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Supercontinuum generation in Mid-IR using Chalcogenide and Germanate Nonlinear Fiber

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ABSTRACT

We demonstrate mid-infrared (mid-IR) supercontinuum generation with bandwidth from 2 to 2.8 μm at 20 dB below the peak in nonlinear step-index chalcogenide fiber using femtosecond mid-IR pulses directly from the oscillator. We compare the results with a supercontinuum generated in a silica-based high germanium content fiber. Supercontinuum generation occurs at 90 mW of launched average pump power that is equal to the 0.9 nJ pulse energy. The distinctive feature of the obtained supercontinuum is its stability and coherence due to the deterministic supercontinuum generation by the femtosecond pump pulses

Keywords: Supercontinuum generation, mid-IR laser, femtosecond laser, nonlinear optics, fiber optics, chalcogenide fiber, germanate fiber.

1. INTRODUCTION

The supercontinuum generation in fibers has received much attention of researchers since the first works by R. Alfano et al[1] . In the last years particular attention is being devoted to supercontinuum generation in the mid-IR due to its broad applicabity to high-resolution spectroscopy, frequency metrology and trace gas analysis because of the presence of a number of molecular absorption lines. This wavelength range is also interesting for the optical coherence tomography (OCT), since the tissue scattering drastically decreases in the water free region between 2 and 2.5 μm allowing for deeper tissue penetration. On the other hand, the water absorption in the tissue strongly increases above 2.3 μm, allowing using such advanced methods like e.g. differential absorption OCT methods for early identification of the cancerous cells.

Supercontinuum reaching out to 4.3 μm[2] and 6 μm[3] has been demonstrated in fluoride fiber, however these laser systems require either complex multistage nonlinear optical conversion and/or amplification stages. In tellurite fibers supercontinuum generation up to 4.8 μm has been demonstrated[4] using a femtosecond Ti:sapphire-pumped OPO, but this required a microstructured PCF fiber to tune the dispersion and confine the mode to increase the nonlinearity. Using femtosecond pulses directly from an oscillator and a simple step-index single-mode fiber have an advantage of generating a stable coherent supercontinuum, required for such applications as metrology or high-sensitivity spectroscopy. Such continuum has not been yet demonstrated in the mid-IR due to the absence of the corresponding femtosecond sources.

In this work we demonstrate supercontinuum in a conventional (not PCF) step-index chalcogenide fiber, using a recently developed source of high power femtosecond pulses based on Cr:ZnS laser – a high power alternative to Cr:ZnSe – and compare it with the results using germinate-doped silica fiber. Low-noise, smooth spectrum and good coherence of the spectral components makes it useful for numerous applications, in particular for OCT and high-resolution spectroscopy.

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2. EXPERIMENTAL SETUP

2.1 Dispersion measurements

The experimental setup for dispersion measurements of the nonlinear fibers is presented in the Fig. 1. The setup[5] is based on Mach-Zehnder interferometer and consisted of the sample arm with a fiber under test and reference arm with adjustable length varied by the micropositioner. The length of the reference arm was mechanically modulated. The dispersion measurements were performed by equalization of sample and reference arms of the interferometer at the fixed wavelength in the spectral range provided by a broadband light source by obtaining the maximal interference signal. Two different light sources were used in the setup: specially-developed Tm-fiber-based amplified stimulated emission (ASE) source at the wavelength 1.7–2 µm and femtosecond Cr:ZnS laser for the spectral range 2.2–2.4 µm[6]. After the recombination of the beams from both arms, the emission was passed through the monochromator and detected by the sensitive preamplified InGaAs detector. The interference signal was filtered by the selective amplifier, visualized by the oscilloscope and measured by the digital voltmeter.

