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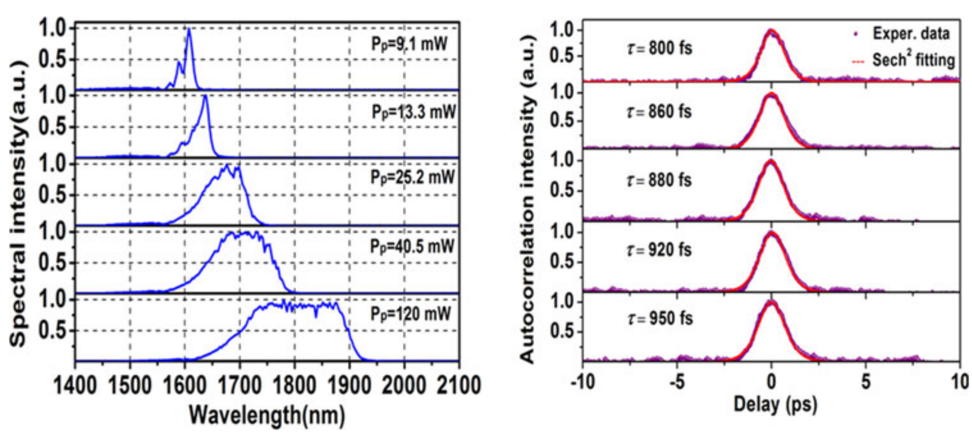

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1.61–1.85 μm Tunable All-Fiber Raman Soliton Source Using a Phosphor-Doped Fiber Pumped by 1.56 μm Dissipative Solitons

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Abstract: We demonstrate soliton self-frequency shift (SSFS) of more than 15.5% of the optical frequency in a phosphor-doped silica fiber for the first time. This fiber shows great potential for supporting Raman-shift solitons above 1.8 μm with a 1.56 μm pumping, which is superior to the SSFS previously reported in conventional single-mode silica fiber. In our experiment, when the amplified dissipative-soliton pulses at 1.56 μm are injected into a 960 m phosphor-doped silica fiber, SSFS is efficiently initiated, and the output spectrum of Raman solitons can be continuously tuned from 1.61 to 1.85 μm. The Raman solitons have the shortest pulse duration of ∼800 fs and the pulse energy of ∼1 nJ. This 1.61–1.85 μm ultrashort laser source can not only fill in the spectral gap between Er^{3+} and Tm^{3+} emissions but has potential applications in multiphoton microscopy and optical tomography as well.

Index Terms: Fiber laser, ultrafast laser, Raman soliton, soliton self-frequency shift.

1. Introduction

Ultrashort pulse fiber lasers have found many applications, including biomedicine, microscopy, material processing, spectroscopy, and scientific research. In particular, because most of bio-tissues have the lower scattering loss and the low water-absorption in ∼1.7 μm spectral region, optical coherence tomography and multiphoton microscopy usually require ultrashort pulse sources operating at 1.7–1.8 μm wavelength [1], which can significantly increase both the penetration depth and resolution. For the past two decades, the great efforts have been made to develop ultrafast fiber lasers in 1–2 μm near-infrared region, but most ultrafast fiber lasers have been just focused

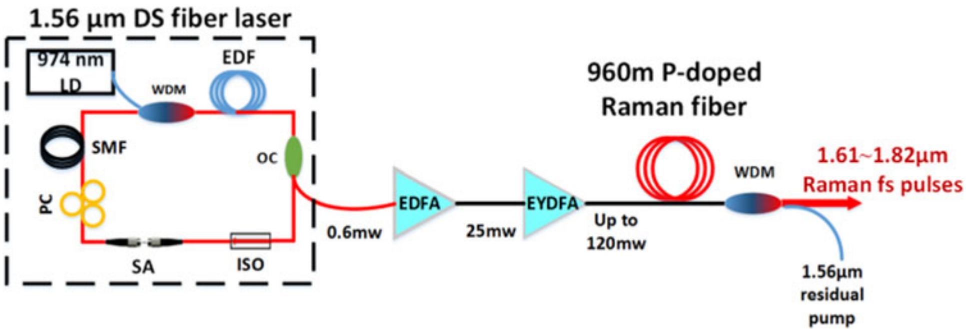

Fig. 1. Experimental setup of 1.61–1.85 μm tunable Raman soliton source. LD: laser diode, WDM: wavelength division multiplexer, EDF: erbium-doped fiber, OC: optical coupler, ISO: optical isolator, SA: saturable absorber, PC: polarization controller.

