PHOTONICS Research

All-in-fiber amplification and compression of coherent frequency-shifted solitons tunable in the 1800–2000 nm range

GRZEGORZ SOBOŃ,[1,*] TADEUSZ MARTYNKIEN,[2] DOROTA TOMASZEWSKA,[1] KAROL TARNOWSKI,[2] PAWEŁ MERGO,[3] AND JAROSŁAW SOTOR[1]

[1]Laser & Fiber Electronics Group, Faculty of Electronics, Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
[2]Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
[3]Laboratory of Optical Fiber Technology, Maria Curie-Sklodowska University, pl. M. Curie-Sklodowskiej 3, Lublin, Poland
*Corresponding author: grzegorz.sobon@pwr.edu.pl

Received 17 January 2018; revised 19 February 2018; accepted 19 February 2018; posted 21 February 2018 (Doc. ID 320061); published 18 April 2018

We report an all-fiber, all-polarization maintaining (PM) source of widely tunable (1800–2000 nm) ultrashort pulses based on the amplification of coherent self-frequency-shifted solitons generated in a highly nonlinear fiber pumped with an Er-doped fiber laser. The system delivers sub-100 fs pulses with energies up to 8.6 nJ and is built entirely from PM optical fibers, without any free-space optics. The all-fiber alignment-free design significantly increases the suitability of such a source for field deployments.

OCIS codes: (190.4370) Nonlinear optics, fibers; (140.4050) Mode-locked lasers; (060.4370) Nonlinear optics, fibers.

https://doi.org/10.1364/PRJ.6.000368

1. INTRODUCTION

Widely tunable and ultrashort-pulsed laser sources operating in the 1.8–2.0-μm spectral band are in demand for many applications in various fields of industry and science. Compact and efficient lasers in this spectral region can be used, e.g., for supercontinuum generation in nonlinear fibers [1], as pumps for mid-infrared parametric oscillators [2], or as sources in surgery or dermatology [3]. Most commonly, ultrashort pulses in this spectral region are generated from mode-locked fiber lasers based on Tm- or Ho-doped gain fibers, utilizing various mode-locking techniques, e.g., nonlinear polarization evolution (NPE) [4,5], semiconductor saturable absorber mirrors (SESAM) [6], graphene [7], and carbon nanotube saturable absorbers [8].

Alternatively, broadband and ultrashort pulses in the 1.8–2.0 μm region can be obtained via nonlinear frequency conversion in highly nonlinear fibers (HNLFs). In principle, a near-infrared pump (e.g., from a mode-locked erbium-doped fiber laser, EDFL) launched to a dispersion-engineered HNLF might be converted toward longer wavelengths due to Raman-induced soliton self-frequency shift (SSFS). The concept of using compact 1.56-μm EDFLs and shifting their output radiation via SSFS toward the 2-μm band utilizing long sections of conventional single-mode fibers was presented by Nishizawa and Goto [9]. Nowadays, usually photonic crystal fibers (PCFs) [10,11], suspended-core fibers [12], or GeO_2-doped silica fibers [13] are used as nonlinear media for SSFS. The usage of fluoride fibers allows for generation of solitons shifted up to 4.3 μm [14]. Recently, we have reported generation of sub-100-fs pulses tunable from 1700 to 2100 nm via SFSS in a microstructured HNLF pumped by a compact EDFL [15]. The main advantage of this approach over classical Tm- or Ho-doped fiber lasers is that the output radiation is easily tunable over a very broad spectral range, unreachable for fiber lasers based on rare-earth-doped gain fibers. Untypical wavelengths like 1650–1800 nm, interesting for deep bio-imaging applications [16], can be easily obtained just by adjusting the pump power launched into the nonlinear fiber [15], without the necessity of building complex short-wavelength Tm-doped lasers [17]. The pulses obtained via SSFS are usually closely transform-limited [18,19] and might maintain their coherence [20], and they also have a broad and smooth spectral envelope [15,19,20]. The SSFS output power can be further scaled by external amplification using the chirped pulse amplification (CPA) technique. The usage of an SSFS-based seed source for the CPA instead of a fixed-wavelength Tm- or Ho-doped laser makes the entire source much more flexible, thanks to the broad tuning capabilities. However, the most powerful CPA sources at 2 μm always utilize bulk pulse compressors based on diffraction gratings [21–24]. The output power of the SSFS-seeded setups can be scaled without a bulk compressor by using the concept of high-dispersion amplifiers. In Ref. [25], 108-fs pulses at 1980 nm with an energy of 31 nJ were achieved. However, the setup utilized free space optics to couple the signal and pump light into a non-polarization-maintaining large-mode-area (LMA) Tm-doped fiber. Real-world applications, especially field-deployable systems (e.g., for environmental monitoring, sensing, range finding) require compact and robust sources without any moving parts, characterized with stable output parameters maintained over long periods of time without any maintenance. Only all-fiber and polarization maintaining (PM) sources can meet these requirements. Recently, Sun et al. reported a compact Tm-doped all-fiber laser, which delivers 65-fs-short pulses with 3.2 nJ energy at 1980 nm wavelength [26]. However, the system was based on an NPE-based oscillator, which requires polarization alignment to initiate and optimize the mode locking. Moreover, the setup was based on standard, non-PM fibers. In this case, the output polarization state is undetermined and may vary over time. The laser operated at a fixed wavelength without any tuning capabilities. In Ref. [27], an all-fiber setup delivering 94-fs pulses with 10.9 nJ energy at 1.93 μm was demonstrated. In Ref. [28], 125-fs pulses at 2 μm with energy of 5 nJ were obtained. However, both setups were based on non-PM fibers and components, and the coherence of the solitons was not investigated.

