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Compact all-fiber 2.1-2.7 μm tunable Raman soliton source based on germania-core fiber

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Abstract: Although ultrafast rare-earth-doped fiber lasers mode-locked at near-infrared and ~3 μm wavelengths have been well developed, it is relatively difficult to achieve ultrafast fiber laser emitting in the 2.1-2.7 μm spectral gap between ~2 μm (Tm fiber) and ~2.8 μm (Er or Ho fluoride fiber). In this paper, we report the generation of 2.1-2.7 μm tunable femtosecond Raman solitons from a compact fusion-spliced all-fiber system using a home-made 1.96 μm ultrafast pump source and a MIR-available germania-core fiber. At first, a Tm-doped double-clad fiber amplifier is used to not only boost up the power of 1957 nm femtosecond seed laser, but also to generate the first-order soliton self-frequency shift (SSFS). The first-order Raman solitons can be tuned from 2.036 to 2.152 μm, have a pulse duration of ~480 fs and can reach a pulse energy of 1.07 nJ. The first-order Raman solitons are further injected into a 94 mol.% germania-core fiber to excite the second-order SSFS. The second-order solitons can be tuned to longer wavelengths, i.e. from 2.157 μm up to 2.690 μm. Our work could provide an effective way to develop compact, all-fiber ultrafast MIR laser sources with the continuous wavelength tuning of 2.1-2.7 μm.

1. Introduction

Ultrashort pulse lasers in the mid-infrared (MIR, 2-20 μm) region have attracted increasing attention due to various applications in gas sensing, chemical detection, spectroscopy, military and medical surgery [1–3]. In particular, MIR fiber-based ultrafast lasers possess inherent advantages such as compact structure, high beam quality, and environmental reliability [4]. Mode-locking of rare-earth-doped fiber laser is generally recognized as an effective technique for high-quality ultrashort pulse generation, but they have been limited to a few wavelengths in the MIR, that is ~2.8 μm, ~3.1 μm and 3.5 μm [5,6]. It should be especially noted that there exists a spectral gap (2.1-2.7 μm) between ~2 μm mode-locked Tm-doped fiber (TDF) lasers [7–11] and ~2.8 μm mode-locked Er- or Ho-fiber lasers [12–16]. Therefore, there is always a challenge to exploit ultrafast fiber lasers in the 2.1-2.7 μm MIR region.

Soliton self-frequency shift (SSFS) is an effective way for extending the wavelength of ultrafast laser to MIR by using specialty optical fibers [17], such as chalcogenide fibers [18], tellurite microstructured fiber [2], and fluoride fibers [19–23]. Cheng et al. achieved the MIR Raman soliton (up to 3.4 μm) in the $AsSe_2$-As_2S_5 microstructured fiber [18]. Koptev et al. demonstrated a 2-2.65 μm tunable, Raman soliton source by the SSFS in microstructured TeO_2-WO_3-La_2O_3 glass fiber [2]. Tang et al. reported the generation of 100 fs Raman solitons tunable from 2 to 4.3 μm in InF_3 fluoride fiber [21]. However, these MIR Raman soliton sources based on the soft-glass fibers require bulk optical components with free-space alignments and specific femtosecond laser pumping, precluding all-fiber structure and increasing the system cost. Therefore, there is always strong motivation to develop compact all-fiber Raman soliton source emitting at 2.1-2.7 μm MIR region, by only using a low-cost and easily-accessible pump source.