on the 1, 1.5, and 2 μm wavelengths, mainly implemented by the conventional rare-earth-doped (Yb^{3+}, Er^{3+}, Tm^{3+}) silica fibers [2]–[8]. Unfortunately, the desired wavelength ($\sim$1.7μm) falls right into the spectral gap between Er^{3+} and Tm^{3+} emissions, and untill now, $\sim$1.7 μm the ultrashort pulse fiber laser has been not exploited fully. Therefore, there always are strong motivations to develop $\sim$1.7 μm ultrashort pulse fiber lasers.

Soliton self-frequency shift (SSFS) in an optical fiber is a significant phenomenon in which intra-pulse Raman gain can amplify the low-frequency spectral component of the soliton pulse using the high-frequency spectral component as a Raman pump [9]. The process can cause a continuous redshift in the soliton spectrum, and therefore the SSFS is often used to obtain wavelength-tunable, high-quality ultrafast laser sources in new spectral regions [10]–[13]. Since the first observation of the SSFS in optical fiber in 1986 [14], SSFS has been widely investigated by employing various kinds of fibers, including standard single-mode silica fibers (SMFs) [16]–[18], microstructured optical fibers (MOFs) [10], [11], [19] and higher order mode fibers (HOMFs) [12]. Very recently, the SSFS in fluoride or chalcogenide soft-glass fiber has been even explored for 2.0-4.3 μm MIR ultrashort pulses [13], [20]–[22]. In general, the MOFs and HOMFs were typically used to extend the accessible region of the SSFS down to the near-IR ($<$1.3 μm [12]) and visible wavelengths [10]. The conventional SMFs were often used to generate the $\sim$1.7 μm SSFS pumped at the 1.55 μm [16]–[18]. However, it should be noted that the SSFS in the silica SMFs pumped by $\sim$1.55 μm ultrafast lasers is mostly limited in $<$1.7 μm wavelength [17], [18], due to the relatively smaller Raman frequency shift (13.2 THz) from SiO_2. Such SSFS in the silica SMFs could not adequately cover the desired spectral region of $\sim$1.7–1.8 μm for applications in multiphoton microscopy and optical coherence tomography [1]. Using an external Raman pump to increase the Raman gain bandwidth, Chestnut and Taylor have successfully extended the SSFS in a silica SMF to 1.72 μm wavelength [23]. Considering this work [23], one could further ask whether a larger Raman-shift fiber can also extend the SSFS to longer wavelength. If yes, phosphor-doped fiber could be very interesting to extend the SSFS into 1.7–1.9 μm spectral region under a $\sim$1.55 μm pumping, because this fiber has a very large Raman frequency shift of 40 THz [24], [25].

Based on the above-mentioned incentives, we experimentally investigated the spectral extension of the SSFS in phosphor-doped silica fiber. In this work, 1.61–1.85 μm tunable femtosecond pulses were successfully achieved using the SSFS in a 960-m phosphor-doped fiber pumped by a 1.56 μm picosecond dissipative-soliton (DS) source.

2. Experimental Designs and Principles

The experimental setup for observing the SSFS in the phosphor-doped silica fiber is shown in Fig. 1. A home-made mode-locked Er-doped fiber laser with a carbon-nanotube saturable absorber was used as pump seed. As given in Fig. 2(a), the mode-locked laser had the center wavelength of $\sim$1.56 μm with a 20 nm linewidth, and delivered the DS pulses at the repetition rate of