Here we demonstrate a compact laser source that delivers ultrashort, coherent pulses in the 1800–2000 nm spectral range, amplified up to 8.6 nJ energy (corresponding to nearly 400 mW of average power), with unprecedented simplicity, built entirely from PM optical fibers. To the best of our knowledge, we report the highest pulse energies obtained from a sub-100-fs all-PM fiber laser setup operating in the 2-μm spectral range, which outperforms the previous reports on all-fiber systems (e.g., Refs. [26,28] with 3.2 nJ and 5 nJ pulse energy, respectively). In contrast to other similar setups with comparable performance [21,22], our system does not contain any free-space optics (i.e., bulk compressors) and is fully alignment-free, offering robust and turn-key operation.

2. EXPERIMENTAL SETUP

The experimental setup of the all-fiber laser source is depicted in Fig. 1. The system is seeded by a compact, all-PM Er-doped fiber oscillator mode-locked with a graphene saturable absorber. The seed is afterward amplified up to 120 mW of average power, and delivers 27-fs-short pulses at 45 MHz repetition rate (details on the Er-fiber laser and amplifier can be found in Ref. [29]). The output of the seed source is directly spliced to a 2.3-m segment of an in-house-made PM-HNLF, which converts the near-infrared input pulses via the SSFS effect toward longer wavelengths (up to approx. 2100 nm). The pulse duration after the PM-HNLF is nearly transform-limited regardless of the soliton wavelength. The frequency-shifted solitons are afterward stretched to approx. 6 ps in an in-house-made PM dispersion-compensating fiber (PM-DCF, 8 m long). The stretched pulses are then amplified in a Tm-doped fiber amplifier (PM-TDF, Nufern PM-TSF-5/125) bi-directionally pumped by a 1565 nm fiber laser based on an erbium/ytterbium-doped fiber (delivering up to 3.5 W of power). Finally, the amplified pulses are compressed in an anomalous-dispersion fiber with a 15-μm core diameter (Nufern PLMA-GSF-15/130). Thanks to the relatively large core size of the compressing fiber (in comparison to a standard PM-1550 fiber), it is possible to achieve higher pulse energies and scale the output power without significant pulse degradation.

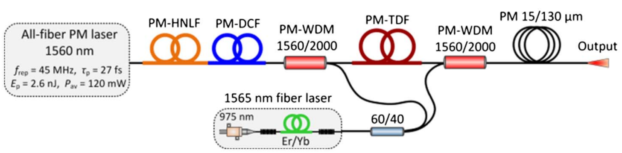

Fig. 1. Experimental setup of the all-fiber tunable laser.

