Supercontinuum generation in an ultrafast laser inscribed chalcogenide glass waveguide

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Abstract: The authors report supercontinuum generation in an ultrafast laser inscribed chalcogenide glass waveguide. The waveguides were fabricated using a Yb:glass cavity-dumped femtosecond oscillator with 600-kHz repetition rate. The waveguides were pumped using an optical parametric amplifier tuned to 1500 nm with a bandwidth of 100 nm. The broadest resulting supercontinuum spanned 600 nm (at -15 dB points) from 1320 to 1920 nm. The supercontinuum was generated in the normal dispersion regime, enhancing stability, and exhibits a smooth spectral shape.

OCIS codes: (130.4310) Nonlinear Integrated Optics; (140.3390) Laser Materials Processing; (320.6629) Supercontinuum Generation.

References and links

1. J.T. Gopinath, M. Soljacic, E.P. Ippen, V.N. Fuflyigin, W.A. King and M. Shurgalin, “Third order nonlinearities in Ge-As-Se-based glasses for telecommunications applications,” J. Appl. Phys. **96**, 6931-6933 (2004).
2. V.G. Ta’eed, N.J. Baker, L. Fu, K. Finsterbusch, M.R.E. Lamont, D.J. Moss, H.C. Nguyen, B.J. Eggelton, D.Y. Choi, S. Madden and B. Luther-Davies, “Ultrafast all-optical chalcogenide glass photonic circuits,” Opt. Express **15,** 9205-9221 (2007).
3. M. Asobe, T. Ohara, I. Yokohama, and T. Kaino, “Low power all-optical switching in a nonlinear optical loop mirror using chalcogenide glass fibre,” Electron. Lett. **32**, 1396-1397 (1996).
4. M.R.E. Lamont, L.B. Fu, M. Rochette, D.J. Moss, and B.J. Eggleton, “2R optical regenerator in As_2Se_3 chalcogenide fiber characterized by a frequency-resolved optical gating analysis,” Appl. Opt. **45**, 7904-7907 (2006).
5. P.A. Thielen, L.B. Shaw, P.C. Pureza, V.Q. Nguyen, J.S. Sanghera and I.D Aggarwal, “Small-core As-Se fiber for Raman amplification,” Opt. Lett. **28**, 1406-1408 (2003).
6. V.G. Ta’eed, L.Fu, M. Pelusi, M. Rochette, I.C.M. Littler, D.J. Moss and B.J. Eggleton, “Error free all optical wavelength conversion in highly nonlinear As-Se chalcogenide glass fiber,” Opt. Express **14**, 10371-10376 (2006).
7. I. Hartl, X.D. Li, C. Chudoba, R.K. Ghanta, T.H. Ko, J.G. Fujimoto, J.K. Ranka and R.S. Windeler, “Ultrahigh-resolution optical coherence tomography using continuum generation in an air-silica microstructure optical fiber,” Opt. Lett. **26**, 608-610 (2001).
8. Th. Udem, R. Holzwarth and T. W. Hänsch, “Optical Frequency Metrology,” Nature **416**, 233-237 (2002)
9. B. Schenkel, R. Paschotta and U. Keller, “Pulse compression with supercontinuum generation in microstructure fibers,” J. Opt. Soc. Am. B **22**, 687-693 (2005).
10. Y. Ruan, W. Li, R. Jarvis, N. Madsen, A. Rode and B. Luther-Davies, “Fabrication and characterization of low loss rib chalcogenide waveguides made by dry etching,” Opt. Express **12**, 5140-5145 (2004).
11. J-F. Viens, C. Meneghini, A. Villeneuve, T.V. Galstian, E.J. Knystautas, M.A. Duguay, K.A. Richardson and T. Cardinal, “Fabrication and characterization of integrated optical waveguides in sulfide chalcogenide glasses,” J. Lightwave Technol. **17**, 1184-1191 (1999).
12. A. Zoubir, M. Richardson, C. Rivero, A. Schulte, C. Lopez, K. Richardson, N. Hô and R. Vallée, “Direct femtosecond laser writing of waveguides in As_2S_3 thin films,” Opt. Lett. **29**, 748-750 (2004).
13. K. Miura, J. Qiu, H. Inouye, T. Mitsuyu and K. Hirao, “Photowritten optical waveguides in various glasses with ultrashort pulse laser,” Appl. Phys. Lett. **71**, 3329-3331 (1997).

