Ultrafast laser fabrication of low-loss waveguides in chalcogenide glass with 0.65 dB/cm loss

Ben McMillen,[1] Botao Zhang,[1] Kevin P. Chen,[1,*] Antonio Benayas,[2] and Daniel Jaque[2]

[1]*Department of Electrical Engineering, University of Pittsburgh, Pittsburgh, Pennsylavania 15261, USA*

[2]*Fluorescence Imaging Group, Instituto de Ciencia de los Materiales “Nicolás Cabrera” (INC), Campus de Excelencia,*
Universidad Autonoma de Madrid-CSIC, Madrid 28049, Spain

**Correspondence author: kchen@engr.pitt.edu*

Received November 21, 2011; revised January 30, 2012; accepted February 8, 2012;
posted February 10, 2012 (Doc. ID 158624); published April 19, 2012

This Letter reports on the fabrication of low-loss waveguides in gallium-lanthanum-sulfide chalcogenide glasses using an ultrafast laser. Spatial beam shaping and temporal pulse width tuning were used to optimize the guided mode profiles and optical loss of laser-written waveguides. Highly symmetric single-mode waveguides guiding at 1560 nm with a loss of 0.65 dB/cm were fabricated using 1.5 ps laser pulses. This Letter suggests a pathway to produce high quality optical waveguides in substrates with strong nonlinearity using the ultrafast laser direct writing technique. © 2012 Optical Society of America

OCIS codes: 350.3390, 130.2755, 160.4330, 130.4310.

Over the last decade, the ultrafast laser has emerged as a powerful tool to shape three-dimensional (3D) photonic circuits in transparent dielectric materials [1]. Research efforts invested since its first demonstration have extended this 3D fabrication approach to a wide array of optical substrates, including those with optical gain [2] and strong optical nonlinearities [3]. One of the unique traits of this fabrication approach is its ability to produce photonic circuits in bulk optical substrates with proven optical quality. It therefore bypasses all challenges associated with multi-step thin film based material synthesis and fabrication techniques. An important aspect of the ultrafast laser device fabrication process is to optimize the processing parameters to improve the optical qualities of these 3D waveguides. This was normally achieved through the proper choice and fine-tuning of several factors including repetition rate, wavelength, writing speed, and pulse energy of the writing laser. In many situations, however, adjustment of these parameters is not sufficient to produce optical devices with satisfactory performance.

An example that highlights this challenge is the ultrafast laser processing of chalcogenide (CHG) glasses. With a high nonlinearity and wide IR transmission window, CHG glasses have recently attracted much attention for potential applications in all-optical switching [4] and mid-IR photonics [5]. However, this large nonlinearity has strong impacts on laser pulse propagation, producing such phenomena as self-focusing. These effects lead to an elongation of the laser modified region within the substrate, yielding multiple guiding regions as reported in early work [6]. More recently, multiple laser passes have yielded more symmetrical features in CHG glasses, producing single-mode guiding in the mid-IR spectral range (3–11 μm) [7]. However, the fabrication of highly symmetric single-mode waveguides at shorter wavelengths (e.g., 1560 nm) remains a significant challenge. The effects of beam distortion due to nonlinear material interaction are difficult to mitigate through the optimization of laser writing parameters alone. Additionally, fabrication of these features is made more difficult due to the high refractive index of CHG glass, which induces spherical aberrations and distorts the focus at depths larger than a few tens of micrometers.

To overcome these challenges, this Letter explores both spatial beam shaping [8] and temporal pulse tuning using adaptive optical elements [9] as means to mitigate spatial and temporal distortion of the writing beam. These efforts result in significant improvements to the quality of waveguides produced in CHG glasses using the ultrafast laser writing technique. Optimization of the spatial profile, as well as the pulse width of the writing beam, leads to a highly symmetric single-mode waveguide at 1560 nm with a minimum propagation loss of 0.65 dB/cm.

Gallium lanthanum sulfide (GLS) CHG glass was chosen as the waveguide substrate for its high nonlinear figure of merit (FOM) and superior environmental stability [10]. Waveguides were formed by focusing the writing beam beneath the surface of a GLS substrate (ChG Southampton) using a 40× aspheric lens (0.68 NA) and translating the sample at a fixed velocity (250 μm/s). A writing depth of ~275 μm was chosen to avoid degradation of the waveguide end-facet optical quality due to sample chipping from regular handling.

Writing pulses were generated using a Coherent RegA 9000 laser system, producing 150 fs pulses at 800 nm and a repetition rate of 250 kHz. The pulse energy of the writing beam was fixed at 400 nJ and circularly polarized before being delivered to the writing stage, which consisted of a three-axis motion stage (Aerotech ABL2002) to which the sample was affixed. After writing, the sample was cut and polished to a high optical grade in preparation for characterization.