Both PM-HNLF and PM-DCF were manufactured in the Laboratory of Optical Fiber Technology, Maria Curie-Sklodowska University, Lublin, Poland. The PM-HNLF has an elliptical-shaped, germanium-doped core (minor and major axes of 2.53 and 3.9 μm, respectively), surrounded by few rings of microstructured holes with averaged distance between the nearest neighboring holes of 3 μm and averaged diameter of the air holes in the first ring equal to 1 μm. An image of the fiber cross-section taken by a scanning electron microscope (SEM) is depicted in Fig. 2(c). The GeO_2 doping level in the core equals 18 mol. %. The fiber has a dispersion coefficient of approx. 26 ps/(nm·km) at 1560 nm wavelength and a high phase modal birefringence at the level of 5×10^{-4}, comparable to panda-type polarization maintaining fibers. The deployment of high pressure during fiber drawing process resulted in lattice squeezing and consequently high modal birefringence. It should be noted that similar fiber structure with all-normal

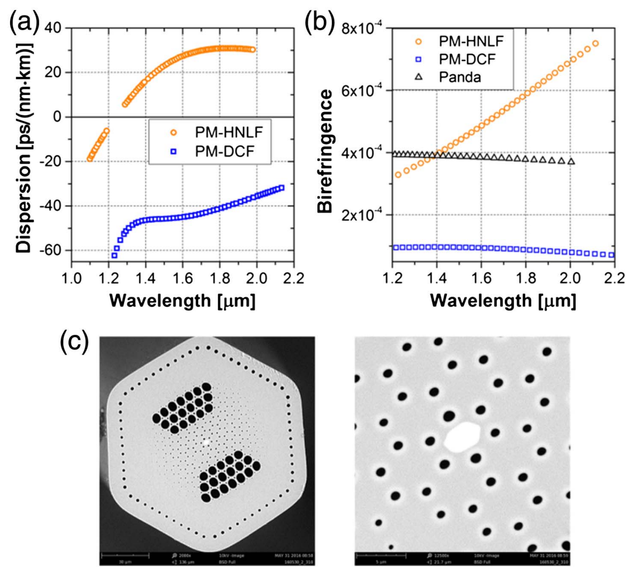

Fig. 2. (a) Measured dispersion and (b) phase modal birefringence of the PM-HNLF (round points), PM-DCF (squared points) and standard panda fiber (triangle points); (c) SEM images of the PM-HNLF end facet.

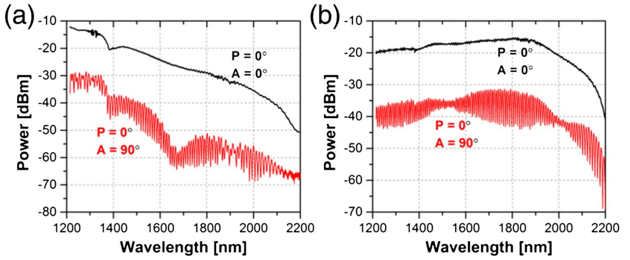

Fig. 3. Transmission spectra registered for the polarizer and the analyzer aligned in parallel (black line) and crossed (red line) for both fibers: (a) PM-HNLF; (b) PM-DCF.

dispersion was presented in Ref. [30]. However, in the employed PM-HNLF, the relative size of the holes is about 3 times higher in comparison with the structure presented in Ref. [30]; therefore, the chromatic dispersion is anomalous above 1300 nm. The PM-DCF has also an elliptical core (major axis 3.14 μm, minor axis 2.7 μm), and GeO_2 dopant concentration of 35 mol. %, resulting in a modal birefringence of (0.8–1) × 10^{-4} between 1800 and 2000 nm. The measured dispersion profiles and modal phase birefringence coefficients of both fibers are depicted in Fig. 2. The dispersion profiles [Fig. 2(a)] of both PM-HNLF and PM-DCF were measured by white-light interferometric technique, employing a dispersion-balanced Mach–Zehnder interferometer [31] and a 1.1–2.2 μm supercontinuum source (NKT Photonics SuperK Versa), while spectral interferograms were registered using optical spectrum analyzers (Yokogawa AQ6375 and AQ6370B, OSA). Additionally, for comparison, we present measured birefringence of a single-mode panda-type fiber. Due to the high modal birefringence of both fibers, no polarization crosstalk was observed. The measured polarization extinction ratio (PER) in both fibers was about 20 dB over the entire spectral range of our interest (see Fig. 3). In order to estimate the nonlinear coefficient (γ [$W^{-1}\cdot km^{-1}$]) of both fibers, numerical calculations using full-vectorial finite element method (COMSOL Multiphysics Software) and actual geometry of the fibers (based on SEM images) were performed. The simulations reveal that the nonlinear coefficient of the DCF decreases from 11.7 $W^{-1}\cdot km^{-1}$ at 1.55 μm to 5.1 $W^{-1}\cdot km^{-1}$ at 2 μm, while in case of HNLF the coefficient decreases from 9.8 to 5.7 $W^{-1}\cdot km^{-1}$ in the spectral range of 1.55–2.0 μm.