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14. O.M. Efimov, L.B. Glebov, K.A. Richardson, E. Van Stryland, T. Cardinal, S.H. Park, M. Couzi and J.L. Brunéel, "Waveguide writing in chalcogenide glasses by a train of femtosecond laser pulses," Opt. Mat. **17**, 379-386 (2001).
15. R.R. Thomson, S. Campbell, I.J. Blewett, A.K. Kar, and D.T. Reid, "Optical waveguide fabrication in z-cut lithium niobate ($LiNbO_3$) using femtosecond pulses in the low repetition rate regime," Appl. Phys. Lett. **88**, 111109 (2006).
16. R. Osellame, M. Lobino, N. Chiodo, M. Marangoni, G. Cerullo, R. Ramponi, H.T. Bookey, R.R. Thomson, N. D. Psaila and A.K. Kar, "Femtosecond laser writing of waveguides in periodically poled lithium niobate preserving the nonlinear coefficient," Appl. Phys. Lett. **90**, 241107 (2007).
17. W. J. Tomlinson, R. H. Stolen, and C. V. Shank, "Compression of optical pulses chirped by self-phase modulation in fibers," J. Opt. Soc. Am. **1**, 139-149 (1984).
18. K.R. Tamura, H. Kubota and M. Nakazawa, "Fundamentals of Stable Continuum Generation at High Repetition Rates," IEEE J. Quantum. Electron. **36**, 773-779 (2000).
19. K.S. Bindra, H.T. Bookey, A.K. Kar, B.S. Wherrett, X. Liu and A. Jha, "Nonlinear optical properties of chalcogenide glasses: Observation of multiphoton absorption," Appl. Phys. Lett. **79**, 1939-1941 (2001).
20. N.D. Psaila, R.R. Thomson, H.T. Bookey, A.K. Kar, N. Chiodo, R. Osellame, G. Cerullo, G. Brown, A. Jha, and S. Shen, "Femtosecond laser inscription of optical waveguides in Bismuth ion doped glass," Opt. Express **14**, 10452-10459 (2006).
21. D. Blömer, A. Szameit, F. Dreisow, T. Schreiber, S. Nolte and A. Tünnermann, "Nonlinear refractive index of fs-laser-written waveguides in fused silica," Opt. Express **14**, 2151-2157 (2006).
22. M. Hughes, W. Yang and D. Hewak, "Fabrication and characterization of femtosecond laser written waveguides in chalcogenide glass," Appl. Phys. Lett. **90**, 131113 (2007).

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1. Introduction

Chalcogenide glasses are particularly attractive materials for use in a variety of optical devices due to their large nonlinearities. Nonlinear refractive indices of the order of 1000x fused silica have been reported, allowing nonlinear effects to be exploited at low optical powers [1]. Chalcogenide glasses also exhibit excellent transparency well into the mid-infrared, making them useful for passive and active infrared optics [2]. They are also highly photosensitive, displaying a wide range of photo-induced phenomena such as photo-darkening, photo-bleaching, and photo-contraction [2].

This plethora of useful effects and the ability to form fibers and waveguides has led to chalcogenide based devices being used for a wide range of applications including all optical switching [3], all optical 2R regeneration [4], Raman amplification [5], wavelength conversion using cross phase modulation (XPM) [6], and ultrashort pulse compression [2].

One application of highly nonlinear waveguiding devices that has received significant research attention is the generation of broadband continuum radiation. Such broadband continuum sources open up great opportunities as intense sources for sensing, Optical Coherence Tomography (OCT) [7], frequency comb generation [8], or pulse compression for few-optical-cycle pulse production [9]. For such applications, the generated radiation has to be temporally stable and spectrally smooth. For OCT, the attainable imaging resolution is inversely proportional to the bandwidth of the source, favoring broadband low-coherence radiation [7]. Near-infrared wavelengths are preferred for OCT because of their increased penetration depth. The fabrication of broadband integrated supercontinuum sources is highly desirable in order to create compact cost effective sources.

Several methods have been used to fabricate chalcogenide waveguide devices, mostly using thin film deposition techniques followed by etching or laser writing to produce waveguiding structures [10-12]. Conventional thin film deposition techniques raise significant issues concerned with maintaining the stoichiometry between the bulk and the thin film [2], however pulsed laser deposition has been successfully employed to fabricate chalcogenide waveguides with the same stoichiometry as the bulk glass [10].