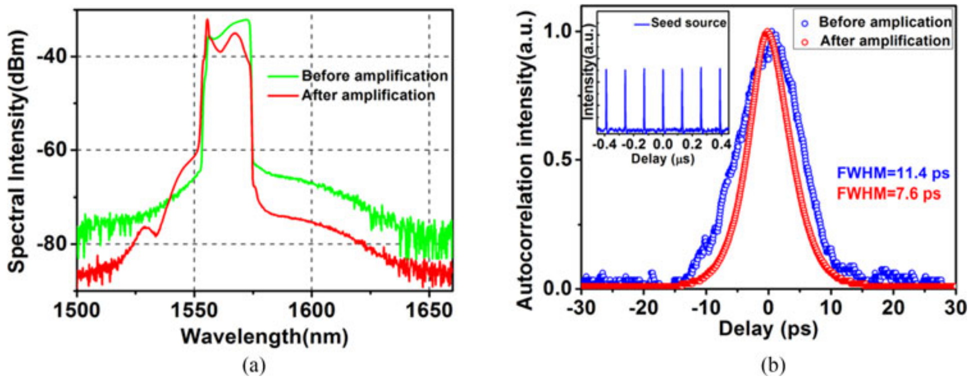

Fig. 2. (a) Optical spectra of the 1.56 μm DS pump source before and after amplification, respectively. (b) Autocorrelation traces of the 1.56 μm DS pump source before and after amplification (Inset) Typical pulse train.

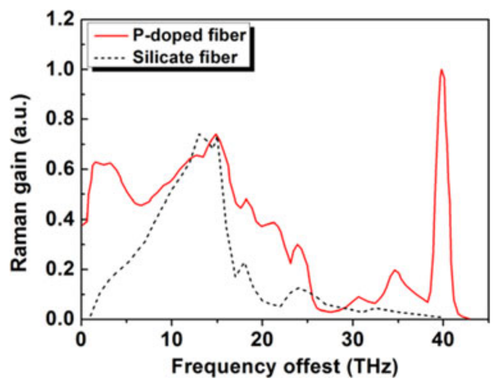

Fig. 3. Raman spectra of the phosphor-doped fiber (solid) and the conventional silica fiber (dash), respectively.

7.719 MHz [see the inset of Fig. 2(b)]. Compared with the conventional solitons, this DS with the large chirp is favorable to high-efficiency amplification. The pump seed with the average power of 0.6 mW was firstly pre-amplified by an Er-doped fiber amplifier (EDFA), and further amplified by an Er/Yb-codoped double-clad fiber amplifier (EYDFA). The total average power can be eventually boosted up to 120 mW. The optical spectra before and after amplification didn't obviously change, as seen in Fig. 2(a). As shown in Fig. 2(b), the pulse duration before and after amplification is 11.4 ps and 7.6 ps, respectively. Therefore, the amplified DS pulses had the maximum peak power of ~2.2 kW, and the large time-bandwidth product of ~19 (i.e. strong positive chirp). In our experiment, a 960 m phosphor-doped silica fiber (also usually as Raman fiber [24], [25]) was used for exciting the SSFS. This fiber with the core/cladding diameter of 4/125 μm has the cut-off wavelength of ~1000 nm, the zero-dispersion wavelength of about 1270 nm and the loss coefficients of ~1 dB/km at 1064 nm. The 1.56 μm pumping wavelength locates in the strong anomalous dispersion region of the phosphor-doped fiber, which is very favorable to form the SSFS. We also measured the Raman spectrum of the phosphor-doped fiber [24], as given in Fig. 3. Meanwhile, for comparison purpose, we also place the Raman spectrum of the conventional silica fiber in Fig. 3. The Raman spectrum of the phosphor-doped fiber has two dominant Raman shifts at the 1-25 THz and 40 THz, which are assigned to the frequency shifts of SiO_2/GeO_2 and P_2O_5, respectively. The Raman gain coefficients of the two peaks are about 0.8×10^{-3} and 1.3×10^{-3} $W^{-1}\cdot m^{-1}$. Moreover, the nonlinear refractive index of the fiber is about 2.5×10^{-20} m^2/W, similar to that of the standard silica SMF. It can be clearly seen from Fig. 3 that 1) the SiO_2/GeO_2 Raman shift of this fiber is much wider than one of the conventional silica fiber and that 2) in particular, the P_2O_5 Raman