3. EXPERIMENTAL RESULTS

The performance of the presented source was characterized using the following equipment: optical spectrum, Yokogawa AQ6375 analyzer; pulse duration, APE PulseCheck autocorrelator; power, Gentec Maestro power meter with XLP12-3S-VP detector; beam diameter (M^2 parameter), Thorlabs BP209-IR2 beam profiler.

The used PM-HNLF enables continuous tuning of the output soliton central wavelength up to 2080 nm just by changing the power of the 1560 nm pump laser. Exemplary optical spectra recorded directly after the PM-HNLF are depicted in Fig. 4. The average power stored in the shifted soliton varies between 6–11 mW, depending on the central wavelength, and the full width at half-maximum (FWHM) bandwidth reaches 40 nm.

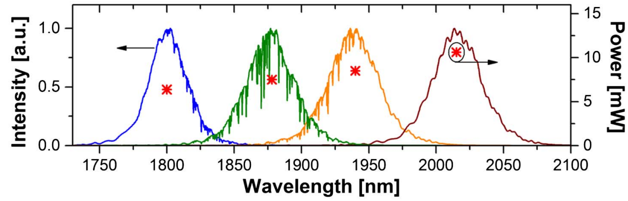

Fig. 4. Exemplary spectra of the frequency shifted solitons recorded directly at the output of the PM-HNLF, with indicated average power of the soliton.

In contrast to our previous work [15], here the shifted solitons are generated in a highly birefringent fiber, which ensures their linear polarization state.

The shifted solitons are highly coherent, which was proven by measuring the interference between two consecutive pulses in an unequal-path Michelson interferometer, similar to that presented in Refs. [32,33]. The measured spectral interference signals at different soliton wavelengths are plotted in Fig. 5. The fringe visibility function is defined as $V(\lambda) = [I_{max}(\lambda) - I_{min}(\lambda)]/[I_{max}(\lambda) + I_{min}(\lambda)]$, where I_{max} and I_{min} are the maximum and minimum intensities in the interferogram, respectively [34]. The amplitude of the modulation in the interference signal directly corresponds to the degree of coherence of the generated pulses [32–34]. Here, the visibility is at the level of 0.9 for solitons between 1800 and 2000 nm. Similar to previous reports on SSFS in nonlinear fibers, we observe a slight degradation of the coherence at longer wavelengths [20,35]; nonetheless, the visibility at 2075 nm is still higher than 0.6.

After amplification, the pulses are compressed in a segment of large-core single-mode fiber. Due to its dispersion slope, it was necessary to adjust the compressing fiber length at each wavelength to obtain the shortest possible pulses. After adjustment, we have obtained sub-180-fs pulse duration in the entire tuning range from 1800 to 2000 nm. For a fixed compression fiber length, the pulse duration might increase up to 1 ps over the entire tuning range. Figure 6 shows five exemplary optical spectra at different wavelengths and corresponding autocorrelation traces of amplified and compressed pulses. It can be seen that longer wavelengths require shorter lengths of the compressing fiber for optimized performance. The shortest obtained pulse duration was ~97 fs at 1972 nm input

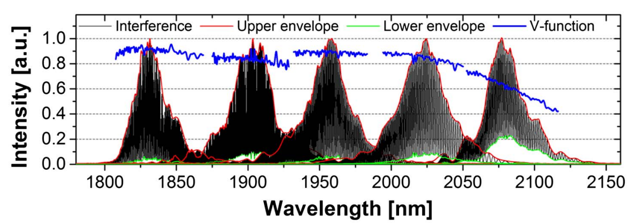

Fig. 5. Interference patterns of consecutive soliton pulses, measured at different wavelengths. Blue line represents the calculated fringe visibility function. Red and green lines show the upper and lower envelopes of the interferograms, used for obtaining I_{max} and I_{min}, respectively.