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Germania-core fibers can offer the opportunity to develop MIR all-fiber ultrafast laser enabling up to ~3 μm [24]. Germanium dioxide (GeO_2) is closely related chemically to silicon dioxide, sharing many properties that make it an excellent material for the manufacture of single-mode fibers and a higher optical nonlinearity [24]. Furthermore, germania-core fiber can be fusion-spliced with standard silica fiber with low loss, guaranteeing the advantage of compact all-fiber MIR system. In recent years, heavily-doped GeO_2 fiber (HDGF) has been employed in the 2-3 μm wavelength range by a few research groups [25–28]. However, almost all of these previous works presented the MIR supercontinuum or multi-color spectrum generation from the HDGFs pumped in near-zero or normal dispersion regime [25,26], and usually required a bandpass filter to select out the desired MIR-wavelength pulses from some dispersive-wave or secondary solitons [27]. Such ultrashort pulses are relatively unstable, and more importantly, the energy transfer to the desired MIR wavelength is significantly reduced. Therefore, more efforts should be made to advance the performance of MIR Raman solitons in terms of spectral purity and stability. Our group developed a high-quality SSFS source by designing a HDGF pumped in the anomalous dispersion regime, but the tunable wavelength of the Raman solitons was restricted to <2.42 μm, due to the relatively high loss at >2.5 μm of the used 64 mol.% GeO_2-doped silica fiber [29]. Most recently, Delahaye et al. reported a HDGF-based all-fiber Raman soliton source by shifting 1.56 μm ultrafast pulses to ~2.9 μm ones. However, their system is complex with three-stage SSFS processes (i.e. 1.56 μm seed pulses →high-power amplification →1.85 μm first-stage SSFS →2.25 μm second-stage SSFS and amplification → ~2.9 μm third-stage SSFS), and they didn't still realized the continuously wavelength tunability of MIR Raman solitons because only few lengths of germania-core fibers were used to obtain different wavelengths [30]. Therefore, it is still desirable to perfectly fill the whole 2.1-2.7 μm spectral gap by compact all-fiber Raman soliton sources with further improving system designs.

In this paper, we propose and demonstrate a 2.1-2.7 μm continuously tunable, HDGF-based all-fiber Raman soliton source with a simpler structure. In our system, a sub-picosecond mode-locked TDF laser operating at 1957 nm was used as a seed source. The seed signal was amplified in a Tm-doped double-clad fiber amplifier (TDFA) where the first-order Raman SSFS was also excited to effectivly generate femtosecond pulses (~480 fs) in the tunable wavelength range of 2.036-2.153 μm. The first-order Raman solitons further pumped a 94 mol.% germania-core fiber to generate the second-order Raman SSFS. The second-order Raman solitons could be continuously tunable from 2.157 to 2.690 μm. Compared with [30], our system by shifting ~2 μm ultrafast pulses to 2.1-2.7 wavelength-tunable Raman solitons is more compact and efficient.

2. Experimental set-up

Figure 1(a) shows the experimental setup of the all-fiber MIR Raman soliton source. The seed source is a home-made TDF laser passively mode-locked by a carbon nanotube saturable absorber. The seed laser centered at 1957 nm delivered sub-picosecond pulses, and was firstly pre-amplified in a Tm/Ho-codoped single-clad fiber amplifier, then launched into the two-cascaded Raman soliton system. A TDFA is used to further boost up the pulse power, and also acts as the first-stage SSFS system. The TDFA consists of a 10 m long double-clad TDF with the 6/125 μm core/inner-clad diameter and a 793/1960 nm combiner together with a 793 nm laser diode (LD). The first-order Raman solitons can be regarded as the pump of the second-stage SSFS in a 94 mol.% germania-core fiber with a core diameter of 6 μm.

As shown in Fig. 1(b), we numerically calculated the material dispersion of the 94 mol.% GeO_2 glass, and the total dispersion (including waveguide dispersion) of the germania-core fiber. The zero-dispersion wavelength of the 94 mol.% germania-core fiber was 1407 nm. The dispersion value of 48 ps/nm/km at our pump wavelength (1957 nm) shows strong anomalous dispersion, manifesting that it is possible to efficiently excite the SSFS for high-quality MIR Raman soliton with our designs [29,31]. Figure 1(c) gives the measured loss spectrum of the

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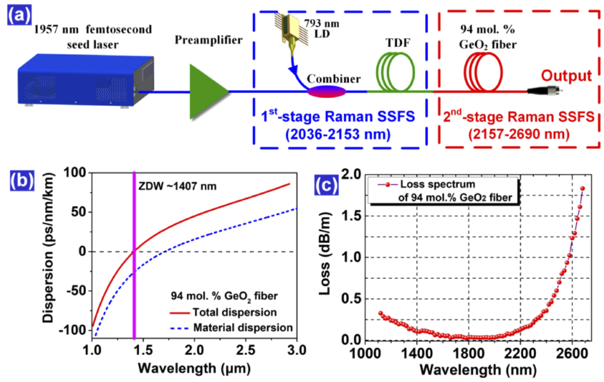