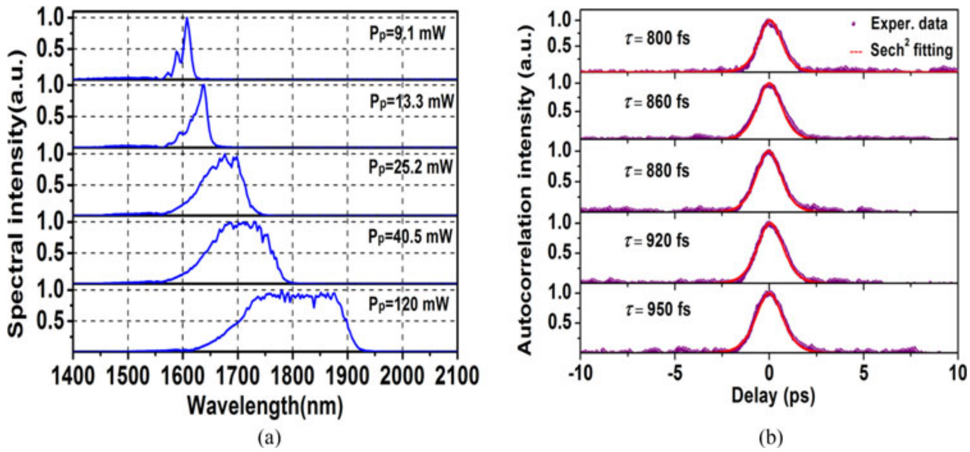

Fig. 4. (a) SSFS spectra and (b) the autocorrelation traces under the different pump average powers of 9.1, 13.3, 25.2, 40.5, and 120 mW, respectively.

shift (i.e. 40 THz) is extremely large, which could efficiently transfer the 1.56 μm pump energy to $\sim$1.97 μm. In view of the two facts, it can be expected that the SSFS in the phosphor-doped fiber could be extended to longer wavelength (possibly $>$ 1.8 μm).

The amplified DS pulses at 1.56 μm was finally injected into the 960-m phosphor-doped fiber. A 1550/1700 nm wavelength division multiplexer (WDM) was used to filter out the residual pump light for obtaining the pure Raman solitons in $\sim$1.7 μm. The splicing loss between the phosphor-doped fiber with the standard SMF can be as low as $\sim$0.5 dB. The output optical spectrum was monitored by an optical spectrum analyzer (OSA, Ocean Optics NIRQuest512-2.5). The pulse characteristics were measured by an autocorrelator (FR-103XL, Femtochrome Research Inc.) and a 11 GHz photodetector, together with a high-speed oscilloscope or radio-frequency spectrum analyzer.

3. Experimental Results and Discussions

In our experiment, when the injection average power of the 1.56 μm DS pulses was increased above 9.1 mW (corresponding to $\sim$0.15 kW), the center wavelength of the soliton pulse was shifted toward the longer wavelength side (i.e. $\sim$1.61 μm), as shown in the top of Fig. 4(a). In particular, the soliton spectrum exhibited a quasi-sech^2 profile, except for the spectral ripples induced by the OSA. We also measured the corresponding autocorrelation trace [the top of Fig. 4(b)] of the soliton pulses. The pulse breakup was not observed, and the output still kept the single-pulse soliton with a pulse width of 800 fs, if a sech^2 fit is used. These are the typical features of self frequency-shifted soliton, clearly confirming the occurrence of the SSFS. Because the SSFS depends on the pump peak power, we investigated the evolution of the SSFS spectrum with increasing the pump average power. Fig. 4(a) gives the typical Raman-soliton spectra under the different average pump powers of 9.1, 13.3, 25.2, 40.5, and 120.0 mW. One can clearly see that the central wavelength of Raman solitons can continuously red-shift from 1.61 to 1.85 μm, which is wider than the SSFS in the conventional SMF [17], [18]. The maximum shift of optical frequency is more than 15.5%. Meanwhile, we also measured the autocorrelation traces with these different pump powers. As shown in Fig. 4(b), the Raman solitons always kept the single-soliton state without pulse-splitting behavior, and the pulse width had a slight broadening from 800 to 950 fs. Considering the spectral bandwidth of $\sim$180 nm at the maximum pump power of 120 mW, the time-bandwidth product of the Raman soliton is 15.7. Such wide optical spectrum and the large time-bandwidth product of the Raman solitons could be attributed to the following facts: 1) the wide and large Raman shifts of the phosphor-doped fiber as given in Fig. 3 and 2) the large chirp ($\sim$19) of the 1.56 μm DS pump-pulses. It is well known that large-chirped DS pulses can be strongly compressible outside the cavity. However, due to the lack of the required device (e.g., a