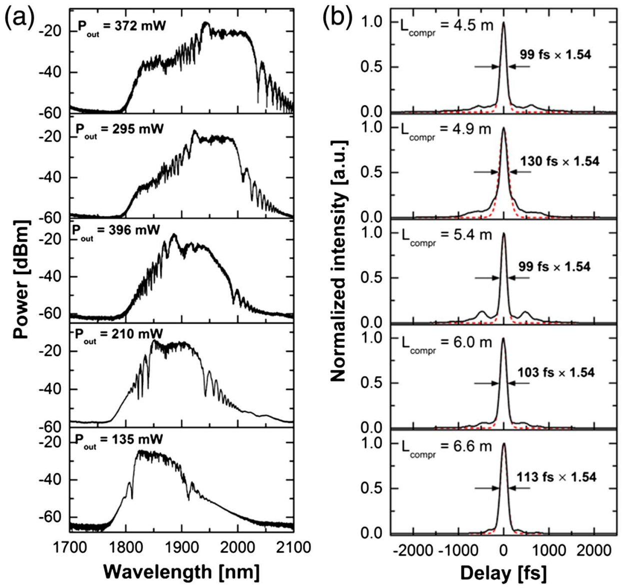

Fig. 6. (a) Measured optical spectra after amplification for different input soliton wavelengths, and (b) corresponding autocorrelation traces, with indicated length of the PM 15/130 compressing fiber. Dashed line: sech^2 fit.

soliton wavelength, with 357 mW of average output power, which corresponds to an energy of 7.8 nJ.

The maximum average output power of 395 mW (8.6 nJ pulse energy with 100 fs duration) was obtained at 1910 nm soliton wavelength and 3.5 W of pumping power. In general, the output power is greater than 100 mW in the entire tuning range. A graph showing the maximum achievable output power and pulse energy at different seed wavelengths is depicted in Fig. 7.

It is worth emphasizing that despite a relatively large core diameter of 15 μm, the compression fiber was truly single-mode over the entire tuning range and delivered a clean, TEM_{00} Gaussian beam. In order to confirm the geometrical properties of the output beam, we have measured its profile after passing through a lens with 50 mm focal length. The results are depicted in Fig. 8. The presented measurement was performed at 1950 nm wavelength and maximum output power; nevertheless, the beam remains single-mode over the entire tuning range. The calculated mean M^2 parameter is equal to 1.01, which confirms the excellent beam quality.

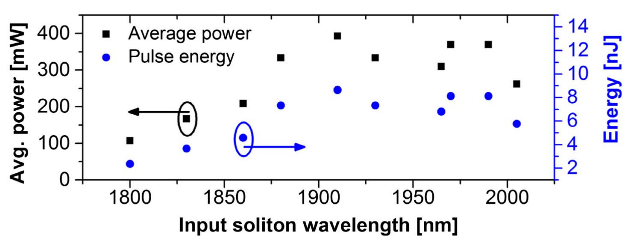

Fig. 7. Average output power (square points, left scale) and pulse energy (round dots, right scale) after amplification and compression versus input soliton wavelength.

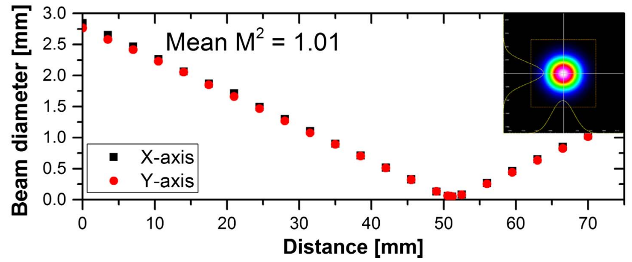

Fig. 8. Output beam quality measurement, indicating a mean M^2 parameter value of 1.01 at 1950 nm.

