Supercontinuum generation in dispersion engineered highly nonlinear ($\gamma = 10$ /W/m) As_2S_3 chalcogenide planar waveguide

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Abstract: We demonstrate supercontinuum generation in a highly nonlinear As_2S_3 chalcogenide planar waveguide which is dispersion engineered to have anomalous dispersion at near-infrared wavelengths. This waveguide is 60 mm long with a cross-section of 2 µm by 870 nm, resulting in a nonlinear parameter of 10 /W/m and a dispersion of +29 ps/nm/km. Using pulses with a width of 610 fs and peak power of 68 W, we generate supercontinuum with a 30 dB bandwidth of 750 nm, in good agreement with theory.

OCIS codes: (320.6629) Supercontinuum generation ; (230.7390) Waveguides, planar.

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1. Introduction

Supercontinuum (SC) generation is both of fundamental interest and has applications in spectroscopy, medical imaging and broadband sources [1]. Broadband SC generation relies on both strong nonlinearity and anomalous dispersion, which leads to solitonic effects and efficient four-wave mixing (FWM) [2]. Early experiments focused on fiber based geometries, particularly photonic crystal fiber (PCF), in which the dispersion could be engineered due to strong confinement associated with the air-holes [3, 4]. Although strong confinement can be achieved in silica PCF, the low nonlinearity of silica necessitates kilowatt peak powers for SC generation. Recently, efforts have focused on increasing the optical fiber nonlinearity by using nonlinear glasses and this has led to reports of highly nonlinear lead-silicate fibers [5] and bismuth based PCFs [6, 7]. In this context the chalcogenide glass family is particularly attractive as these glasses can have optical nonlinearities several hundred times that of silica, are transparent in the mid-infrared, and are easily drawn into optical fibers. Furthermore, chalcogenide optical fibers have been tapered down to submicron dimensions, further increasing the effective nonlinearity and providing strong dispersion engineering [8, 9].

More recently, planar geometries are being considered for SC sources with the promise of scalable, low cost fabrication and the potential for integrated optical chip solutions. Psaila *et al.* recently reported supercontinuum generation in a laser inscribed chalcogenide waveguide [10]. However, these waveguides have a large effective area giving a low nonlinearity and almost no waveguide dispersion to counter the intrinsic normal material dispersion of the glass. Subsequently, μJ pulses with tens of megawatts peak-powers were required to achieve SC generation. Silicon-on-insulator (SOI) is very attractive for photonic integration and there have been recent efforts to demonstrate SC in SOI nanowires [11, 12]. Silicon offers a high nonlinearity, of similar magnitude to As_2S_3 chalcogenide glass, and exhibits low loss in the near infrared. Furthermore, despite the high normal material dispersion of silicon at near infrared wavelengths, its high refractive index enables strong confinement resulting in anomalous dispersion. However, silicon suffers from two-photon absorption (TPA), which

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clamps the spectral broadening associated with SC generation and limits the achievable bandwidth [11, 13].

In this paper we report broadband SC generation in an As_2S_3 chalcogenide planar waveguide which has been dispersion engineered to shift the zero-dispersion point (ZDP) of the vertically polarized TM mode to 1510 nm. The horizontally polarized TE mode remains in normal dispersion because the waveguide is not fully etched and is much wider than it is high. Short 610 fs pulses at a wavelength of 1550 nm and a peak power of 68 W (corresponding to 60 pJ) were launched into the TM mode resulting in SC spectra with a 30 dB bandwidth of 750 nm, and 60 dB bandwidth greater than an octave – a promising step towards on-chip SC sources. The low TPA and absence of nonlinear loss due to free-carriers, combined with this first demonstration of dispersion engineered waveguides, make chalcogenide an attractive platform for on-chip supercontinuum sources and other nonlinear devices.

