Raman soliton generation in microstructured tellurite fiber pumped by hybrid Erbium/Thulium fiber laser system

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Abstract. We demonstrate a fibre laser source generating ultrashort pulses tunable in the range 2-2.5 μm. The source is based on a hybrid Er/Tm fiber laser system and microstructured suspended-core tellurite fiber where Raman soliton shifting occurs. Nonlinear soliton dynamics is studied and possibility of tuning beyond 3 μm is shown.

1. Introduction

Ultrashort fiber laser sources widely tunable in the mid infrared (IR), including sources in the "molecular fingerprint" spectral range of 2-3 μm, are interesting for many applications: molecular spectroscopy, instrumentation, chemical sensing, material processing, ecology monitoring, biomedicine, defense and security. Soliton self-frequency shift (SSFS) in soft-glass fibers is a promising way to develop such sources via nonlinear wavelength conversion [1-3]. Tellurite glasses and fibers offer the advantages of chemical stability, wide transparency range of 0.4 – 5.5 μm, large linear (n > 2) and nonlinear (approximately 20 times higher than for silica glass) refractive indices, moderate melting temperature (280-440°C). A possibility of producing high quality, low loss conventional solid and microstructured tellurite glass fibers has been demonstrated successfully [2-5]. Although zero dispersion wavelength (ZDW) for the majority of tellurite glass compositions is typically beyond 2 μm, microstructured fiber geometry for dispersion management and shifting of ZDW to the range shorter than 1.5 μm can be used. This enables operation in the anomalous dispersion range with conventional Er: fiber or Tm: fiber sources, which is required for SSFS.

In this paper we experimentally and numerically study SSFS in the "molecular fingerprint" spectral range in a self-made microstructured suspended-core tellurite fiber pumped by 150-fs optical pulses at 2 μm from the hybrid Er/Tm:fiber laser source output. Wavelength tunability of the Raman solitons in the 2-2.5 μm range is achieved by pump energy varying. The verified numerical model is used to show Raman soliton shift in the range beyond 3 μm for increased pump energy.

2. Experimental and theoretical results

Figure 1 shows the optical layout of the experimental setup. It is based on a hybrid Er/Tm fiber laser source and the self-made highly nonlinear microstructured suspended-core tellurite fiber. The hybrid

Er/Tm fiber laser source consists of a passive mode-locked Er-doped fiber oscillator at 1.57 µm, Er: fiber amplifier, a silica-based fiber wavelength convertor for pulses tuning up to 2 µm due to SSFS, and Tm: fiber amplifier [6]. The hybrid Er/Tm fiber laser source can generate optical pulses at 2 µm having energy of 4 nJ and duration of 150 fs with a repetition rate of 49 MHz [6]. Suspended-core microstructured fiber with six holes has been produced from TeO_2-WO_3-La_2O_3 (TWL) glass with reduced content of 3d-transition metals and hydroxyl groups impurities by drilled preforms stretching [7]. Optical loss level in the fiber is lower than 1.5 dB/m at wavelengths of 1.1-1.6 µm with minimum of 0.7 dB/m at 1.4 µm and no more than 3.5 dB/m in the range of 1.5-2 µm. The effective core diameter of the fiber is about 3 µm.
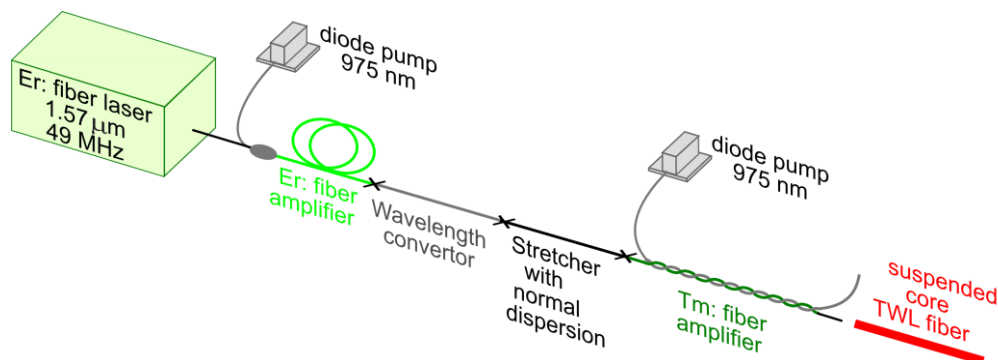
**Figure 1.** The optical layout of the experimental setup