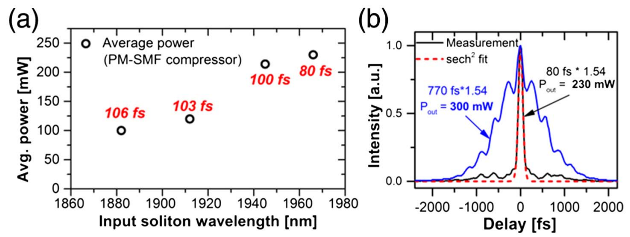

Fig. 9. Amplification performance with standard PM single-mode fiber used as compressor. (a) Obtained maximum average power with indicated pulse duration at each wavelength; (b) pulse autocorrelation recorded at output power of 230 mW and 300 mW.

The polarization of the output beam was truly linear with PER value of 24 dB at ~1.9 μm wavelength.

Additionally, we have characterized the performance of the amplifier with a standard PM single-mode fiber (i.e., PM1550-XP, Nufern) used as compressor. In the experiment, the remaining part of the setup was unchanged (i.e., seed, stretcher, amplifier), and only the 15/130-μm compressing fiber was replaced with the PM1550-XP. The performance of the system is summarized in Fig. 9. The maximum achievable output power without significant pulse distortion was 230 mW (obtained at 1.65 W of pumping power), which corresponds to a pulse energy of 5 nJ, similar to that obtained in Ref. [28] (also with the use of single-mode fibers). The obtained pulse duration was 80 fs [see Fig. 9(b)], which is shorter than the shortest pulse measured with the 15/130-μm compressing fiber (97 fs). However, the achievable output power and the energy are approximately 45% lower in comparison to those obtained with the large-core fiber used as a compressor [see Fig. 9(a)]. Further increase of the pumping power results in pulse distortion, i.e., build-up of a pronounced pedestal and side-wings in the autocorrelation trace, as can be seen in Fig. 9(b) (blue trace).

4. SUMMARY AND CONCLUSIONS

We have demonstrated an all-fiber, all-PM, widely tunable source of ultrashort pulses characterized by unprecedented simplicity. The laser system is capable of generating sub-100-fs pulses with energies up to 8.6 nJ (average power up to 395 mW). Output power higher than 100 mW is maintained over the entire tuning range from 1800 to 2000 nm. Our study shows that a simple frequency-shifting scheme applied to an

Er-doped fiber laser can be a promising alternative to Tm- or Ho-doped fiber lasers. It provides tunable, nearly-transform-limited and highly coherent pulses suitable for further amplification. Our setup outperforms previously reported SSFS experiments in terms of output pulse energy in the sub-100-fs regime [20,24]. The all-fiber, all-PM, alignment-free design significantly increases the suitability of such sources for real-world applications and field deployments.

Funding. Ministerstwo Nauki i Szkolnictwa Wyzszego (MNiSW) (IP2015 072674); Statutory Funds of the Faculty of Electronics, Politechnika Wrocławska (PWr).