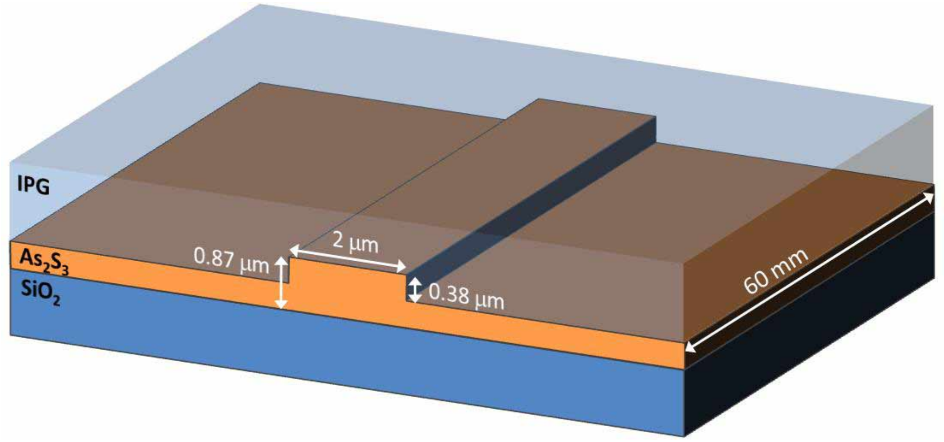

Fig. 1. Schematic of the dispersion engineered As_2S_3 waveguide.

2. Device architecture

The geometry of the As_2S_3 waveguide is illustrated in Fig. 1. Using thermal evaporation, a 0.87 µm layer of As_2S_3 was deposited onto a thermally oxidized silicon substrate. The 2 µm wide, 6.0 cm long waveguides were defined using photolithography and created using inductively coupled plasma reactive ion etching with CHF_3 gas to reduce the slab height by 380 nm [14]. The waveguide chip was then coated in a protective coating layer of inorganic polymer glass (IPG^{TM}). The propagation loss (α) of the waveguide was estimated to be 0.6 dB/cm.

As shown in Fig. 2(a), the dispersion of bulk As_2S_3 is strongly normal at near-infrared wavelengths. However the dispersion experienced by a propagating mode is a combination of both the material properties and the geometry of the waveguide. Reducing the transverse dimensions (height and width) will increase the wavelength-dependence of the mode effective index and can result in anomalous waveguide dispersion. This waveguide dispersion can offset the normal material dispersion to give a total dispersion that is both near zero and anomalous [15]. Dispersion engineering has been used with other high-index, normal-dispersion materials, such as silicon [16] and AlGaAs [17], as well as bismuth [6] and chalcogenide [9] fibers through use use of tapering. Because this waveguide is not fully etched, and because its height is much smaller than its width, the TM polarisation experiences more waveguide dispersion than the TE polarisation. This can be seen in Fig. 2(b) and (c)

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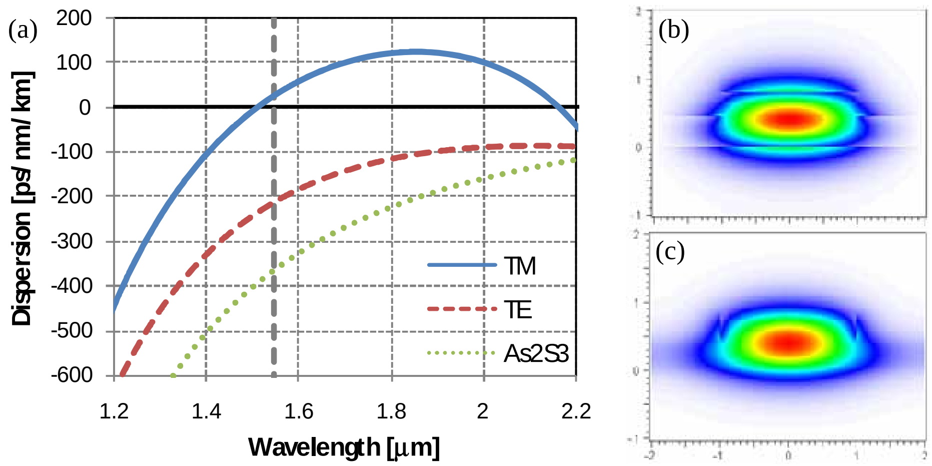

Fig. 2. (a) Dispersion of the As_2S_3 waveguide for both the fundamental TM and TE modes as calculated using RSoft FemSIM, compared to the material dispersion. The vertical dashed line denotes λ = 1550 nm. (b) The mode field for the fundamental TM mode (vertically polarized). (c) The mode field for the fundamental TE mode (horizontally polarized).

since the TM mode interacts with the waveguide boundary much more than the TE mode. Simulations using RSoft FemSIM^{TM}, shown in Fig. 2(a), predict that the TE mode has a reduced dispersion at 1550 nm, in comparison to the material value, but remains normal; whereas the TM mode has low anomalous dispersion.