To evaluate dispersion and fundamental mode field distribution of the TWL fiber, we approximate it by axially symmetric tellurite wire waveguides located in air. We applied the standard procedure for finding electric and magnetic field components and wavenumber β of the mode HE_{11} as the exact solution of Maxwell's equation for step index profiles [8]. So, the calculated, group velocity dispersion ($\beta_2 = d^2\beta/d\omega^2$, where ω is the angular frequency), changes from -260 ps^2/km for a signal at 2 µm down to -680 ps^2/km for a signal at 2.5 µm. The estimated nonlinear coefficient is 430 $(W\ km)^{-1}$ and 330 $(W\ km)^{-1}$ for these wavelengths. ZDW is about 1.55 µm.

The pulses from the hybrid Er/Tm fiber source are coupled into a 50-cm piece of TWL fiber located back-to-back. We use relatively long piece of the fiber due to low launched energy (in order of several tens of pJ). The input pulses are located in the anomalous dispersion range, the estimated soliton numbers [9] are N = 1.5 for 30 pJ and N = 2.4 for 80 pJ. So, the nonlinear dynamics associated with up to two solitons formation and their SSFS [9]. Initially we have tuned the coordinates of laser source output and TWL fiber input to maximize SSFS. After that, we have slowly changed their relative positions to waste part energy. This way of energy decreasing in the fundamental mode is very simple and allows us to save temporal and spectral structure of input signal. We obtained SSFS up to 2.5 µm. Figure 2 demonstrates experimentally measured spectra together with sech-approximations of the Raman solitons. Their spectral widths correspond to Fourier transform-limited duration in order of 100 fs.

To model pulse propagation in the TWL fiber, where ultrabroad wavelength conversion is observed, we have employed the numerical model based on the one-way wave equation dealing with the full electric field of light as in our previous paper [10]. We take into account the calculated profiles of dispersion and nonlinear coefficient, an instantaneous Kerr nonlinearity and retired Raman one (as in paper [11]), and the actual optical loss. To integrate the one-way wave equation, we use the split-step Fourier method [9].

The provided numerical simulation confirms that the red-shifted tunable pulses are high-quality sech-shape solitons. A good agreement between experimental and theoretical Raman soliton spectra for varying input energies is achieved. Indeed, the calculated pulses are Fourier transform-limited ones with duration in order of 100 fs (see Fig. 2). The experimentally measured spectral components up to

