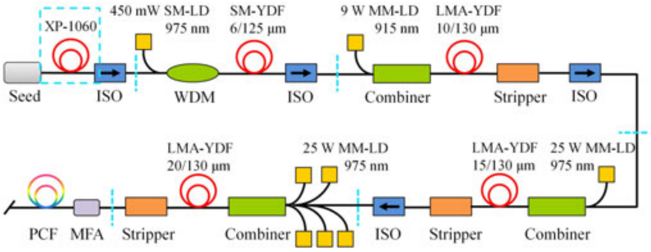
IEEE Photonics Journal
An IEEE Photonics Society Publication

An All-Fiber Supercontinuum Source With 30.6-W High-Power and Ultrawide Spectrum Ranging From 385 nm to Beyond 2400 nm

Volume 9, Number 2, April 2017

Xin Zou
Jifang Qiu
Xiaodong Wang
Zi Ye
Chang Sun
Tingwu Ge
Jian Wu, *Member, IEEE*



DOI: 10.1109/JPHOT.2017.2686869
1943-0655 © 2017 IEEE

An All-Fiber Supercontinuum Source With 30.6-W High-Power and Ultrawide Spectrum Ranging From 385 nm to Beyond 2400 nm

Xin Zou,[1] Jifang Qiu,[1] Xiaodong Wang,[1] Zi Ye,[1] Chang Sun,[2] Tingwu Ge,[2] and Jian Wu,[1] *Member, IEEE*

[1]State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Institute of Laser Engineering, Beijing University of Technology, Beijing 100124, China

DOI:10.1109/JPHOT.2017.2686869

Manuscript received February 27, 2017; revised March 20, 2017; accepted March 21, 2017. Date of publication March 23, 2017; date of current version April 12, 2017. This work was supported in part by the 863 program (2015AA015503), the 973 program (2014CB340100), the NSFC program (61307055, 61475022, 61331008, 61335009, 61471054), the SRFDP program 20130005110013, and the Fundamental Research Funds for the Central Universities. Corresponding authors: Jifang Qiu and Jian Wu (e-mail: jifangqiu@bupt.edu.cn, jianwu@bupt.edu.cn).

Abstract: An all-fiber high power, blue-enhanced supercontinuum generation in a piece of uniform photonic crystal fiber pumped by a picosecond Yb-doped master oscillator power amplifier (MOPA) is experimentally demonstrated. The MOPA source is seeded by an actively dissipative soliton mode-locked Yb-doped fiber laser with a fundamental repetition rate of approximately 15.33 MHz and a large chirp. By introducing giant chirp to the seed pulses and optimizing the pump power in every stage of the MOPA, an SC with 30.6-W output average power and an extremely wide spectrum of 385 nm to beyond 2400 nm is obtained.

Index Terms: Supercontinuum generation, photonic crystal fibers, optical amplifiers, chirping.

1. Introduction

Supercontinuum (SC) generation, which originates from a combination of nonlinear effects, such as self-phase modulation (SPM), the stimulated Raman scattering (SRS), and four wave mixing (FWM), has been an intensively researched topic over the past few years. Due to the advantages of broadband spectrum and compactness, optical fiber based supercontinuum sources, especially those with spectra covering visible to mid-infrared region, have been applied to various fields like wavelength division multiplexing, sensing and detection, micro-spectroscopy, etc. In particular, the visible part (390-780 nm) of the source has attractive applications relating to biophotonics [1]–[4]. Generally, the blue-enhanced or ultraviolet (UV) SC can be achieved efficiently by using tapered or special designed photonic crystal fiber (PCF), which means that the short wavelength edge that can be reached is around 400 nm [5], [6]. Another effective way to generate an ultraviolet-enhanced SC is introducing large chirp to the pumped pulses of the PCF. Using this method, the shortest wavelength edge that can be obtained is 370∼380 nm [7], [8]. However, all those SC laser sources often have relatively low average power (mW or W level), probably limited by the nonlinear effects

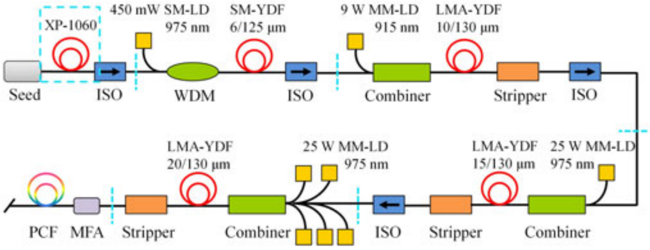


Fig. 1. Scheme of the all-fiber high power SC source (ISO: Isolator, WDM: Wavelength division multiplexer, SM-LD: Single mode laser diode, SM-YDF: Single mode-Yb doped fiber, LMA-YDF: Large mode area-Yb doped fiber, MM-LD: Multi-mode laser diode).