To characterize the laser-written waveguides, a combination of several laser diode sources (1560 nm DFB, 635 nm) and an IR CCD camera were used. Mode-field diameters (MFDs) were obtained through image analysis of CCD captured images of guided modes at 1560 nm. The Fabry-Pérot technique [11] was incorporated to measure losses by using the same DFB laser diode and an integrating sphere detector. Micro-Raman measurements were performed as described elsewhere [12].

The strong nonlinearity present in GLS substrates presents a significant challenge for ultrafast laser processing. Figures 1A–1E show an optical microscope image of laser-induced features written with a pulse width of 240 fs along with supported guiding modes. These images were acquired simultaneously so that the guiding region may be located within the cross-section of the laser-written features. Highly asymmetric features are seen due to a combination of spherical aberration and strong nonlinear material interaction (Fig. 1A), which is consistent with the work of Hughes *et al* [6]. One guided mode was observed at 1560 nm in the "head" of the modified zone (Fig. 2C), with a second guiding zone present near the "tail" of the same feature (Fig. 2E). MFD observed in both regions are significantly larger than the width of visible damage tracks, giving rise to poor optical confinement. Guided modes at 635 nm are shown at these two coupling points for comparison (Figs. 2B and 2D).

To improve the shape of the index profile, a temporal pulse shaper (Bio-Photonics FemtoJock) was used to stretch the pulse to 2 ps in order to reduce the lengthening of the focal volume due to nonlinear-induced self-focusing, as shown in Fig. 1F. This leads to significant improvement in laser-induced waveguide profiles and gives rise to a much stronger mode confinement at both 635 and 1560 nm as evidenced by Fig. 1G and 1 H. These results show a strong dependence of waveguide performance on the duration of the writing laser pulse, which suggests that Kerr self-focusing is the primary driving mechanism behind feature elongation. This explanation, however, does not account for the increase in feature width at the longer pulse width of 2 ps. The wider modified zone suggests that the outcome of this laser fabrication process is prone to thermal effects. CHGs, which have similar properties to heavy-metal oxide glasses, have been shown to be susceptible to residual heating [13].

The results presented in Fig. 1 show a strong dependence of waveguide characteristics on the temporal duration of the writing laser pulse, warranting further study of the processing parameters to achieve optimal waveguide performance. In order to take advantage of this effect and to further explore the impact of pulse width on the guided-mode characteristics of GLS laser-written waveguides, the astigmatic beam shaping technique [8] was used to further improve focal distortion. This method of beam correction employs a cylindrical telescope, providing a demagnification factor of 3 in the y-direction (perpendicular to the waveguide writing direction), purposefully introducing astigmatism at the objective's focus. For the results presented in Fig. 2, the free-space focal plane offset (astigmatic difference) was measured to be ~21 μm, with a pretelescope beam diameter of 1.2 mm. Temporal effects were explored by varying the writing laser pulse width from 150 fs to 4.5 ps, while keeping the pulse energy (400 nJ), translation speed (250 μm/s), and writing depth (~275 μm) constant.

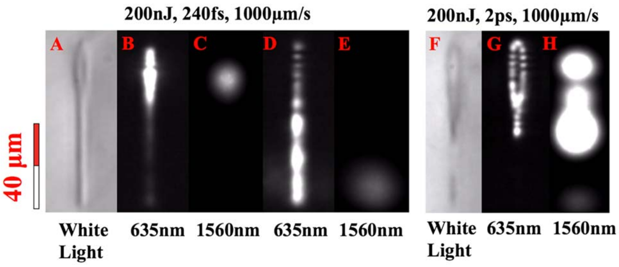

Fig. 1. (Color online) Guided mode analysis for pulse width dependence in the waveguide writing process for features written at 2 ps and 240 fs, respectively.

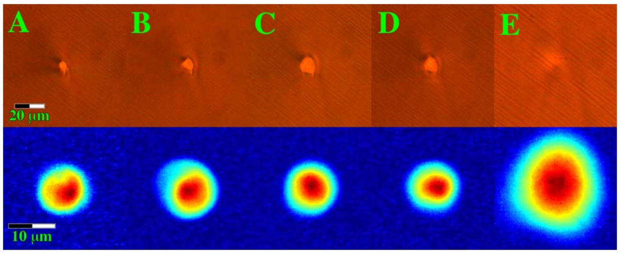

Fig. 2. (Color online) End facet view of laser written waveguides in GLS CHG glass using the astigmatic beam shaping technique. A, 2.75 ps; B, 2.1 ps; C, 1.5 ps; D, 1 ps; E, 500 fs. Minimum MFD was 11.3 μm at 1.5 ps. Features written at 4.5 and 3.75 ps only guided at 635 nm and were not visible under a standard white-light microscope.