2.2 µm may correspond to signal which propagates not only in the fundamental mode but also in the cladding or in the higher modes.
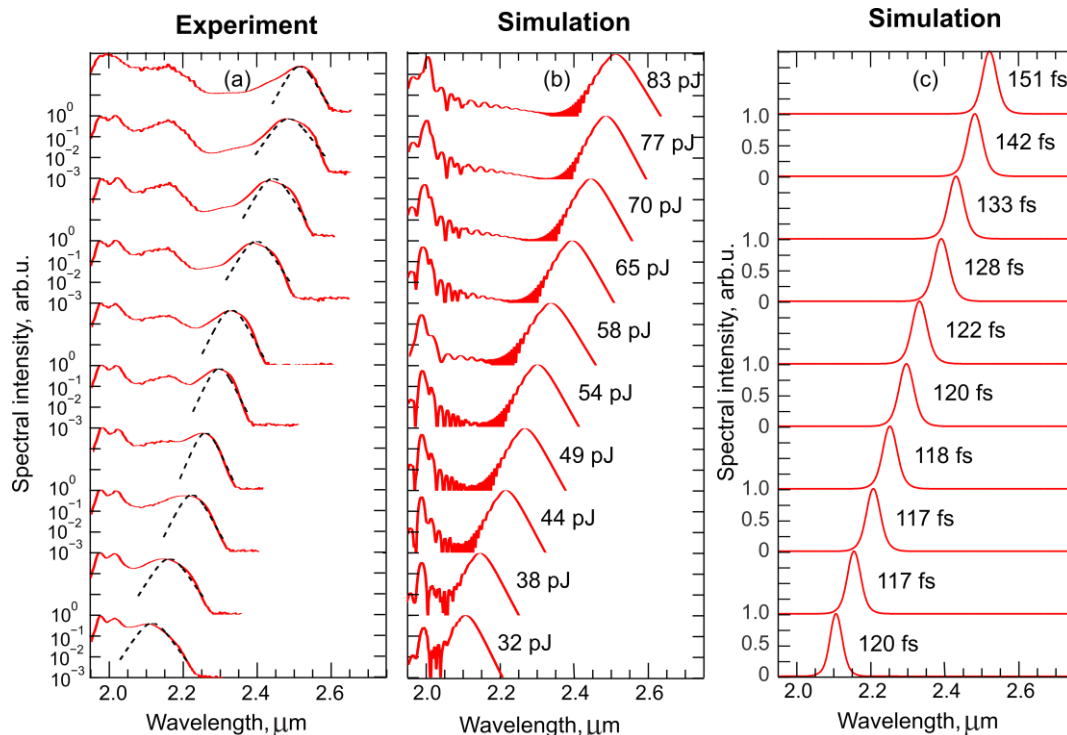
Figure 2. Wavelength tunability of the Raman solitons which is achieved by pump energy varying at the output of 50-cm piece of TWL fiber: (a) experimentally measured spectra together with sech-approximations of the Raman solitons, (b) simulated spectra with represented input energies, (c) filtered Raman soliton spectra with represented pulse durations.

In spite of experimentally reached SSFS in the TWL fiber is up to 2.5 µm with low input energy in order of several tens of pJ, we believe, the developed fiber laser system can be used for Raman soliton obtaining in the spectral range beyond 3 µm. As one can see from Fig. 2, the higher input energy, the longer Raman soliton central wavelength is. So, for spectral range extending, it is necessary to operate with higher energies and shorter fiber pieces (due to mid IR loss). We have simulated propagation of 150-fs pump pulses at 2 µm with increased energies using the verified numerical model. Figure 3 demonstrates the central wavelengths and energies of the most red-shifted solitons vs propagation distance respectively. The SSFS up to 3.6 µm for input energy of 1 nJ is limited by high mid-IR loss and large anomalous group velocity dispersion.
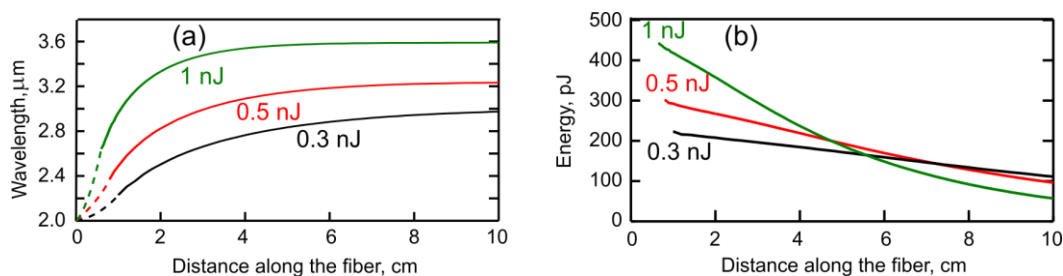
Figure 3. Calculated central wavelengths (a) and energies (b) of the Raman solitons versus propagation distance. The input pump-pulse energies are indicated.

3. Conclusion

The fiber laser source generating high-quality pulses with a spectral sech-shape and Fourier transform-limited duration in order of 100 fs tunable in the range 2-2.5 μm is presented. It is based on Raman soliton self-frequency shifting in the self-made suspended-core microstructured TeO_2-WO_3-La_2O_3 glass fiber pumped by hybrid Er/Tm system. Experimental and theoretical studies, which are in a good agreement, of nonlinear pulse dynamics in the tellurite fiber are demonstrated. The verified numerical model is used to show Raman soliton shift in the range beyond 3 μm for increased pump energy.

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