The reduction in the waveguide's transverse dimensions also enhances the nonlinearity of the mode by reducing the effective area (A_{eff}). Both the TE and TM modes have an A_{eff} of 1.23 μm^2, and combined with the high nonlinear index (n_2) of As_2S_3 at 3.0×10^{-18} m^2/W, results in a nonlinear parameter (γ) of 10 /W/m or 9,100 times the γ of silica SMF fiber.

3. Experimental results and analysis

The experimental layout is shown in Fig. 3. A 10 MHz mode-locked fiber laser produced pulses with a peak power of 136 W. Frequency resolved optical gating (FROG) measurements gave a full-width at half-maximum (FWHM) of 610 fs at the waveguide input. Light was coupled into the waveguide via lensed fibers, achieving a reflection and coupling loss of 3.7 dB per facet. This results in a coupled peak power of 68 W, or ~0.6 mW of average power. A polarization controller (PC) was used to select either the TE or TM modes of the waveguide and the coupled power was varied by moving the lensed fiber further from the input facet. The output light was again collected using a lensed fiber and sent to both a power meter, to monitor the average power difference between data sets, and an optical spectrum analyzer (OSA) to record the output spectra.

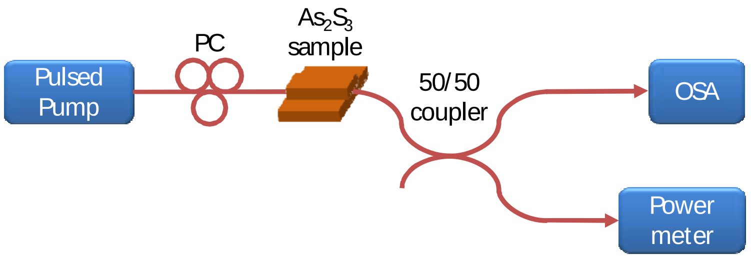

Fig. 3. Experimental set-up for measuring SC generation in the As_2S_3 waveguide. PC is the polarization controller, and OSA is the optical spectrum analyzer

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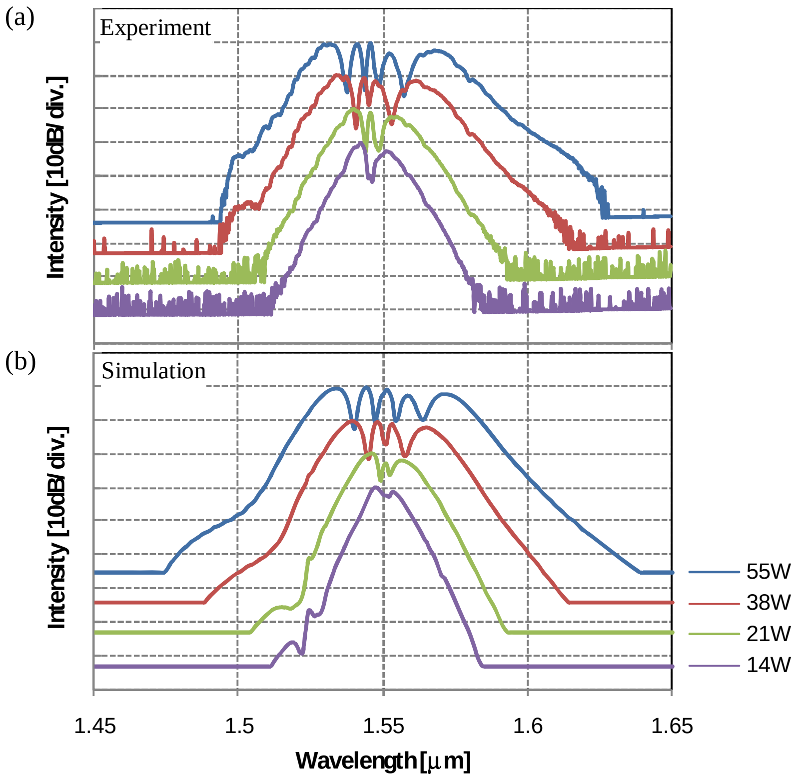

Fig. 4. (a) Experimental SC spectra for pulses of varying peak power coupled into the TE mode of the waveguide. (b) Simulated SC spectra for the same peak powers and polarization mode using the dispersion curves shown in Fig. 2(a).

