Stimulated Brillouin scattering amplification in centimeter-long directly written chalcogenide waveguides

Shahar Levy,1 Victor Lyubin,2 Matvei Klebanov,2 Jacob Scheuer,3 and Avi Zadok1,*

1Faculty of Engineering, Bar-Ilan University, Ramat-Gan 52900, Israel
2Department of Physics, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel
3School of Electrical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel

*Corresponding author: Avinoam.Zadok@biu.ac.il

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Stimulated Brillouin scattering (SBS) amplification is obtained in directly written As2Se3 channel waveguides. Centimeter-long waveguides were written using a Ti:sapphire femtosecond laser, operating at a central wavelength of 810 nm. The cross-section of the waveguides was of 4 μm × 1 μm. A Brillouin frequency shift of 7.5 GHz is observed, in general agreement with corresponding previous studies. The SBS gain spectrum in the short waveguides is comparatively broad, with a full width at half-maximum of 200 MHz. We attribute the broad linewidth to the spatial evolution of the electromagnetic field profile along the waveguide. © 2012 Optical Society of America

Chalcogenides (ChGs) are a family of glasses that contain one of the chalcogen elements: S, Se, or Te. They are characterized by a broad transparency window, reaching well into the middle infrared (mid-IR) wavelengths [1], and by pronounced optical nonlinearities. Compared to silica, for example, the nonlinear refractive index of As2Se3 glass is about 1000 times larger [2]. The Brillouin scattering coefficient, which governs the coupling of counter-propagating optical waves via electrostriction, is about 100 times larger in As2Se3 than in silica [3]. ChG glasses are molded into lenses for mid-IR imaging [4], and drawn into fibers that primarily serve for high-power mid-IR beam delivery in medical applications [5]. ChG glass fibers are also used in remote spectroscopic sensing of solutions and gasses [6]. The nonlinear properties of ChG glass fibers make them an attractive platform for all-optical signal processing over relatively short lengths, based on stimulated Brillouin scattering (SBS) [7], stimulated Raman scattering [8], and Kerr nonlinearity [8,9].

Planar waveguides can be defined in thin films of ChG glasses, pre-deposited on different substrates. ChG waveguides can be patterned either through reactive ion beam etching (RIE) [10], or via direct laser-beam lithography [11]. ChG glass waveguides were extensively studied in chip-level all-optical signal processing based on the Kerr effect [2,12], and were employed in chip-level mid-IR spectroscopy [13]. Recently, Pant et al. provided the first demonstrations of SBS in ChG planar waveguides [14–17]. The SBS amplification of probe waves by as much as 16 dB was obtained in 7 cm long waveguides, defined using RIE [14]. A Brillouin frequency shift $\nu_B$ of approximately 7.7 GHz and an amplification bandwidth of 34 MHz were observed [14].

Herein we report the SBS amplification of probe waves in 1 cm long waveguides that are directly written in As2Se3 films. The results provide an independent verification of the previous works in similar devices, fabricated using RIE [14]. While the observed $\nu_B$ is close to the previously reported values [14], the SBS gain spectrum is considerably broader: it consists of more than one peak and its full width at half-maximum (FWHM) is 200 MHz. Possible explanations for the broad gain bandwidth are discussed at the conclusion of this paper.

Films of As2Se3 glass were deposited by thermal evaporation of crushed glassy material from a quartz crucible, in vacuum [18,19]. The evaporation chamber pressure was 2–5 × 10–6 Torr. One-micrometer-thick films were deposited onto silica-on-silicon substrates [see Fig. 1(a)]. The thickness of the silica layer was 2 μm. Centimeter-length waveguides were directly written by irradiation from a femtosecond Ti:sapphire laser,
operating at a central wavelength of 810 nm. The illumination of ChG glasses with an intense light beam at this wavelength range introduces a permanent local increase in the refractive index \[20\], which can be used to form a channel waveguide \[11\] [Fig. 1(b)]. The laser pulses were 200 fs long; their repetition rate was 80 MHz and their average power was attenuated to 3 mW. The laser beam was focused using a microscope objective lens to an intensity of 25 kW/cm\(^2\). During the writing process, the As\(_2\)S\(_3\)-coated samples were translated through the focal point of the beam using a computer-controlled, three-axes piezo-electric stage, at a speed of 4 \(\mu\)m/s. The width of the waveguides was 4 \(\mu\)m. Based on the characterization of similar processes by Zoubir \textit{et al.} \[11\], the accumulated laser fluence was sufficient to saturate the refractive index modifications in the exposed regions. We therefore estimate an index change of 0.08 \[11\] [see Fig. 1(c) for a top view of a waveguide, written in a film that was deposited on a microscope slide].

Light was coupled in and out of the waveguides using tapered fibers [see Fig. 1(d) for the coupling of visible light, used for illustration purposes only]. The mode radius at the tapered fiber output was 2 \(\mu\)m. Simulations suggest a coupling loss of 3.5 dB between the tapered fiber and the waveguide. The measured end-to-end loss of a 1 cm long waveguide at 1550 nm wavelength was 8 dB. Propagation loss is therefore estimated as 1 dB/cm.