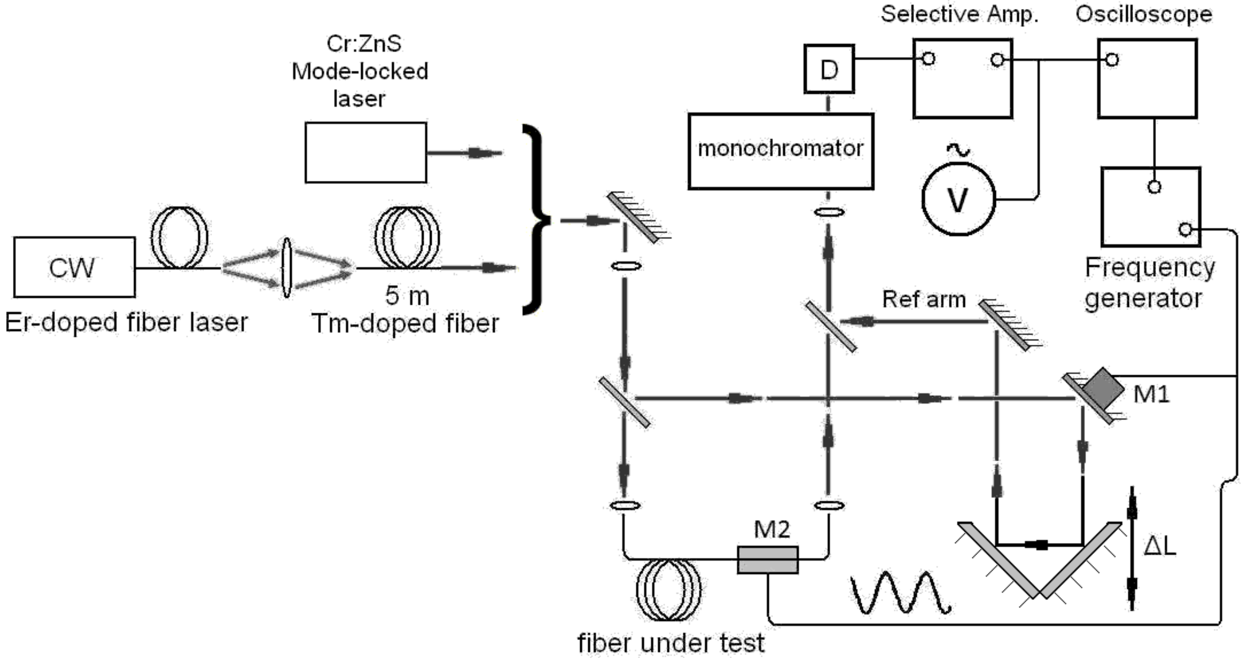

Figure 1. The experimental setup for the dispersion measurements.

2.2 Supercontinuum generation

The experiments for supercontinuum generation were performed in the setup schematically shown in the Fig. 2. Femtosecond Kerr-lens mode-locked Cr:ZnS laser[7, 8] was used as a pump source. The laser provided 69-fs pulses with energy up to 3.8 nJ centered at the wavelength of 2.39 µm. About 90% of the laser emission was delivered to the input of the nonlinear fiber, while the remaining 10% was directed to FTIR spectrometer for the continuous control of the laser parameters. The pulse duration was measured by the custom-made two photon absorption based autocorrelator. For the focusing of the laser emission into the fiber and collimating the fiber output we used the set of antireflection-coated IR aspheric lenses, nevertheless the coupling efficiency was still far from optimum and reached 30%. The fiber input facet was cleaved at the angle of 82° to exclude backreflection to the oscillator. The output pulse energy was measured after the collimating lens and assumed equal to the launched energy.