Embedded channel waveguides have also been fabricated in nonlinear materials using ultrafast laser waveguide inscription (ULWI) [11,13-16]. ULWI has distinct benefits in its experimental simplicity, requiring only the translation of the bulk sample through the focus of the pulse train to inscribe a waveguide, and its flexibility, making it applicable to a broad class

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of materials. This avoids the need for expensive clean room facilities and complex thin film deposition techniques. As the light matter interaction is highly nonlinear, buried waveguides can be fabricated, enabling the production of three-dimensional structures.

In this letter we demonstrate supercontinuum generation in an ultrafast laser inscribed chalcogenide glass waveguide. We have used a broadband optical parametric amplifier (OPA) as the pump source and generate a continuum spanning 600 nm centered on 1620 nm. The generated spectrum is spectrally smooth and is generated in the normal dispersion regime, enhancing the stability of the supercontinuum source [17,18].

2. Experimental

2.1 Waveguide fabrication

The precursor composition of the substrate glass was $79GeS_2$-$15Ga_2S_3$-6CsI. The inclusion of the dopants Ga_2S_3 and CsI serve to increase the bandgap, reducing the multi-photon absorption (MPA) coefficient whilst maintaining the nonlinear refractive index (n_2) [19]. MPA has been shown to detrimentally affect the amount of spectral broadening by introducing additional loss leading to a reduction in the effective interaction length [2]. The glass fabrication procedure is described extensively in reference [19]. The nonlinear refractive index of the glass was measured to be 6×10^{-19} m^2W^{-1} using the z-scan technique, approximately 22× that of fused silica. The bandgap of the glass is 2.69 eV corresponding to a band edge of 459 nm.

Waveguides were fabricated using a Yb:glass cavity dumped oscillator emitting ~350 fs pulses at a central wavelength of 1040 nm. The repetition rate of the laser was set to 600 kHz. The pulse train was focused to a depth of approximately 200 μm using a ×50, 0.6 NA microscope objective, however the beam did not fill the full aperture of the lens, resulting in an effective $NA_{eff} = 0.3$. A schematic diagram of the waveguide fabrication setup is shown in reference [20]. The sample was translated perpendicular to the laser beam and polarization directions. A wide range of pulse energies and translation speeds were investigated, with pulse energies from 83 to 492 nJ and translation speeds from 250 to 4000 μm/s. After fabrication the waveguide facets were cut and polished to give a final sample length of 8.4 mm.

2.2. Waveguide characterization

Waveguide characterization commenced approximately one year after fabrication, thus demonstrating the stability of the photo-induced structures. Previous studies have shown strong time dependence on the guiding properties, particularly with damage induced structures [15]. The waveguide facets were observed using a microscope operating in transmission mode. The fabricated waveguides all show an elongated shape along the axis of the incident fabrication beam. Figure 1(a) shows a facet image of a waveguide fabricated using 317 nJ pulses and a translation speed of 500 μm/s. The elongated structure in the centre is ascribed to the formation of a plasma filament, due to self-focusing of the fabrication beam. The size of the elongated structure scales with the pulse energy of the fabrication laser, which further supports filamentation as a formation mechanism for the elongated structure. This interesting phenomenon is under investigation and will be reported upon at a later date.

The guiding properties of the waveguides were investigated by imaging the end facet of the waveguide onto an Electrophysics-7290A IR Vidicon camera whilst coupling 1480 nm light in from the opposite end using direct fiber-waveguide butt-coupling. Waveguides fabricated with pulse energies above 83 nJ were observed to be highly multimode, with several guiding regions. Figures 1(b) to 1(d) show near-field images of the various modes guided by the waveguide fabricated using 317 nJ pulses and a 500 μm/s translation speed.