(such as Raman effect) caused by high peak power of pulses launched into the PCF, which might introduce potential risk to the system.

As for relatively high average power SC generation, numerous works also have been done. The output average power of those generated SCs is often higher than 30 W [9]–[16]. However, they cannot be seen as the blue-enhanced SCs, which means that the short wavelength edges can hardly reach $<$400 nm. And this probably dues to the lack of pulse energy that transferred to dispersive waves, which is considered to be the main reason to form the short-wavelength of the SC. Since there is a trade-off between high average power and blue-enhanced spectrum, a scheme to make a balance between them is highly desired in research fields.

Here, we report a high power, blue-enhanced, ultra-wide SC generation in a piece of uniform PCF pumped by a picosecond dissipative soliton (DS) Yb-doped fiber laser. The seed pulses are amplified through an all-fiber master oscillator power amplifier (MOPA) system. By introducing giant chirp to the seed pulses of the MOPA, and optimizing the pump power of every stage in the MOPA, the high average SC power of 30.6 W and the optical spectrum covering the whole visible and most of the near infrared (NIR) region (spanning from 385 nm to beyond 2400 nm) can be simultaneously obtained. This is the SC source that can generate the widest spectrum at $\sim$30 W average power using uniform PCF, to the best of our knowledge.

2. Experimental Setup

The experimental setup of the SC source consists of a seed laser, an all-fiber MOPA and a SC generation module, which is shown in Fig. 1. The seed laser is an actively harmonic DS mode-locked fiber laser with a fundamental pulse repetition rate of $\sim$15.33 MHz. A piece of $\sim$1.19 km SMF (XP-1060) is added after the seed laser to increase the chirp [8]. The MOPA is comprised of three preamplifiers and a main amplifier, whose key components are all clearly depicted in Fig. 1. The length of gain fibers used in preamplifiers are 1 m (SM-YDF, 6/125 μm), 10 m (LMA-YDF, 10/130 μm) and 5 m (LMA-YDF, 15/130 μm), respectively. The gain fiber used in the main amplifier is a piece of LMA-YDF with 20/130 μm core/cladding diameter. Five multi-mode laser diodes (LDs) with wavelength at 975 nm are used as the pump sources for the main amplifier, and the maximum power of each laser diode is 25 W. A $(6 + 1) \times 1$ high power pump combiner is used to deliver pump light into the gain fiber. A home-made mode field adaptor (MFA) is employed as the coupling component between the MOPA system and the PCF. The MFA is made of two types of fibers: LMA-YDF (15/130 μm) and SMF (XP-1060). The mode field diameters at the entrance and at the output of the MFA are 15 μm and 6 μm, respectively. The 1.8 m-long highly nonlinear PCF (SC-4.0-1040) used in the SC generation system exhibits a core diameter of 4 μm, a nonlinear coefficient of 19 $W^{-1}km^{-1}$, and a zero-dispersion-wavelength of 1040 nm. And its dispersion curve and the attenuation curve are showed in Fig. 2. The output of the PCF is spliced with a piece of 40 cm-long multi-mode fiber (62.5/125 μm) with an 8° angle cleaved facet serving as the end-cap, which effectively reduces back reflection and increases the PCF facet damage threshold. The output optical spectrum is measured by three optical spectrum analyzers (AQ6373, AQ6370B, AQ6375) simultaneously. The seed pulse duration is measured by an autocorrelator (FR-103XL).

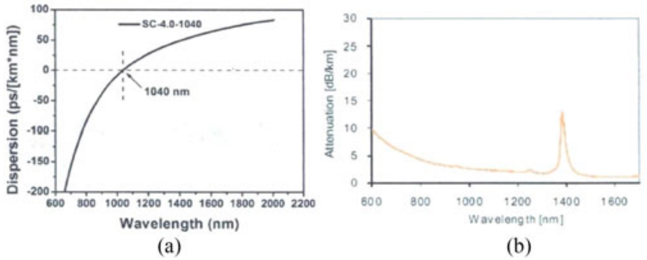


Fig. 2. Dispersion curve (a) and the attenuation curve (b) of the PCF (SC-4.0-1040).