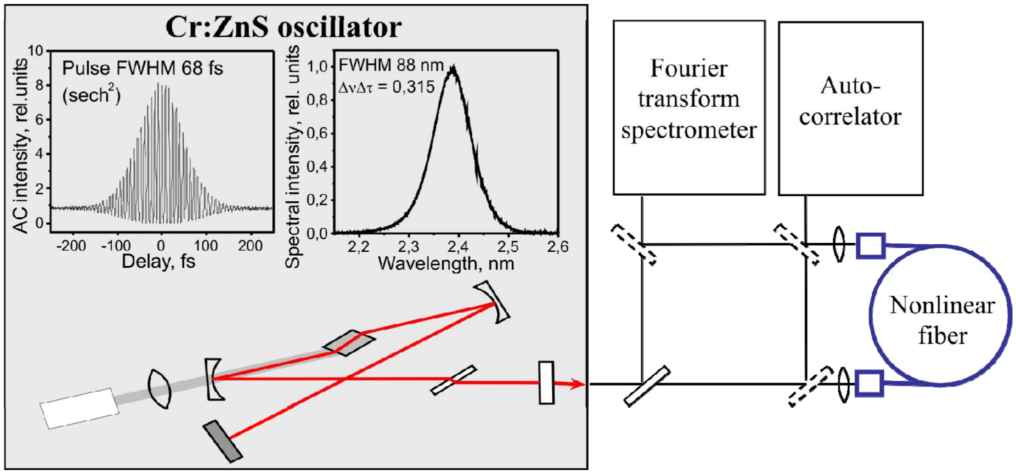

Figure 2. The experimental setup for supercontinuum generation in nonlinear fibers.

Nonlinear fibers used in the experiments were fabricated at Fiber optics research center, Russian Academy of Sciences. The first sample[9] was a silica-based fiber with a highly GeO_2-doped core co-doped with 0.2 wt.% of Tm^{3+}. The core diameter estimated from the draw parameters was approximately 3 µm, numerical aperture 0.49, the core consisted of 55% GeO_2 and 45% SiO_2. In the optical loss spectrum (Fig. 3a) one can clearly see the peaks corresponding to the cut-off frequency at 1.43 µm, thulium absorption band at about 1.6 µm, and phonon-assisted absorption band starting from 2.2 µm.

The second fiber under investigation was a $As_{39.7}S_{60.3}$ chalcogenide fiber[10] with a core diameter of about 9.5 µm. Larger core diameter resulted in an order-of-magnitude bigger mode area, but this is traded against nearly two orders of magnitude higher nonlinear coefficient of $n_2 = 4\cdot10^{-14}$ cm²/W [11]. The optical losses were reported at the level of 0.1–0.3 dB/m at the wavelength of interest (Fig. 3b) [12].

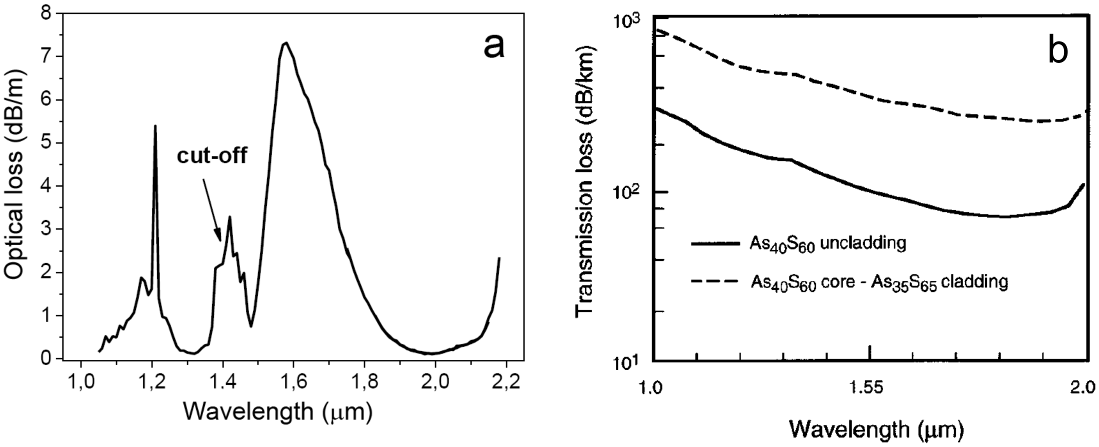

Figure 3. Optical losses reported in the germanate (a) and chalcogenide (b) fibers. Data taken from Ref. [9] and Ref. [12]