Fig. 1. (a) The schematic of the experimental setup. (b) The material dispersion curve of 94 mol.% GeO_2 glass and the total dispersion curve of the 94 mol.% germania-core fiber, ZDW: zero-dispersion wavelength. (c) The loss spectrum of the 94 mol.% germania-core fiber.

germania-core fiber. Benefiting from the very high dopant of 94 mol.% GeO_2, the fiber shows a relatively low loss (e.g. 0.3 dB/m @2.4 μm, 1.8 dB/m @2.7 μm) in the MIR region, implying that the SSFS in the fiber could extend to longer MIR wavelength. The whole system is constructed by directly fusion-splicing, maintaining the compact all-fiber structure. In our experiment, the optical spectrum was measured by an optical spectrum analyzer (Thorlabs, OSA205C), and the ultrafast pulses were monitored by a 12.5 GHz photodetector (<2.3 μm wavelength) or a 250 MHz photodetector (2.2-4 μm) together with a 40 GS/s real-time oscilloscope.

3. Experimental results and discussion

To begin with, we recorded the characteristics of the 1957 nm mode-locked seed laser. As shown in Fig. 2(a), the mode-locked optical spectrum centered at 1956.7 nm has a 5.4 nm full width at half maximum (FWHM). The output spectrum has the typical feature of soliton spectrum with obvious symmetrical Kelly sidebands [32], indicating a stable mode-locking state in anomalous dispersion regime [33,34]. The typical oscilloscope trace of the mode-locked pulses is described in Fig. 2(b). The pulse repetition rate is 35.305 MHz (corresponding to the pulse period of 28.33 ns), and no significant intensity fluctuation was observed, further confirming the excellent stability of our seed laser. We also measured the pulse duration with a home-built autocorrelation system. As plotted in the inset of Fig. 2(b), the experimental data can be well fitted by a sech^2 pulse shape. The pulse duration (1/1.763 of the FWHM pulse duration) [35] is 980 fs, and the time-bandwidth product is calculated to be 0.41, revealing near-transform-limited pulses. The average output power of the 1957 nm seed laser is 1.4 mW, and was pre-amplified up to 18.7 mW. The spectrum shape and the pulses after the pre-amplifier remained almost unchanged, showing a 3-dB bandwidth of 5.1 nm and a pulse duration of 1.2 ps.

The 1957 nm pre-amplified ultrafast pulses were then injected into the first-stage SSFS system (i.e. the double-clad TDFA). The small core and the 10 m length of the Tm-doped double-clad fiber used in the TDFA can accumulate enough nonlinearity to effectively excite SSFS effect. Figure 3(a) shows the evolution of the output spectrum of the first-order Raman solitons. As the 793 nm pump power of the TDFA increased from 1.45 to 1.57 W, the center wavelength of the first-order Raman solitons could be continuously tuned from 2036 to 2153 nm. One can easily distinguish the new spectral component (i.e. Raman soliton), and the solitons can rapidly shift out the Tm^{3+} gain band owing to the SSFS effect. Interestingly, there was no residual 1957 nm light in the output spectra [Fig. 3(a)], indicating that the 1957 nm seed pulses were efficiently transferred to the Raman solitons. Moreover, the Raman-soliton spectrum includes no (or weak)

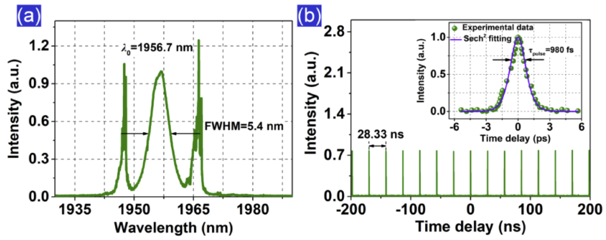

Fig. 2. 1957 nm sub-picosecond seed laser. (a) Optical spectrum. (b) Typical oscilloscope traces. Inset: the measured autocorrelation trace.

