Octave-spanning Supercontinuum From As_2S_3-silica Double-nanospike Waveguide Pumped by Femtosecond Cr:ZnS Laser at 2.35 μm

Nikolai Tolstik[1,2], Shangran Xie[3], Evgeni Sorokin[2], John C. Travers[3], Johann Troles[4], Philip St.J. Russell[3], and Irina T. Sorokina[1]

[1] Department of Physics, Norwegian University of Science and Technology, N-7491 Trondheim, Norway
[2] Institut für Photonik, TU Wien, Gusshausstrasse 27/387, A-1040 Vienna, Austria
[3] Max Planck Institute for the Science of Light, Guenther-Scharowsky Str. 1, 91058 Erlangen, Germany
[4] Université de Rennes I, Sciences Chimiques de Rennes, 35042 Rennes, France
nikolai.tolstik@ntnu.no

Abstract: We generate a 1.2 to 3.6 μm supercontinuum using a As_2S_3-silica double-nanospike waveguide pumped by femtosecond Cr:ZnS laser. Varying the core diameter allows the group velocity dispersion to be fine-tuned, thus maximizing supercontinuum bandwidth.

OCIS codes: 140.4050 Mode locked Lasers; 060.2390 Fiber optics, infrared; 320.6629 Supercontinuum generation

1. Introduction

Supercontinuum (SC) generation has become the most common way to realize sources emitting broad optical spectra. SC sources nowadays find numerous applications including spectroscopy, sensing, microscopy and optical coherence tomography (OCT). The mid-infrared spectral range is particularly important for sensing applications, because of the location of "fingerprints" of different molecules. As_2S_3, as one of the chalcogenides, is a good candidate for SC generation in the mid-IR due to its high nonlinearity and broad transmission window.

A pressure-assisted melt-filling technique for fabricating hybrid waveguides with silica cladding and chalcogenide core was recently introduced [1, 2]. The technique allows realization of chalcogenide waveguides with high refractive index contrast and μm core diameters. High modal confinement in such waveguides increases the effective nonlinearity, while varying the core diameter allows the group velocity dispersion (GVD) to be engineered, thus giving the opportunity to create structures with outstanding potential for SC generation. In order to improve the coupling efficiency into such ultrahigh-NA waveguide structures, a "double-nanospike" structure with inverse nanotapers at both ends of the waveguide has been implemented [3]. By pumping the double-nanospike waveguide with an Er-doped femtosecond fiber laser, an octave-spanning supercontinuum reaching 2.5 μm was demonstrated. In order to fully exploit the broad transparency range of the chalcogenide waveguide, it is beneficial to further red-shift the pump source. Femtosecond Cr:ZnS lasers emitting at 2.4 μm have been extensively developed in recent years, and are now capable of delivering sub-50-fs pulses at watt-level average powers [4]. The aim of the work reported here was to combine both technologies to generate an ultra-broadband supercontinuum in the mid-IR using moderate pump pulse energies.

2. Experimental setup

A schematic view of the double-nanospike structure is shown in Fig.1 (a). The waveguides were produced using a modified pressure-assisted melt-filling technique [3]. Adjusting the waveguide parameters at the fabrication stage, namely d, L_{NS1}, d_{NS1} and L_{NS2}, allows the waveguide GVD to be controlled, together with the near-field mode radii and divergence angles for input and output light. Two different samples, with core diameters (d) 3.2 and 1.3 μm, were used in the experiments. For the 2.35 μm pump wavelength (vertical green dashed line in Fig. 1 (b)) the 3.2 μm sample provided weak anomalous dispersion close to the zero dispersion point, whereas the 1.3 μm sample provided anomalous dispersion and two zero dispersion points on opposite sides of the pump wavelength.

The pump laser was a mode-locked Cr:ZnS laser [5]. The laser setup is shown in Fig. 2a. The laser was pumped by a commercial Er-doped fiber laser, and mode-locking was achieved using a graphene-based saturable absorber mirror. In order to maximize the femtosecond pulse energy and avoid soliton breakup with subsequent pulse doubling (caused by the high third-order optical nonlinearity of the active medium [6]), the active crystal was moved along the cavity axis 2-3 mm away from the point of minimum mode waist. This resulted in 450 mW of average output power at a pulse repetition frequency of 90 MHz, corresponding to a pulse energy of ~5 nJ extracted from the oscillator. To prevent the saturable absorber from degradation the laser was routinely operated at around 3.5 nJ pulse energy.The pulse duration was measured to be ~100 fs (Fig. 2b).

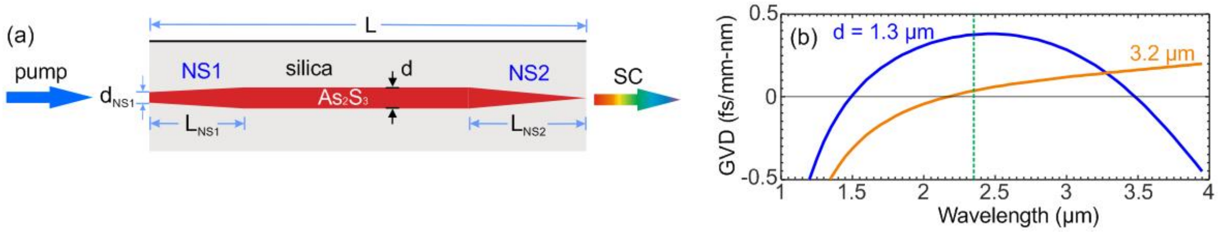

Fig. 1. (a) The schematic view of the double-nanospike As_2S_3-silica hybrid waveguide. (b) Simulated GVD curves for the two values of core diameter used in the experiment.