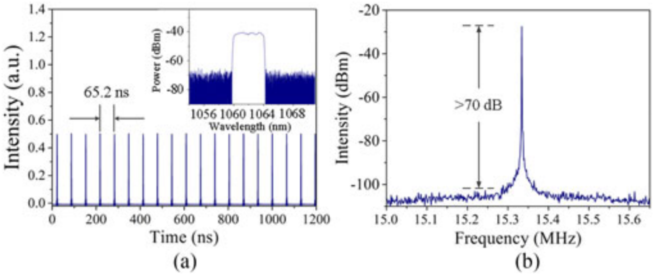


Fig. 3. (a) Pulse train at 15.33 MHz repetition rate. (Inset) Optical spectrum. (b) RF spectrum of the pulses.

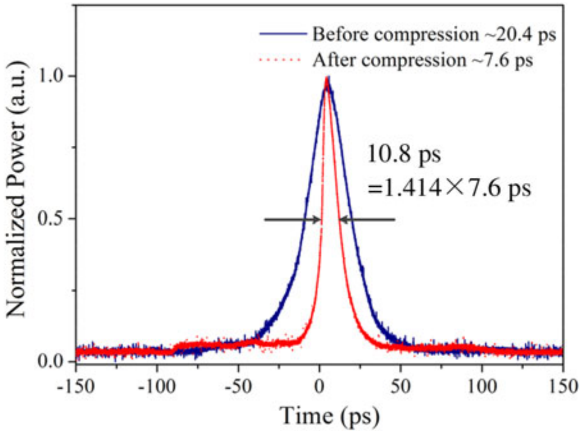


Fig. 4. Autocorrelation trace of the seed pulses (before and after compression).

3. Experimental Results and Discussions

3.1. Chirped Seed Pulses Amplification and SC Generation Without the 1.19 km SMF

Under pump power of ~320 mW, stable mode-locking of the seed laser is observed with an output power of ~9 mW. The pulse train with an interval of ~65.2 ns, corresponding to a repetition rate of ~15.33 MHz, is clearly shown in Fig. 3(a). The optical spectrum of the pulse centered at 1062 nm with 3.4 nm spectral bandwidth (3 dB) is also shown in the inset of Fig. 3(a). The steep spectral edges indicate that the DS is obtained. The RF spectrum of the seed pulses at 15.33 MHz is shown in Fig. 3(b). The signal-to-noise ratio (SNR) of more than 70 dB is observed, indicating the quite stable mode-locking.

The full width at half maximum (FWHM) of the seed pulse (blue solid line) is ~20.4 ps, as is shown in Fig. 4, and the time-bandwidth product (TBP) is calculated as ~18.4, indicating that the seed

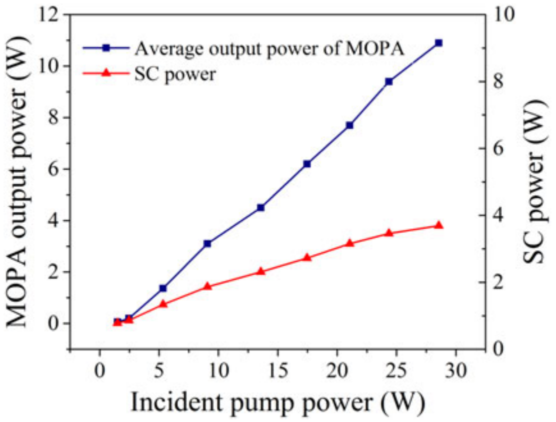


Fig. 5. Average output power of MOPA and SC with increased pump power under the condition of no SMF added before the first preamplifier.

pulse actually has a large chirp which is beneficial for blue-enhanced SC generation [7]. Besides, the seed pulse duration can be compressed to ~7.6 ps (red dot line) using two blazed gratings (THORLABS, GR25-1210), which further proves that the DS seed pulse has a large chirp.

Because higher output power is more likely to generate a SC with wider spectra, and the main limitation of pulsed fiber laser power scaling is nonlinear effects such as SPM and stimulated Raman scattering (SRS) [17], it is essential to suppress the nonlinear effects (especially SRS) in the MOPA for a higher output power. As the SRS threshold depends not only on the peak power density, but also on the effective fiber length of the main amplifier and the signal power coupled into the main amplifier [18], two approaches are used to achieve this goal. The LMA-YDF used in the main amplifier is highly doped (8.7 dB/m absorption) and its length is precisely calculated (2.2 m); the signal power coupled into the main amplifier is carefully designed, keeping at a relatively low level, which is an effective way to increase the SRS threshold [19].