ASE emission because no spectral intensity can be observed at the ASE peak of ~2025 nm. At the pump power of 1.57 W, we investigated in details the output characteristics of the first-order Raman solitons. As seen in Fig. 3(b), the interval of the first-order Raman solitons remains 28.33 ns, which is same as the period of the 1957 nm seed pulses [Fig. 2(b)]. Figure 3(c) gives the measured autocorrelation trace of the first-order Raman soliton. Both the autocorrelation trace [Fig. 3(c)] and the optical spectrum [the bottom of Fig. 3(a)] can be well fitted with sech^2 profiles, which is typical soliton feature. The first-order Raman soliton has a spectral bandwidth of 39.0 nm at the central wavelength of 2153 nm and a pulse duration of 480 fs. Figure 3(d) shows the RF output spectrum with a wide frequency span of 3 GHz, and no RF spectral modulation manifests the stable operation of the first-order Raman solitons. Furthermore, as plotted in Fig. 3(e), we also measured the average output power of the first-order Raman solitons as a function of the pump power. The maximum power is 37.5 mW corresponding to the pulse energy of 1.07 nJ. Taking into account the chromatic dispersion and the effective area of the double-clad TDF, the 1.07 nJ energy reveals the fundamental soliton from the condition for soliton existence. The slope conversion efficiency was ~15.3% by linear fitting. The low efficiency of the amplifier system is mainly attributed to the facts: 1) due to SSFS in the TDFA, the soliton is quickly going out of the Tm^{3+} gain bandwidth as it propagates and it cannot be amplified further, 2) the thulium doped fiber used in the amplifier is somewhat long, allowing the possibility of reabsorption.

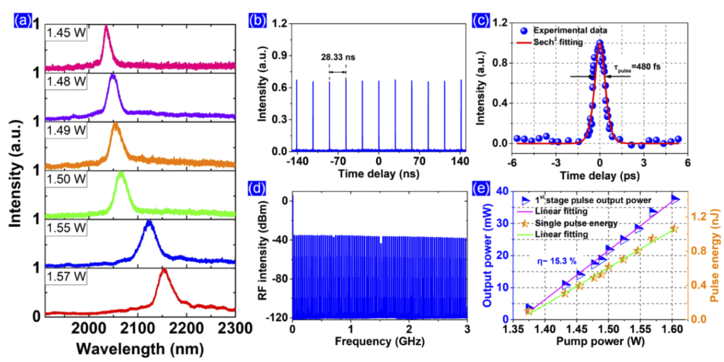

Fig. 3. (a) The spectral evolution of the first-stage Raman solitons as the 793 nm pump power increased. (b) Typical oscilloscope traces at the pump power of 1.57 W. (c) Corresponding pulse duration. (d) The RF spectrum with a span of 3 GHz. (e) The average output power and pulse energy as a function of the 793 nm pump power for the first-stage Roman solitons.

In order to further extend the wavelength of Raman solitons, the 2036-2153 nm first-order Raman solitons were launched as pump pulses into a piece of 94 mol.% germania-core fiber for the second-stage Raman soliton generation. When 0.5 m- and 2 m-long germania-core fibers were used in our experiments, we observed the second-order SSFS processes in Figs. 4(a) and

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4(b), respectively. The output spectrum of the cascaded Raman solitons from the 0.5 m-long germania-core fiber can be tuned from 2215 to 2608 nm [Fig. 4(a)]. Comparatively, the 2 m-long germania-core fiber can achieve a wider tuning range of 2156.8 to 2690.4 nm [Fig. 4(b)], which should be attributed to the fact that the longer fiber can accumulate more nonlinearity to shift the Raman solitons into longer wavelength [35]. Interestingly, the output spectra always kept single-color Raman-soliton envelope without the appearance of secondary soliton. Namely, the high-purity MIR Raman solitons were achieved in our experiment by pumping the germania-core fiber in the strong anomalous dispersion regime (instead of the near-zero or normal dispersion regime used in [25-28]). In addition, once the soliton wavelength is beyond 2.53 μm, the strong fringes in the output spectral envelope [Figs. 4(a) and 4(b)] can be easily observed. The spectral positions of the different fringes under different pump powers were fixed , without moving as the soliton spectrum shifting. Thus, they should be attributed to the water-vapor absorption peaks around ~2.7 μm during the spectrum measurement in the used OSA [36].