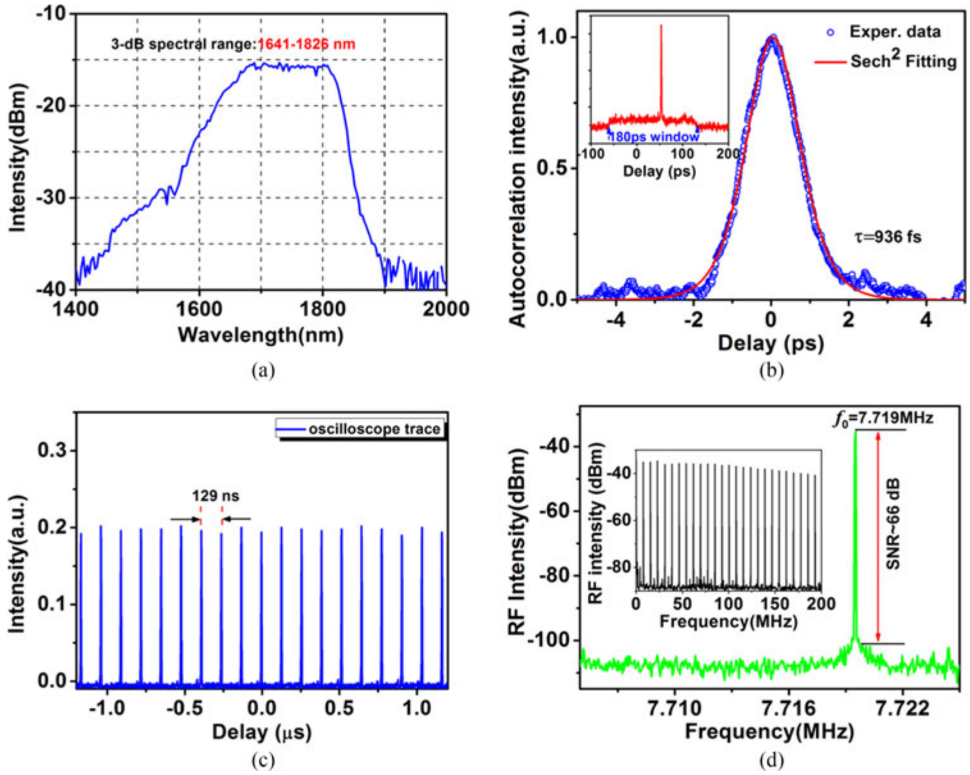

Fig. 5. Output characteristics of Raman solitons at the pump average power of 70 mW. (a) Typical optical spectrum. (b) Autocorrelation trace (Inset) Autocorrelation trace with a scanning window of 180 ps. (c) Oscilloscope trace. (d) RF spectrum at the fundamental frequency peak (Inset) RF spectrum in 200 MHz span.

pair of gratings) at ∼1.7 μm, we did not carry out the Raman-soliton compression in our lab, and this will be our further work.