Figure 2 shows the experimental setup for SBS amplification measurements. Light from a tunable laser diode, at an optical frequency of \(\nu_0\) in the 1550 nm wavelength range, is split to pump and probe branches. Light in the probe branch undergoes double-sideband suppressed-carrier modulation at a radio frequency of \(\nu \sim \nu_B\). The probe light is then amplified by an erbium-doped power amplifier (EDFA) and coupled into the waveguide under test from the right-hand side. At the output of the waveguide, the lower sideband at frequency of \(\nu_0 - \nu\) is selected by a narrow-band fiber Bragg grating (FBG), whereas the complementary sideband at \(\nu_0 + \nu\) and residual pump back-scatter are rejected. The filtered probe wave is then detected and observed on an oscilloscope. The pump wave is modulated by a semiconductor optical amplifier at a 200 kHz repetition rate with a duty cycle of 10%, and amplified by a second erbium-doped fiber amplifier (EDFA). The peak power of pump pulses is therefore 10 times higher than the average output power of the EDFA. The pump wave is coupled into the waveguide from the left-hand side, and collected at the opposite end for loss monitoring.

SBS amplification of the probe wave as a function of the modulation frequency \(\nu\) is monitored in the following manner. In the absence of SBS amplification, the probe wave at the output of the device is continuous. In the presence of SBS, the probe is amplified during the “on state” of pump pulses, and a 10% duty cycle modulation is imprinted on the output probe (see Fig. 3). Probe power amplification is observed directly in the time domain. This measurement scheme can resolve less than 0.5% gain.

Figure 4 shows the measured SBS power gain as a function of the modulation frequency \(\nu\). The average pump power coupled into the waveguide was 16.5 dBm. The graph shows a clear dependence of gain on frequency. A maximum amplification by 4% is observed at a frequency shift of 7.45 GHz, in close agreement with the previously reported values of 7.7 GHz in etched ChG glass waveguides \[14\]. A second gain peak is observed at a frequency offset of 7.55 GHz, and the FWHM of the overall gain spectrum is rather broad, approximately 200 MHz. For comparison, Pant \textit{et al.} obtain a gain FWHM of \(\sim35\) MHz \[14\], in accord with the corresponding values in ChG glass fibers \[7\].

A possible explanation for the difference between the SBS gain spectrum of Fig. 4 and that of previous studies may have to do with the evolution of optical modes in propagation along the waveguide. Simulations indicate that the waveguide supports multiple propagating modes. Figure 5 shows the transverse profiles of the first- and fourth-order TE modes, obtained using commercial software (COMSOL). Modes of order higher than four do not propagate in the waveguide. Since \(\nu_B\) scales with the modal effective index, multi-mode propagation could
manifest in a multiple peaks in the Brillouin gain spectrum. The effective indices noted in Fig. 5 correspond to an expected separation of 220 MHz between $\nu_B$ values. However, simulations suggest that coupling losses into all high-order modes are 16 dB or worse; hence propagation in multiple guided modes is unlikely to contribute to SBS amplification.

A more probable explanation can be found in the work of Hotate et al., who measured the distributed Brillouin gain spectrum with millimeter resolution along a 50 cm long silica waveguide [21]. Their results indicate a spatial evolution of $\nu_B$ over several centimeters, with variations of tens of megahertz occurring over centimeter-scale lengths [21]. The variations were attributed to the gradual adaptation of the electromagnetic field profile in transition from the input fibers into the waveguide. It is therefore possible that the broad SBS gain spectrum of Fig. 4 represents an effective averaging over a longitudinally varying Brillouin shift.

Modal evolution could also account for the relatively modest maximum gain of Fig. 4. Given a Brillouin gain coefficient of $\beta_B = 0.7 e^{-9 [m/\text{W}]}$ [14], probe power amplification by a factor of 2 was to be expected. However, the broad gain spectrum suggests that SBS amplification for a given $\nu$ is effectively confined to a section that is about six times shorter than the physical length of the waveguide. The expected amplification over such short sections is about 10%.

It is anticipated that SBS amplification in the longer, lower-loss waveguides of [14] was dominated by a region of uniform propagation following the input modal transition. A much stronger gain (16 dB) obtained in the fundamental mode of those devices was likely to overshadow that of higher-order modes or transition regions. While the explanation in terms of optical mode evolution appears plausible, its confirmation requires further study. An alternative mechanism for the spectral broadening could be due to multiple acoustic modes in the sample, each propagating at a different speed of sound [22]. The Brillouin threshold for the devices, estimated as several Watts, could not be reached without facet damage. The expected power of spontaneous Brillouin scattering is on the order of ~80 dBm. Such power levels are much weaker than that of residual pump back-scatter, which leaks through the FPG to the photo-detector.

In conclusion, SBS amplification of probe waves was demonstrated in 1 cm long waveguides, directly written in As$_2$S$_3$ films using femtosecond laser irradiation. To the best of our knowledge, this is only the second independent report of SBS in ChG waveguides, and the first in which the waveguides are directly written. A Brillouin shift of approximately 7.5 GHz was observed, with a maximum gain of about 4%. Pump pulses of 10% duty cycle and an average power of 16.5 dBm were used. The broad gain spectrum, with an FWHM of 200 MHz, is possibly due to the longitudinal evolution of the optical field profiles, together with an overall weak amplification. Ongoing work is dedicated to the fabrication of longer, lower-loss devices in As$_2$S$_3$, and of waveguides in other ChG glasses that are expected to display even more pronounced SBS.

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References