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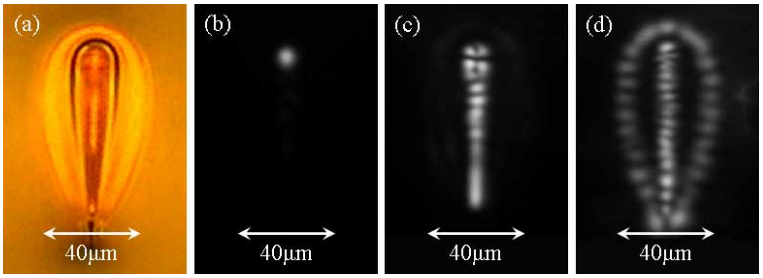

Fig 1. Diagram showing (a) microscope image of waveguide facet, (b) light coupled into the top central region of the waveguide, (c) light coupled into the central elongated region, (d) light coupled into all guiding regions simultaneously. The fabrication beam entered the sample from the top.

Figure 2 shows the experimental setup for continuum generation. The waveguides were pumped by an OPA (model Spectra Physics OPA-800) which was tuned to a central wavelength of 1500 nm. The bandwidth of the OPA was approximately 100 nm at the -15 dB points. The OPA was in turn pumped by a regeneratively amplified Ti:Sapphire laser (Spectra Physics Spitfire) emitting 1 mJ pulses at a repetition rate of 1 kHz with a pulse width of 70 fs. The OPA pump source was linearly polarized, aligned vertically with respect to the waveguide shown in Fig. 1. The output of the OPA was passed through a neutral density (ND) filter wheel and coupled into and out of the waveguide under test using ×10, 0.25 NA microscope objectives. The sample and both objectives were mounted on separate x-y-z translation stages. The output of the waveguide was coupled into a highly multimode silica patch cord (600 µm core) and fed into an Ocean Optics NIR512 near infrared spectrometer covering 850-1700 nm with a resolution of 3 nm. The patch cord was also fed separately into a BWTek BTC500E Mid-infrared spectrometer covering 1700-3000 nm with a resolution of 5 nm.

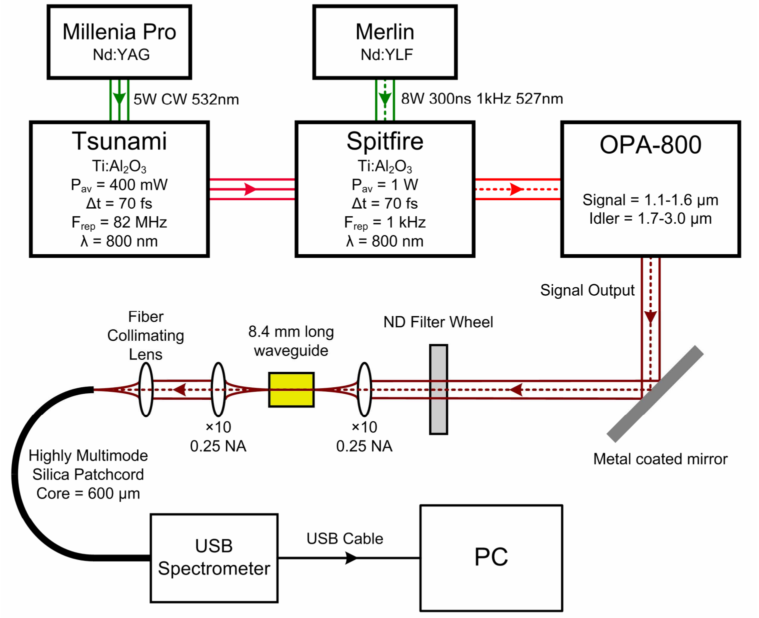

Fig 2. Diagram of experimental setup for continuum generation

Pulse energies of up to 11 µJ (measured before the coupling objective) at a repetition rate of 1 kHz were coupled into the waveguide under test. The broadest continuum was generated by the waveguide fabricated using 317 nJ pulses and a translation speed of 500 µm/s, as shown in Fig. 1. The elongated central guiding region was used (as shown in Fig. 1(c)) as this gave the largest obtained signal and broadest continuum. The obtained continuum spectrum is shown in Fig. 3. It exhibits a -15 dB bandwidth spanning approximately 600 nm from 1320 nm to 1920 nm. The continuum is spectrally smooth, with a maximum peak to peak deviation of ±1.7 dB over the entire -15 dB bandwidth. No degradation was observed in the continuum spectrum over a period of approximately 10 minutes during which the spectrum was captured.