3. RESULTS AND DISCUSSION

3.1 Dispersion measurements

The results of the dispersion measurements as well as calculations are plotted in Fig. 4. Zero-dispersion wavelength (ZDW) of germinate fiber was found to be around 2.5 µ making in very promising for the supercontinuum generation in this spectral range. Thin solid lines (Fig. 4a) shows the calculated dispersion for two different core diameters, which value is rather uncertain due to the lack of the direct measurements. Dispersion of the chalcogenide fiber, on the other hand, was found to be normal with a dispersion parameter value of –100 ps/nm·km at the wavelength of 2.4 µm and ZDW located near 4 µm (Fig. 4b).

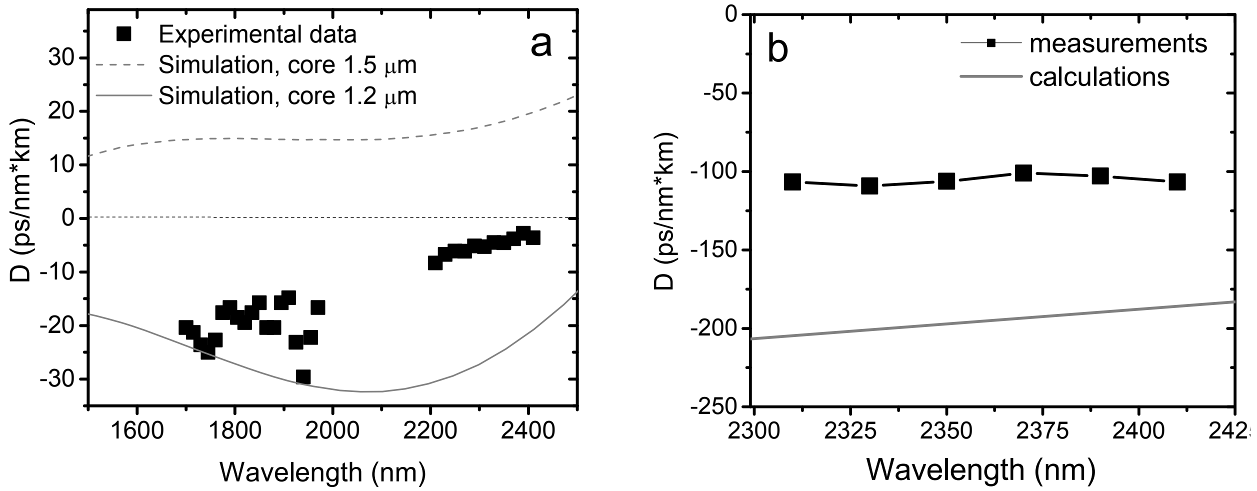

Figure 4. The results of the dispersion parameter measurements and calculations for the germanate fiber (a) and chalcogenide fiber (b).

3.2 Supercontinuum generation

The results of the experiments on supercontinuum generation are presented in the Fig. 5. Apart from the spectrum of the input laser pulse (thick black curve), spectra of emission outcoming of 1.2-m chalcogenide fiber (thin black curve) and 9-cm and 65-cm germanate fibers (grey and red curves, respectively).

As mentioned, the efficiency of laser emission coupling into the fiber was far from optimum. The maximal pulse energy measured at the fiber output was equal to 0.88 nJ for chalcogenide fiber and 0.68 nJ for germinate fiber. Nevertheless, the supercontinuum spectral bandwidth measured at the level of -20 dB reaches 800 nm and 600 nm for the chalcogenide and germinate fiber, respectively. In the spectral region around 2.6 µm the spectra are affected by the distinctive water vapor absorption lines originating from the open-air emission propagation between the fiber and spectrometer. Red wing of the supercontinuum in germanate fiber is also suppressed by the phonon-assisted absorption in silica, this can be clearly seen as the position of the long-wavelength border does not depend on the fiber length, contrary to the position of the short-wavelength border. The shape of the supercontinuum spectrum in germanate fiber is generally modulated due to the self-phase-modulation effect, while supercontinuum in the chalcogenide fiber is stable and maintains clear symmetrical shape, that is advantageous for the spectroscopic applications.