Fig. 4(a) shows the experimentally measured spectra for TE-polarized pulses at varying input powers. Because the dispersion of this mode is normal, D = –210 ps/nm/km at $\lambda = 1550$ nm, no solitonic behaviour or four wave mixing occurs and the observed spectra are simply broadened by self-phase modulation. This is confirmed by the good agreement obtained between the experiment and simulations using the split-step Fourier method (SSFM) to solve the nonlinear Schrodinger equation – Fig. 4(b). The numerical model includes self-steepening and Raman terms, with the Raman gain spectrum modeled following the results from Li *et al*. [18]. The nonlinear index was taken to be $n_2 = 3.0\times10^{-18}\,\mathrm{m}^2/\mathrm{W}$, with a fractional Raman contribution of $f_R = 0.11$, and the nonlinear (two-photon) absorption coefficient was $\alpha_2 = 6.2\times10^{-15}$ m/W [19]. The input pulse shape and phase was taken directly from the FROG trace.

Although the TE mode remained in the normal dispersion regime, from Fig. 2(a) the TM-polarization is expected to have anomalous dispersion between 1510 nm and 2170 nm, with value +29 ps/nm/km at 1550 nm. The experimental spectra shown in Fig. 5(a) indeed demonstrate that this mode has anomalous dispersion, again supported by SSFM simulations at varying input powers as shown in Fig. 5(b). Note that the OSA used had an upper wavelength limit of 1700 nm, whereas the simulation had no upper limit. Thus, the broadest experimentally measured SC spectrum was over 500 nm wide at -30 dB, while the simulation implies a bandwidth of 750 nm, as shown in Fig. 6(a). The noise floor of the experimental data was below -60 dB, and at this level the simulation shows a SC bandwidth spanning over 1400 nm, or 1.4 octaves.

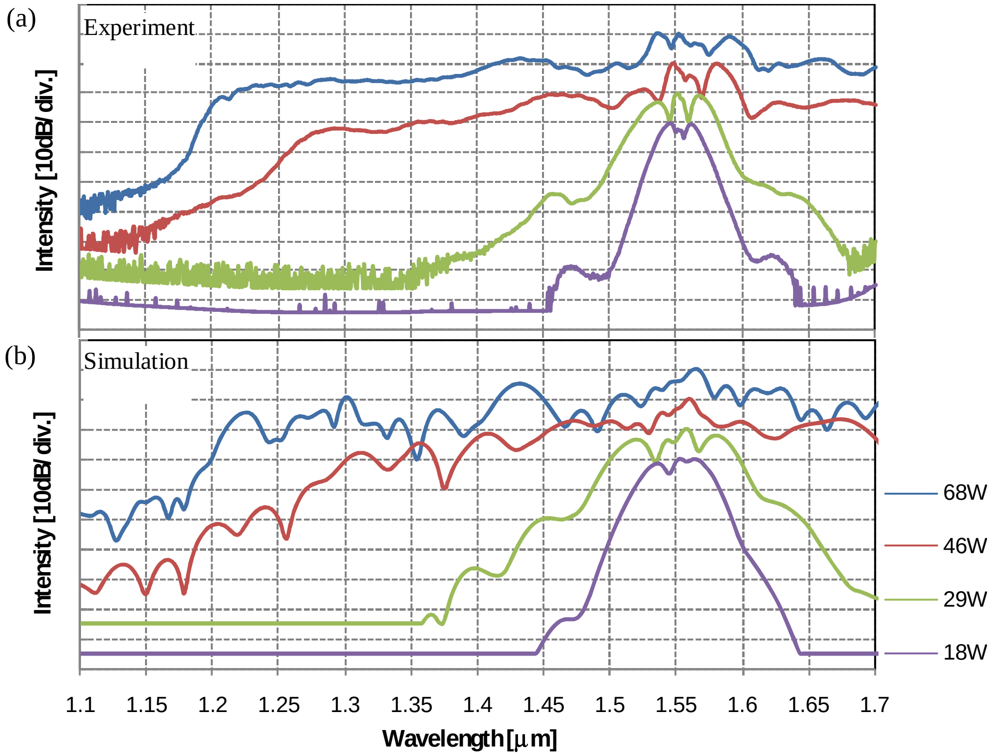

Fig. 5. (a) Experimental SC spectra for pulses of varying peak power coupled into the TM mode of the waveguide. (b) Simulated SC spectra for the same peak powers and polarization mode using the dispersion curves shown in Fig. 2(a).