REFERENCES

1. J. Luo, B. Sun, J. Liu, Z. Yan, N. Li, E. L. Tan, Q. Wang, and X. Yu, "Mid-IR supercontinuum pumped by femtosecond pulses from thulium doped all-fiber amplifier," Opt. Express **24**, 13939–13945 (2016).
2. A. Khodabakhsh, R. Ramaiah-Badarla, L. Rutkowski, A. C. Johansson, K. F. Lee, J. Jiang, C. Mohr, M. E. Fermann, and A. Foltynowicz, "Fourier transform and Vernier spectroscopy using an optical frequency comb at 3-5.4 μm," Opt. Lett. **41**, 2541–2544 (2016).
3. G. Hüttmann, C. Yao, and E. Endl, "New concepts in laser medicine: towards a laser surgery with cellular precision," Med. Laser Appl. **20**, 135–139 (2005).
4. P. Li, A. Ruehl, U. Grosse-Wortmann, and I. Hartl, "Sub-100 fs passively mode-locked holmium-doped fiber oscillator operating at 2.06 μm," Opt. Lett. **39**, 6859–6862 (2014).
5. Y. Tang, A. Chong, and F. W. Wise, "Generation of 8 nJ pulses from a normal-dispersion thulium fiber laser," Opt. Lett. **40**, 2361–2364 (2015).
6. J. Jiang, C. Mohr, J. Bethge, A. Mills, W. Mefford, I. Hartl, M. E. Fermann, C. Lee, S. Suzuki, T. R. Schibli, N. Leindecker, K. L. Vodopyanov, and P. G. Schunemann, "500 MHz, 58 fs highly coherent Tm fiber soliton laser," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (online) (Optical Society of America, 2012), paper CTh5D.7.
7. J. Sotor, M. Pawliszewska, G. Sobon, P. Kaczmarek, A. Przewolka, I. Pasternak, J. Cajzl, P. Peterka, P. Honzátko, I. Kašík, W. Strupinski, and K. Abramski, "All-fiber Ho-doped mode-locked oscillator based on a graphene saturable absorber," Opt. Lett. **41**, 2592–2595 (2016).
8. J. Wang, X. Liang, G. Hu, Z. Zheng, S. Lin, D. Ouyang, X. Wu, P. Yan, S. Ruan, Z. Sun, and T. Hasan, "152 fs nanotube-mode-locked thulium-doped all-fiber laser," Sci. Rep. **6**, 28885 (2016).
9. N. Nishizawa and T. Goto, "Widely wavelength-tunable ultrashort pulse generation using polarization maintaining optical fibers," IEEE J. Sel. Top. Quantum Electron. **7**, 518–524 (2001).
10. J. Takayanagi, T. Sugiura, M. Yoshida, and N. Nishizawa, "1.0-1.7-μm wavelength-tunable ultrashort-pulse generation using femtosecond Yb-doped fiber laser and photonic crystal fiber," IEEE Photon. Technol. Lett. **18**, 2284–2286 (2006).
11. R. Pant, A. C. Judge, E. C. Magi, B. T. Kuhlmey, M. de Sterke, and B. J. Eggleton, "Characterization and optimization of photonic crystal fibers for enhanced soliton self-frequency shift," J. Opt. Soc. Am. B **27**, 1894–1901 (2010).
12. T. Cheng, R. Usaki, Z. Duan, W. Gao, D. Deng, M. Liao, T. Kanou, M. Matsumoto, T. Misumi, T. Suzuki, and Y. Ohishi, "Soliton self-frequency shift and third-harmonic generation in a four-hole As_2S_5 microstructured optical fiber," Opt. Express **22**, 3740–3746 (2014).
13. E. A. Anashkina, A. V. Andrianov, M. Y. Koptev, V. M. Mashinsky, S. V. Muravyev, and A. V. Kim, "Generating tunable optical pulses over the ultrabroad range of 1.6-2.5 μm in GeO_2-doped silica fibers with an Er:fiber laser source," Opt. Express **20**, 27102–27107 (2012).
14. Y. Tang, L. G. Wright, K. Charan, T. Wang, C. Xu, and F. W. Wise, "Generation of intense 100 fs solitons tunable from 2 to 4.3 μm in fluoride fiber," Optica **3**, 948–951 (2016).
15. G. Soboń, T. Martynkien, K. Tarnowski, P. Mergo, and J. Sotor, "Generation of sub-100 fs pulses tunable from 1700 to 2100 nm from a compact frequency-shifted Er-fiber laser," Photon. Res. **5**, 151–155 (2017).
16. N. G. Horton, K. Wang, D. Kobat, C. G. Clark, F. W. Wise, C. B. Schaffer, and C. Xu, "In vivo three-photon microscopy of subcortical structures within an intact mouse brain," Nat. Photonics **7**, 205–209 (2013).
17. C. Li, X. Wei, C. Kong, S. Tan, N. Chen, J. Kang, and K. K. Y. Wong, "Fiber chirped pulse amplification of a short wavelength mode-locked thulium-doped fiber laser," APL Photon. **2**, 121302 (2017).
