MHz PRF single line FSL modified regions are inscribed in GPGN glass with pulse energies varying from 60 to 120 nJ with 20 nJ intervals (Fig. 9a–e). The guiding structures (WG) formulated in the single line FSL modified regions are represented as WG11–WG14 (red arrows in Fig. 9b–e for pulse energies varying from 60 to 120 nJ, respectively). Figure 9a illustrates the structural features of the single line FSL modified region. A red arrow indicates the direction of incoming FSL pulses.

Figure 6. PL in single line induced WGs (WG5–WG8 in blue) and double line induced WGs (WG9–WG10 in brown) as a function of FSL pulse energy. Minimum PL of ~0.2 dB/cm is measured for WG10.

Figure 7. ~1 µm laser operation in WG5 and WG6 with slope efficiencies, ηslope, 7% and 10%, respectively.

Figure 8. (a) Laser operation in double line induced WG9 and WG10 with improved 19% and 28% slope efficiencies. At Pin > 800 mW, the laser signal power dropped due to thermal lensing within the WGs. (b) WG10 laser operation at 1060 nm with a FWHM ~ 5 nm.
The modified region is a heat accumulated region with varying index layers. The heat accumulated region comprises the following four structures located radially around the central focal volume (Fig. 9a):

(i) An elongated dark structure at the focal volume in the center of the modified region labeled as C1 in Fig. 9a. As explained earlier, the dark structure represents the low refractive index at the FSL exposed area. The elongation of the focal volume is the result of strong self-focusing even at low pulse energy of 60 nJ.

(ii) A bright circular-shaped guiding structure C2.

(iii) An elliptical shaped annulus structure C3 around C2.

(iv) An outer annulus structure C4 around C3.

The 5 MHz modified region inscribed with 60 nJ pulse energy (Fig. 9b) is similar to the 1 MHz PRF single line FSL modified region written with 200 nJ pulse energy (Fig. 5e), but with larger dimensions and a more dense elliptical-shaped annulus structure around C1. The additional heat accumulation in C1 compared to B1 \( \tau_{\text{thermal}}(5 \text{ MHz}) \approx 200 \text{ ns} \ll \tau_{\text{thermal}}(1 \text{ MHz}) \approx 1 \mu\text{s} \) results in much higher plasma density which upon immediate quenching of the glass melt densifies around C1 and results in C3. The uniform spherical cooling of the focal volume leads to the formation of non-uniform bright and dark index layers surrounding C1. The additional increase in pulse energy from 60 to 80 nJ (Fig. 9c) suppresses the formation of C2 structure (~ 12 μm) originating from the center of the modified region (Fig. 9c). As the pulse energy further increases, C2 enlarges in size such that it becomes multimode again (Fig. 9d–e).

**PL in 5 MHz induced WGs and near-IR WG laser operation.** Table 3 lists the PL and laser slope efficiencies measured in the 5 MHz inscribed WGs. The PL reduces from WG11 to WG13 as the FSL pulse energy increases from 60 to 100 nJ (Fig. 10a). The additional heat accumulation in C1 compared to B1 \( \tau_{\text{thermal}}(5 \text{ MHz}) \approx 200 \text{ ns} \ll \tau_{\text{thermal}}(1 \text{ MHz}) \approx 1 \mu\text{s} \) results in much higher plasma density which upon immediate quenching of the glass melt densifies around C1 and results in C3. The uniform spherical cooling of the focal volume leads to the formation of non-uniform bright and dark index layers surrounding C1. The additional increase in pulse energy from 60 to 80 nJ (Fig. 9c) suppresses the formation of C2 structure (~ 12 μm) originating from the center of the modified region (Fig. 9c). As the pulse energy further increases, C2 enlarges in size such that it becomes multimode again (Fig. 9d–e).
All the WGs are found to lase at the expected wavelength of ~1 µm with slight variation in operating wavelengths depending upon the WG diameter (i.e. due to the population inversion ratio modifying the ground state absorption). The highest laser slope efficiency of ~13% is achieved for WG13 with the lowest PL and operating at a wavelength of 1056 nm (Fig. 10b).

Conclusion
We fabricated a range of waveguides in a RE-doped lead-germanate GPGN glass using FSL in three different PRF i.e. 100 kHz (athermal regime), 1 MHz and 5 MHz (thermal regime), and verified their lasing capability in a near-IR region. The aim of the study is to optimize the FSL parameters in such a way that low propagation loss guiding structures are induced in GPGN glass for their efficient utilization in near to mid-IR laser applications. Irradiating GPGN glass with FSL pulses results in positive refractive index change in the GPGN glass in the vicinity of focal volume (above, below or around the focal volume depending on the writing regime). The refractive index contrast (Δn) for athermal waveguides is ~1 × 10^{-4} while for thermal waveguides Δn increases to ~5 × 10^{-4}. It is concluded that the heat accumulation in thermal regime is responsible for the generation of smooth guiding structures with large Δn. This in turn suppresses the impact of aberrations and self-focusing on the guiding region thus reducing the PL in thermally inscribed WGs in the GPGN glass. The lowest loss of ~0.2 dB/cm at 1550 nm is measured in a 1 MHz written double-line WG. To the best of our knowledge, the PL of 0.2 dB/cm is the lowest loss reported in a FSL inscribed WG in germanate glass.

There is still room for further improvement in the WG laser slope efficiencies by reducing the PL in WGs with careful tuning of variable FSL parameters in such a way that induced WGs are still single mode. Moreover, the self-focusing, which arises due to the interaction of high power FSL pulses with GPGN glass, needs to be further explored (theoretically and experimentally) to minimize its impact on the inscribed WGs in GPGN glass (more specifically in athermal regime).

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