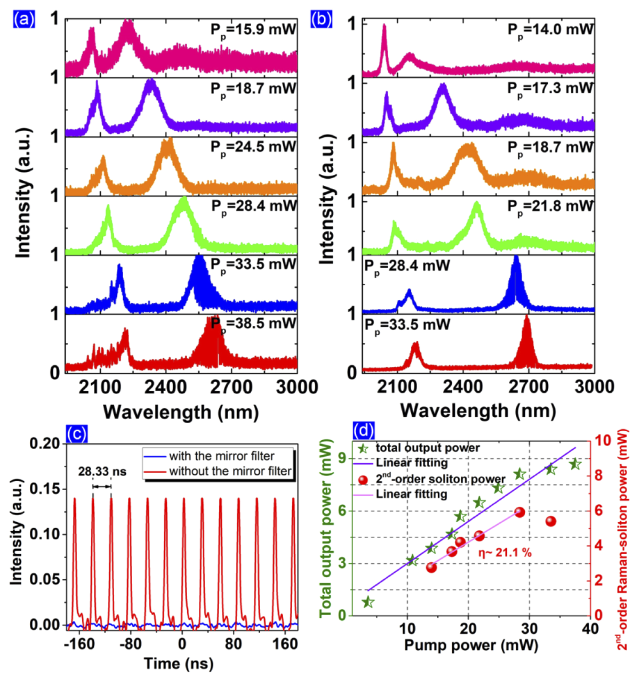

Fig. 4. The spectral evolution of the second-stage cascaded Raman solitons with (a) a 0.5 m-long HDGF and (b) a 2 m-long HDGF. (c) The typical oscilloscope traces of optical pulses at the pump power of 33.5 mW with and without the mirror filter. (d) The total average output power and the second-order Raman soliton power as a function of the pump power.

To clearly understand the second-stage SSFS process in the 2 m germania-core fiber, we filter out the second-order Raman solitons from the total output power using a dielectric-coated mirror with a highly reflective waveband of 2.5-3 μm wavelength. Figure 4(c) gives the oscilloscope traces of the second-order Raman solitons at the pump power of 33.5 mW without (red line) and with (blue line) the dielectric-coated reflective mirror, respectively. The pulse intensity with the mirror filter is much weaker than that without the mirror filter, indicating that the second-order Raman soliton at >2.5 μm wavelength is predominant in the total output. The pulse-to-pulse interval of the second-order Raman solitons is still 28.33 ns, implying the stable and pure Raman-soliton conversion without supercontinuum generation. Figure 4(d) plots the total output power and the only second-order Raman-soliton power as a function of the pump

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power (i.e. the first-order Raman-soliton power). The real conversion efficiency is only ~21.1%. This should be attributed to the facts: 1) the considerable loss (e.g. ~4 dB loss at 2.7 μm) of the 2 m-long germania-core fiber, 2) the quantum defect during the SSFS, and 3) the water-vapor absorption to >2.53 μm second-order Raman solitons in the air. The maximum power of the second-order Raman solitons is ~6 mW with the pulse energy of ~0.18 nJ. The output power has a significant saturation when the pump power is more than 30 mW, because in this case the second-order Raman-soliton wavelength is beyond 2.55 μm [see Fig. 4(b)] and falls into the sharp increasing loss of the germania-core fiber and the water-vapor absorption band. Finally, we tried to directly measure the pulse duration of the second-order Raman solitons, but unfortunately the operating wavelength of our home-built autocorrelator is limited to <2.4 μm. However, the pulse duration can be conservatively estimated to be <480 fs, because the SSFS process normally compresses the pump pulses. Moreover, considering the large spectral bandwidth of 52 nm centered at 2690.4 nm and assuming a time-bandwidth product of 0.315, the pulse duration of the second-order Raman solitons can be optimistically estimated to be 146 fs.

4. Conclusion

In summary, we reported the generation of 2.1-2.7 μm tunable Raman solitons in a compact all-fiber laser system. The system consisted of a 1957 nm sub-picosecond seed laser, a double-clad TDFA as the first-order SSFS stage and a 94 mol.% germania-core fiber as the second-order SSFS stage. We obtained the first-order Raman solitons with a 39.0 nm spectral bandwidth at 2153 nm, 480 fs pulse duration and 1.07 nJ pulse energy. By combining the advantages of both the cascaded pumping scheme and the MIR germania-core fiber, stable and high-purity Raman solitons with the continuously tunable range of 2157-2690 nm have been achieved. The second-order Raman solitons show a large spectral bandwidth of 52 nm and an estimated duration of 146 fs. This work may pave a path towards compact and high-performance MIR ultrafast fiber laser sources fully covering the spectral gap of 2.1-2.7 μm.

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