18. J. H. Lee, J. van Howe, C. Xu, and X. Liu, "Soliton self-frequency shift: experimental demonstrations and applications," IEEE J. Sel. Top. Quantum Electron. **14**, 713–723 (2008).
19. J. Luo, B. Sun, J. Ji, E. L. Tan, Y. Zhang, and X. Yu, "High-efficiency femtosecond Raman soliton generation with a tunable wavelength beyond 2 μm," Opt. Lett. **42**, 1568–1571 (2017).
20. G. Soboń, T. Martynkien, P. Mergo, L. Rutkowski, and A. Foltynowicz, "High-power frequency comb source tunable from 2.7 to 4.2 μm based on difference frequency generation pumped by an Yb-doped fiber laser," Opt. Lett. **42**, 1748–1751 (2017).
21. H. Hoogland, A. Thai, D. Sánchez, S. L. Cousin, M. Hemmer, M. Engelbrecht, J. Biegert, and R. Holzwarth, "All-PM coherent 2.05 μm thulium/holmium fiber frequency comb source at 100 MHz with up to 0.5 W average power and pulse duration down to 135 fs," Opt. Express **21**, 31390–31394 (2013).
22. N. Coluccelli, M. Cassinerio, P. Laporta, and G. Galzerano, "Single-clad Tm-Ho:fiber amplifier for high-power sub-100-fs pulses around 1.9 μm," Opt. Lett. **38**, 2757–2759 (2013).
23. H. Hoogland, S. Wittek, W. Hänsel, S. Stark, and R. Holzwarth, "Fiber chirped pulse amplifier at 2.08 μm emitting 383-fs pulses at 10 nJ and 7 MHz," Opt. Lett. **39**, 6735–6738 (2014).
24. R. A. Sims, P. Kadwani, A. Sincore, L. Shah, and M. Richardson, "1 μJ, sub-500 fs chirped pulse amplification in a Tm-doped fiber system," Opt. Lett. **38**, 121–123 (2013).
25. G. Imeshev and M. E. Fermann, "230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber," Opt. Express **13**, 7424–7431 (2005).
26. B. Sun, J. Luo, Y. Zhang, Q. Wang, and X. Yu, "65 fs pulses at 2 μm in a compact thulium-doped all-fiber laser through dispersion and nonlinearity management," IEEE Photon. Technol. Lett. **30**, 303–306 (2018).
27. P. Wang, H. Shi, F. Tan, and P. Wang, "Tunable femtosecond pulse source from 1.6 to 2.3 μm with 100 kW peak power in an all-fiber system," Chin. Opt. Lett. **14**, 091405 (2016).
28. M. Y. Koptev, E. A. Anashkina, A. V. Andrianov, S. V. Muravyev, and A. V. Kim, "Two-color optically synchronized ultrashort pulses from a Tm/Yb-co-doped fiber amplifier," Opt. Lett. **39**, 2008–2011 (2014).
29. J. Sotor and G. Soboń, "24 fs and 3 nJ pulse generation from a simple, all polarization maintaining Er-doped fiber laser," Laser Phys. Lett. **13**, 125102 (2017).
30. K. Tarnowski, T. Martynkien, P. Mergo, K. Poturaj, A. Anuszkiewicz, P. Béjot, F. Billard, O. Faucher, B. Kibler, and W. Urbanczyk, "Polarized all-normal dispersion supercontinuum reaching 2.5 μm generated in a birefringent microstructured silica fiber," Opt. Express **25**, 27452–27463 (2017).
31. P. Hlubina, M. Kadulová, and D. Ciprian, "Spectral interferometry-based chromatic dispersion measurement of fibre including the zero-dispersion wavelength," JEOS RP **7**, 12017 (2012).
32. S. Kim, J. Park, S. Han, Y.-J. Kim, and S.-W. Kim, "Coherent supercontinuum generation using Er-doped fiber laser of hybrid mode-locking," Opt. Lett. **39**, 2986–2989 (2014).
33. M. Klimczak, G. Sobon, R. Kasztelanic, K. Abramski, and R. Buczyński, "Direct comparison of shot-to-shot noise performance of all normal dispersion and anomalous dispersion supercontinuum pumped with sub-picosecond pulse fiber-based laser," Sci. Rep. **6**, 19284 (2016).
34. A. F. J. Runge, C. Aguergaray, N. G. R. Broderick, and M. Erkintalo, "Coherence and shot-to-shot spectral fluctuations in noise-like ultrafast fiber lasers," Opt. Lett. **38**, 4327–4330 (2013).
35. T. W. Neely, T. A. Johnson, and S. A. Diddams, "High-power broadband laser source tunable from 3.0 μm to 4.4 μm based on a femtosecond Yb:fiber oscillator," Opt. Lett. **36**, 4020–4022 (2011).