Fig. 5 further summaries the output characteristics of the Raman solitons at the pump average power of 70 mW. The typical optical spectrum of the SSFS in the phosphor-doped fiber is described in Fig. 5(a). The center wavelength of the soliton spectrum located at 1734 nm, and the 3-dB spectral bandwidth is about 85 nm. Although the spectral range is enough wide, indeed this is no supercontinuum spectrum. It is well known that supercontinuum generation in optical fiber is related to soliton fission, but in our experiment, the single-soliton profile with no fission is perfectly remained, as seen in Fig. 5(b). We further measured an autocorrelation trace with a wide scanning window of 180 ps [the inset of Fig. 5(b)]. Note that no pedestal was shown on the autocorrelation trace, which reveals the excellent quality of the Raman solitons. Why did the experimental scheme achieve eventually the SSFS-based Raman solitons, instead of the supercontinuum generation? The possible reasons are given as follows: 1) the 1.56 μm pump wavelength is deep inside the anomalous dispersion region of the phosphor-doped fiber, which is very helpful for forming Raman soliton by the SSFS, 2) the picosecond DS pulses with the relatively low peak power is used as the pump and the phosphor-doped silica fiber doesn't have too high nonlinear index, so supercontinuum generation in the scheme can be effectively prevented. Fig. 5(c) represents the typical oscilloscope trace, and stable pulse trains with the period of 129 ns still remain without any pulse disorder. As shown in Fig. 5(d), we also measured the RF output spectrum of the Raman solitons. The fundamental frequency peak (i.e. pulse repetition rate) located at 7.719 MHz which is in agreement with one of the 1.56 μm pump laser. It is interestingly found that the RF signal-to-noise ratio (SNR) of the Raman soliton can be as high as 66 dB. Furthermore, as plotted in the inset of Fig. 5(d), the RF

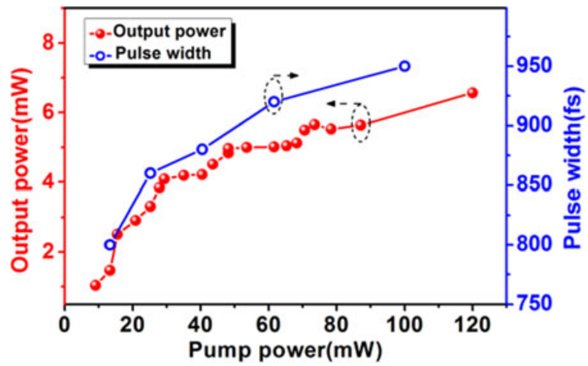

Fig. 6. Output average power and the pulse energy as a function of the pump average power, respectively.

spectrum with a wide span of 200 MHz exhibits no spectral modulation. Both of the performances can be comparable or superior to those of passively/actively mode-locked fiber lasers [26], [27].

In order to further investigate the output characteristics of the SSFS, the average output power and pulse duration of the Raman solitons were measured as a function of the pump average power. As plotted in Fig. 6, the output average power linearly increases with the pump power of $<$40 mW. However, once the pump power is more than 40 mW, the output power becomes a little saturation with the maximum output power of 6.8 mW. The possible reason is that under high pump power, SSFS was so large that the loss of pulse energy for exciting phonons weakens SSFS [20]. When the pump power was increased from 9.1 to 120 mW, the measured pulse width has only a slight broadening from 800 to 950 fs, resulting from the combination of the pump pulse's chirp and the dispersion curve of the phosphor-doped fiber. Correspondingly, we also calculated the pulse energy and the peak power of the Raman solitons. At the maximum pump average power of 120 mW, the maximum pulse energy and peak power are 0.88 nJ and 930 W, respectively, comparable or superior to those of the reported fiber-based Raman soliton sources previously [16]–[21].

4. Conclusion

In summary, we have reported for the first time the generation of 1.61–1.85 μm tunable femtosecond pulses based on the SSFS of a phosphor-doped fiber pumped by 1.56 μm dissipative-soliton pulses. Stable Raman solitons were achieved with the shortest pulse width of 800 fs and the large chirp of $\sim$16. The maximum output average power was 6.8 mW and the corresponding pulse energy was 0.88 nJ. The experimental results reveal that the phosphor-doped fiber with 1.55 μm conventional pulsed pumping could be a promising solution for extending the SSFS to $>$ 1.8 μm wavelength, which could be used as a low-cost, compact ultrafast laser source for biomedical microscopy and imaging.

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