The combined spatial and temporal shaping of the writing laser produced highly symmetric waveguides, as shown in Fig. 2. Guided modes were also found to be symmetric and centered at the laser-modified sites. For pulse widths above 2.75 ps, guiding was only present for 635 nm. For pulse widths between 2.75 and 1 ps, strong mode confinement at 1560 nm was found, indicating optimal writing conditions for minimum mode size. At shorter pulse widths (<1 ps), the mode size increases dramatically, suggesting weak index contrast and poor mode confinement.

Waveguide loss measurements based on the Fabry-Pérot resonance method [11] were performed using a temperature-tunable DFB diode laser with a center wavelength of 1560 nm and a tuning step size of 1 pm. The inset in Fig. 3 shows a fringe pattern for the best result, which was found to occur for features written with a pulse width of 1.5 ps. The waveguide propagation loss, determined by the ratio of the periodic maxima to the minima of the fringe, is calculated as 0.65 dB/cm. The corresponding MFD and loss versus pulse width are plotted together in Fig. 3. The data indicates an optimal processing window between 1 and 2 ps, where the minimum MFD and lowest loss coincide. The MFD is not sensitive to longer pulse widths, however, it rises drastically for pulse widths less than 1 ps.

Waveguide loss is significantly higher outside of this window, especially for shorter pulse widths. The optimal processing conditions identified by this work lie outside of the pulse width ranges typically provided by commercial ultrafast lasers, which may explain the fabrication difficulties encountered by various research groups.

Measurements have yet to be performed to map the refractive index change around the laser modification area; however, the comparable dimension of the laser modified area (~10 μm in Fig. 2C) and the MFD (e.g. 11.3 μm for Fig. 2C) measured for the 1.5 ps pulse width suggests the refractive index change is slightly smaller, but comparable to, the index contrast of a standard telecom fiber.

In order to gain a better understanding of the trends displayed in Fig. 3, confocal Raman imaging was

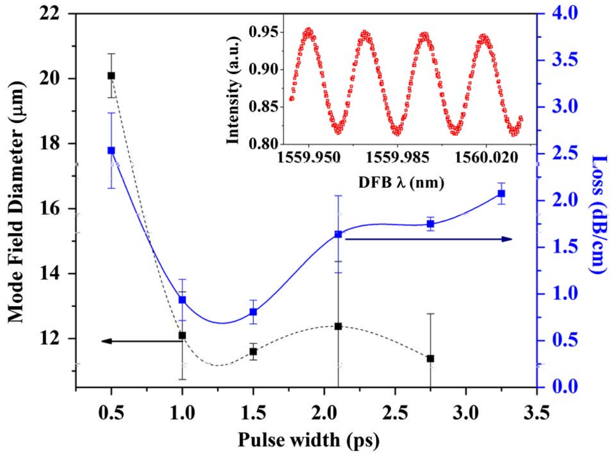

Fig. 3. (Color online) Fringe pattern for the lowest loss feature written at 1.5 ps, with a loss of 0.65 dB/cm (inset) and MFD and loss versus pulse width, showing optimal writing conditions.

performed on several structures fabricated with different pulse widths. Figure 4 shows the spatial variation of the integrated intensity of the band centered around 340 cm^{-1} Raman mode, corresponding to the symmetrical stretching vibrations of GaS_4 tetrahedra [14], as obtained for three characteristic waveguides fabricated with pulse widths of 1, 1.5 and 2.1 ps, respectively.

In all cases, Raman back scattering intensity decreases within the guiding area, indicating the presence of broken bonds and/or extended defects. Both effects indeed contributed to increased propagation losses. In this sense, the Raman images of Fig. 4 suggest the structure fabricated at 2.1 ps has the larger damage degree, thus predicting larger propagation losses. This is consistent with the measurement results shown in Fig. 3, where the propagation loss increases for pulse widths above 2 ps. In the pulse width range 1 to 1.5 ps, Raman data suggests that such pulse widths are long enough to positively modify the GLS refractive index value, however, the magnitude of the associated creation of broken bonds and/or extended defects is not sufficient to lead to a significant amount of propagation losses. After analyzing the information provided by Micro-Raman Imaging, and the trends provided by propagation loss values from Fig. 3, we find that pulse widths shorter than 1 ps cause an increase in propagation losses (i.e. the number of laser-induced defects), as well as spread the refractive index modification over such a large area that the MFD becomes very large, making devices fabricated at these shorter pulse widths of little use in waveguide based photonic circuits.