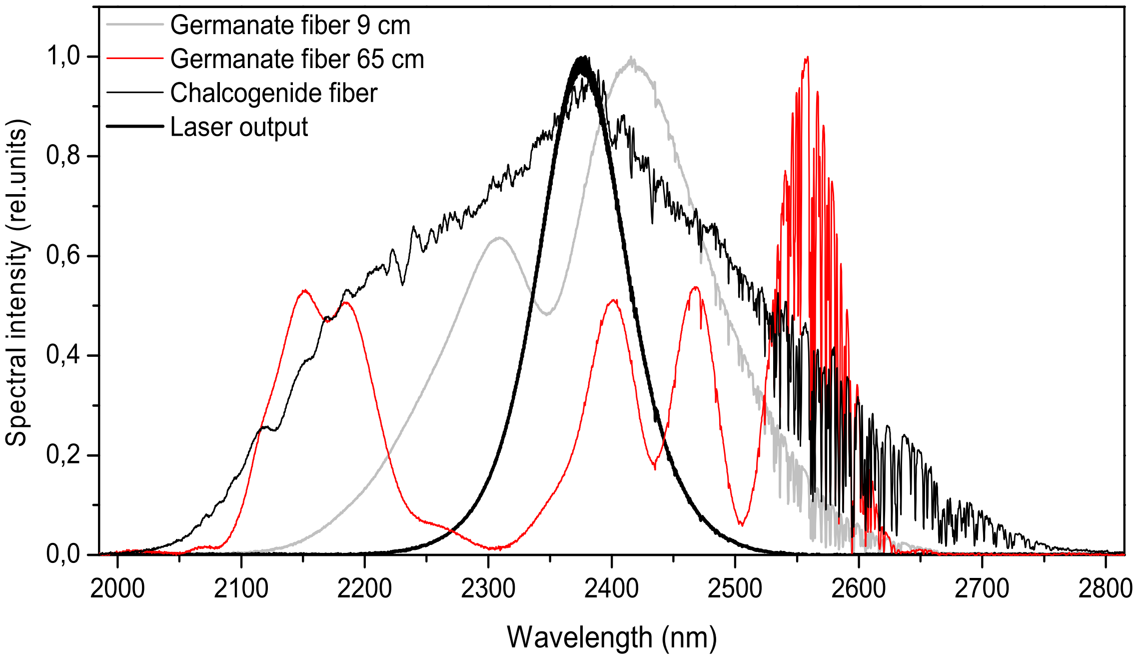

Figure 5. Spectrum put laser pulse (thick black) and the emission outcoming of 1.2-m chalcogenide fiber (thin black), 9-cm (grey) and 65-cm (red) germanate fibers. The noise-like features on the spectra above 2450 nm originate from the atmospheric water vapor absorption lines in the air path after the the fiber and inside the spectrometer.

Chalcogenide fiber is definitely a good candidate for the fiber for supercontinuum generation in the mid-IR. The main limiting factor at the moment is rather high values of the dispersion parameter. Shifting zero-dispersion wavelength closer to the emission line of Cr:ZnS laser will be very important for obtaining the octave-spanning supercontinuum using quite simple femtosecond Cr:ZnS oscillator as a pump source. That could be done by optimizing the core diameter or tapering the fiber[13].

4. CONCLUSION

We have demonstrated for the first time the high quality coherent mid-IR supercontinuum using a simple step-index fiber and a laser pulses directly from the femtosecond Cr:ZnS oscillator. The supercontinuum reaches the bandwidth from 2 to 2.8 µm at 20 dB below the peak level. Optimization of the focusing optics and thus increasing of the launched pulse energy from 1 to 3 nJ, as well as the optimization of the fiber dispersion by controlling its core diameter, will allow generation of a broader supercontinuum reaching well over 3 µm with an ultimate goal of an octave-broad spectrum.

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