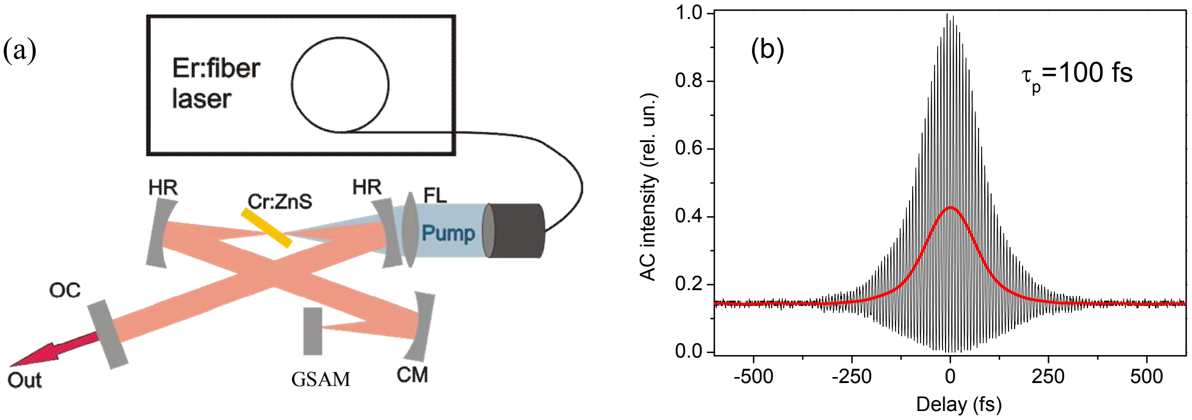

Fig. 2. (a) The schematic view of the femtosecond Cr:ZnS laser setup and (b) interferometric autocorrelation of the laser pulses.

The laser output was isolated using a Faraday rotator, and then a half-wave plate was used to rotate the polarization state, resulting ~1 nJ power energy reaching the waveguide. The laser light was coupled into the waveguide through an AR-coated mid-IR aspheric lens. Another AR-coated aspheric was used to collimate the SC light coupled out of a waveguide. The coupling was adjusted with the aid of an IR camera. The collimated light was delivered to the input of the Fourier transform infrared spectrometer (FTIR) used for the spectral measurements.

3. Results and discussion

Fig. 3 (a) and (c) show the measured SC spectra generated in the two samples at different coupled pulse energies. It can be seen that octave-spanning supercontinua were obtained for both core diameters at a launched pulse energy of ~100 pJ. The broadest supercontinuum, ranging from ~1.2 to ~3.6 μm (–30 dB level), was measured for the 3.2 μm-core waveguide at a maximum launched pulse energy of ~200 pJ. For the 1.3 μm-core sample, a dispersive wave at 4.7 μm was also observed when 70 pJ of pulse energy was launched. We modeled the SC spectral evolution by numerically solving the generalized nonlinear Schrödinger equation in the frequency-domain. The modeled spectra at the output face of both waveguides are plotted in Fig. 3 (b) and (d), and agree very well with experiment. It is worth noting that no optical damage to the As_2S_3 core, nor any spectral instabilities, were observed at these pump energies, indicating that the SC spectrum could potentially be broadened to even longer wavelength by increasing the pump energy as well as optimizing the nanospike design for specific laser beam parameters.

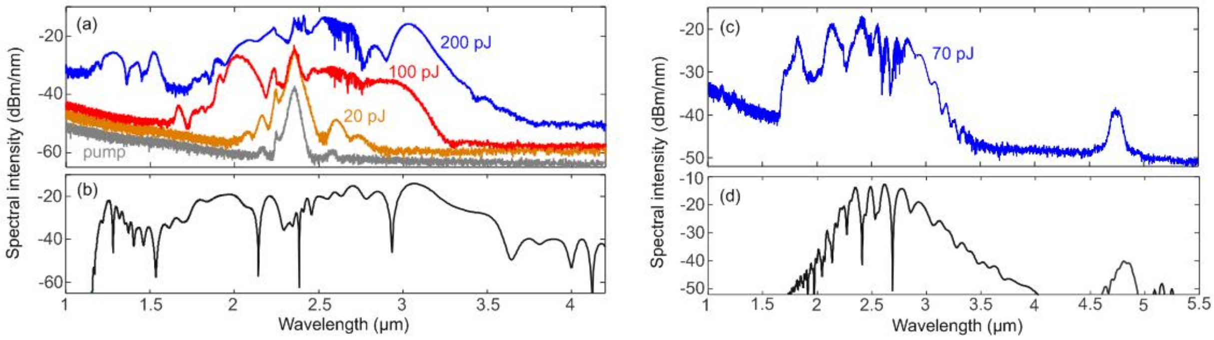

Fig. 3. Measured SC spectra generated by the double-nanospike waveguide at different pump pulse energies for (a) 5-mm-long waveguide with 3.2 µm core diameter and (c) 3-mm-long waveguide with 1.3 µm core diameter. Simulated SC spectrum at the output face of the waveguides with core diameter (b) 3.2 µm and (d) 1.3 µm.

4. Conclusion

In summary, broad supercontinua can be generated in silica-clad As_2S_3-core double-nanospike waveguides by pumping with 100 fs pulses at 2.35 µm from a mode-locked Cr:ZnS laser. A supercontinuum ranging from ~1.2 to ~3.6 µm (–30 dB level) was demonstrated at 200 pJ pump pulse energy. The results could be important for the realization of the first solid-state-laser-based frequency comb in the mid-IR. Further increasing the laser power and the coupling efficiency will result in an even broader supercontinuum spectrum.

Acknowledgements

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