In summary, we report on the fabrication of highly symmetric, low-loss buried waveguides in GLS CHG glasses. Spatial beam shaping and temporal pulse optimization were used to produce waveguides with a loss of 0.65 dB/cm at 1560 nm. Confocal Raman images of the fabricated structures have shown that propagation losses are caused by the high density of defects originated at the waveguide volume for pulse widths greater than 2 ps. We find that the use of 1–2 ps pulses, rather than sub-picosecond pulses as used in previously published work, alleviates nonlinear effects, such as self-focusing. Longer pulse widths combined with spatial beam shaping led to highly symmetric waveguides with high optical confinement. It is worthwhile to point out that results reported in this Letter were obtained with a fixed writing speed (250 μm/s) and a fixed pulse energy (400 nJ/pulse). It is possible that waveguides with better performance may be fabricated by optimizing these parameters. The successful production of 3D waveguides in CHG glasses is an important goal, given the wide applications of these materials in mid-IR photonics and nonlinear optics.

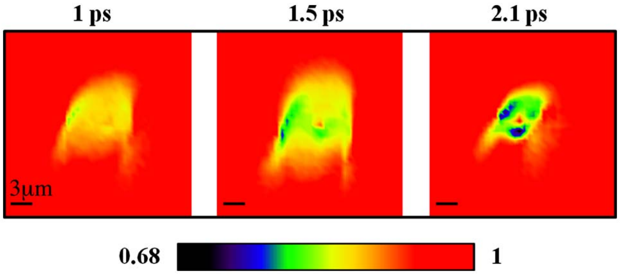

Fig. 4. (Color online) Confocal Raman intensity images of three characteristic waveguides written with pulse widths of 1, 1.5 and 2.1 ps. Scale bar is 3 μm in the three images.

This work was supported by the National Science Foundation (CMMI-0644681 and CMMI-0900564) and by the Spanish Ministerio de Educación y Ciencia (MAT-201016161). A. Benayas would like to thank UAM by 2010-Short Term Travel Grant.

References

1. K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, Opt. Lett. **21**, 1729 (1996).
2. A. Rodenas, A. Benayas, J. R. Macdonald, J. Zhang, D. Y. Tang, D. Jaque, and A. K. Kar, Opt. Lett. **36**, 3395 (2011).
3. M. Pelusi, V. Ta'Eed, L. Fu, and E. Magi, IEEE J. Sel. Top. Quantum Electron. **14**, 529 (2008).
4. M. Galili, J. Xu, and H. Mulvad, Opt. Express **17**, 2182 (2009).
5. N. Carlie, J. Musgraves, B. Zdyrko, I. Luzinov, J. Hu, V. Singh, A. Agarwal, L. Kimerling, A. Canciamilla, F. Morichetti, A. Melloni, and K. Richardson, Opt. Express **18**, 26728 (2010).
6. M. Hughes, W. Yang, and D. Hewak, Appl. Phys. Lett. **90**, 131113 (2007).
7. A. Rodenas, G. Martin, B. Arezki, N. D. Psaila, G. Jose, A. Jha, L. Labadie, P. Kern, A. K. Kar, and R. R. Thomson, "Three-dimensional mid-infrared photonic circuits in chalcogenide glass," ArXiv: 1112.2546 (2011).
8. R. Osellame, S. Taccheo, M. Marangoni, R. Ramponi, P. Laporta, D. Polli, S. De Silvestri, and G. Cerullo, J. Opt. Soc. Am. B **20**, 1559 (2003).
9. A. M. Weiner, Rev. Sci. Instrum. **71**, 1929 (2000).
10. R. Curry, S. Birtwell, A. Mairaj, and X. Feng, J. Non-Cryst. Solids **351**, 477 (2005).
11. G. T. Reed and A. P. Knights, *Silicon Photonics: An Introduction* (Wiley, 2004), p. 94.
12. A. Ródenas, G. A. Torchia, G. Lifante, E. Cantelar, J. Lamela, F. Jaque, L. Roso, and D. Jaque, Appl. Phys. B **95**, 85 (2009).
13. E. Romanova, A. Konyukhov, S. Muraviov, and A. Andrianov, in *Proceedings of 2010 12th International Conference on Transport Optical Networks (ICTON)* (IEEE, 2010), paper We.B.42.
14. G. Lucovsky, J. P. de Neufville, and F. L. Galeener, Phys. Rev. B. **9**, 1591 (1974).