However, the spectral evolution along the waveguide, shown in Fig. 6(b), has a greater symmetry than is generally observed [1]. This can be explained by the soliton fission length of the experiment. The dispersion length L_D of the TM mode was 2.97 m, and at the highest peak power the nonlinear length L_{NL} was 1.5 mm. This gives a very high soliton number, $N = (L_D/L_{NL})^{1/2}$ – greater than 40 – and a soliton fission length of 67 mm, which is comparible to the device length. Because of this, the primary nonlinear process driving the SC generation is FWM rather than soliton fission. This is supported by the appearance of idler terms, which can be seen after 2 cm of propagation. The apparent assymmetry occurs because FWM is balanced in frequency, and not wavelength; however, Raman scattering does introduce a slight shift of energy toward longer wavelengths.

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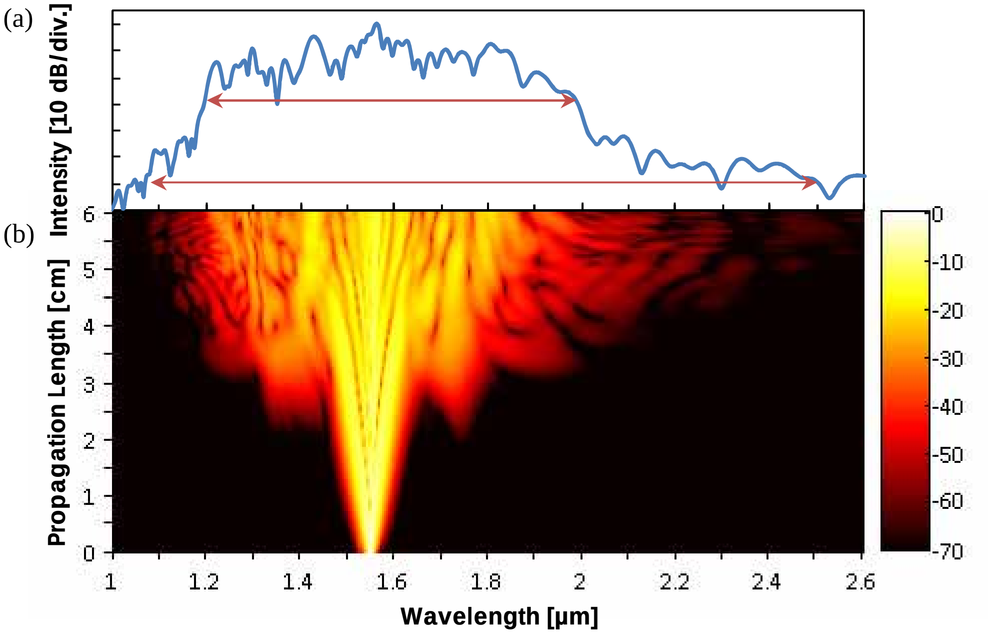

Fig. 6. (a) SC spectrum for an input pulse with 68 W peak power, and (b) Spectral evolution for the same input pulse. The red horizontal lines indicate the -30 dB and -60 dB bandwidths.

4. Conclusion

Highly nonlinear materials such as silicon or chalcogenide glasses are a promising platform for the realization of compact, on-chip SC generation. However, the strong normal dispersion of these materials makes dispersion engineering necessary to achieve the anomalous dispersion needed for four-wave mixing, a key process for efficient SC generation. Here we report, for the first time, the fabrication of an anomalous dispersion chalcogenide planar waveguide, with a dispersion of +29 ps/nm/km and a nonlinear parameter of 10 /W/m. Using this waveguide, we demonstrate broadband SC generation with a -30 dB bandwidth of 750 nm, or a -60 dB bandwidth of over an octave, using a 610 fs pulse with peak power of 68 W and a pulse energy of 60 pJ. This can be compared to a maximum of 0.3 octaves, or 200 nm at a similar wavelength, achieved using 100 fs pulses in a dispersion engineered silicon waveguide [11]. Because of the low TPA and lack of free-carriers in As_2S_3, much high peak powers can be utilized to generate a full SC spectrum, and with further reduction in the effective area of the waveguide this peak power may be reduced while maintaining a comparable SC bandwidth.

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