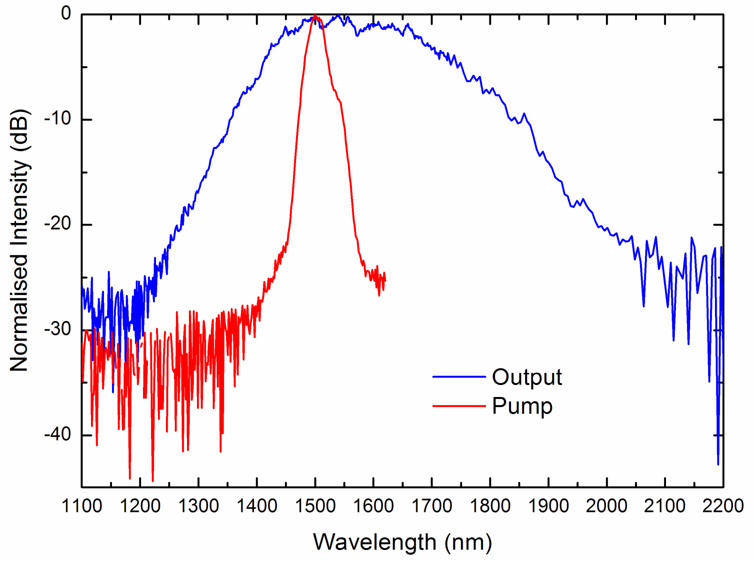

Fig 3. Graph showing supercontinuum and OPA pump spectra

3. Discussion

As the zero dispersion wavelength (ZDW) of chalcogenide glass is well in to the mid infrared, at around 5 µm, we are firmly in the normal dispersion regime. As a result, the primary contribution to spectral broadening is through strong self phase modulation (SPM) along with cross phase modulation (XPM). Pure SPM and XPM lead to strong symmetrical peaks modulating the continuum spectra which are not evident in the spectrum shown here; however the combination of SPM/XPM with normal dispersion leads to significantly smoother spectra [17]. An additional reason for the spectral smoothness may be the highly multimode nature of the waveguide, so that each mode exhibits a different modal area and experiences a different effective nonlinearity and a different degree of broadening. When these spectra are combined at the output of the waveguide, the result is a much smoother spectrum than would be expected for any one individual mode. Interestingly, the central wavelength of the continuum spectrum is also red shifted by 120 nm relative to the pump wavelength, indicating that the broadening is not only due to SPM and XPM but also includes a contribution from Raman scattering. The slope of the Urbach absorption tail in this spectral region is approximately 5×10^{-4} dB/nm for the 8.4 mm long sample. As such, linear absorption has a negligible contribution to the red shift of the spectrum.

Previous studies have shown that the nonlinear refractive index of fused silica is strongly affected by the ultrafast laser inscription process [21]. In particular, it was shown to be strongly dependant upon fabrication parameters, showing a strong decrease as more material modification was induced. This would suggest that using much lower pulse energies to fabricate waveguides may help to preserve the n_2 and thus reduce the required pump pulse energies to generate a significant continuum. Such lower energies could also lead to single-mode guiding, which is useful for many applications. The smaller size of the modified region

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in this case could be increased if necessary by using the multi-scan technique to control the waveguide cross-section [20].

Further improvements could also be achieved by using a glass composition with significantly higher n_2 such as GLS or Ge-As-Se based glasses [1,22]. Another issue is that in the wavelength range used in this experiment, the material has a very strong positive dispersion which could result in rapid temporal broadening of the pulse as it propagates through the waveguide, quickly reducing the peak powers and thus the amount of spectral broadening attained. This could potentially be addressed by controlling the position of the ZDW point through careful waveguide design. Whilst it is desirable to remain in the normal dispersion regime for our application due to enhanced stability of the continuum, moving closer to the ZDW could improve the amount of broadening [18]. The use of a longer waveguide than the 8.4 mm used for these experiments could also dramatically improve performance and reduce the pulse energies required to create continuum radiation.

4. Conclusion

To conclude, we have demonstrated near-infrared supercontinuum generation in an ultrafast-laser inscribed chalcogenide glass waveguide. The supercontinuum radiation was generated using a highly multimode waveguide pumped by an OPA source. A continuum spanning 600 nm from 1320 to 1920 nm was observed, with a relatively smooth spectrum. The waveguides were highly stable over time, as the characterization was carried out approximately one year after fabrication. The source has promising properties for use in OCT.

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