In order to reduce the signal power coupled into the main amplifier, the pump powers of three preamplifiers are adjusted to a relatively low level: 300 mW, 1.2 W and 960 mW, respectively. The average power of the chirped seed pulses is amplified to ~200 mW. Limited by the Raman effect during the amplification, it can only be amplified to ~10.9 W through the main amplifier with the pump power of ~26.1 W. The average output power of the MOPA as a function of the incident pump power is shown in Fig. 5 (blue line with squares), which shows that the amplification efficiency of the MOPA at the highest pump power level is ~34.8%. The highest SC output power that can be achieved is ~3.8 W, as depicted by the red line with triangles in Fig. 5.

The generated SC covers the wavelength range from ~418 nm to beyond 2400 nm, which is clearly shown in Fig. 6. That is to say, the large-chirped DSs (i.e. the seed pulses) and the optimized pump power of MOPA are beneficial to a wide SC generation, especially for the broadening of SC in short wavelength range. However, there are still some aspects remain to be improved, e.g. the optical spectrum of generated SC cannot cover the whole visible region, the amplification efficiency of the MOPA is not high enough, and the SC output power is relatively low.

3.2. Giant-Chirped Seed Pulses Amplification and SC Generation With the 1.19 km SMF

Although the DS seed pulses has a large chirp, energies channeled into the dispersive waves are still not enough to generate a wider SC covering the whole visible region [20]. Therefore, a piece of 1.19 km-long SMF is added after the seed laser to introduce giant chirp to pulses launched into the amplifiers [7]. The pulse duration of the giant-chirped seed pulse is broadened and the peak power is reduced. Thus, the pump power can be increased to higher levels without Raman effect. Since the low amplification efficiency of the MOPA may be caused by the low efficiency in pump absorption, a method is used to solve this problem. The gain fiber in the main amplifier is coiled

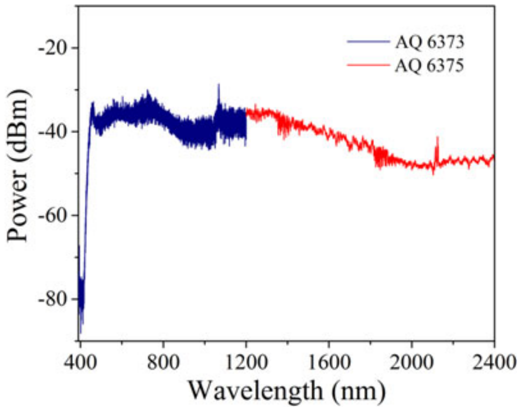


Fig. 6. SC output spectrum with 3.8 W output power, seeded by large-chirped DSs.

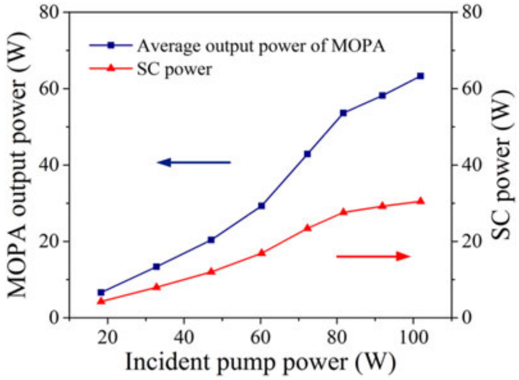


Fig. 7. Average output power of MOPA and SC with increased pump power under the condition of a piece of 1.19 km-long SMF added before the first preamplifier.

in a shape of kidney. The kidney shaped geometry may provide a better mode mixing in the pump core of the gain fiber, which is beneficial to increase pump absorption [21]. With further optimizing the pump power of preamplifiers (which makes the signal power launched into the main amplifier stay at a low level), the output power of the MOPA will be higher, leading to a wider SC.

The power of giant-chirped seed pulses is amplified to ∼280 mW through three preamplifiers, with the pump power of each stage of 300 mW, 820 mW and 2.2 W, respectively. The average power of giant-chirped pulses is amplified to ∼63.3 W by the main amplifier with the pump power of ∼98.6 W. The average output power of the MOPA as a function of the incident pump power is shown in Fig. 7 (blue line with squares). Thanks to the kidney shaped fiber geometry, the amplification efficiency of the MOPA at the highest pump power level is increased to ∼62.1%. Besides, the coupling efficiency of the home-made MFA is in excess of 80% in a high-power operation condition. By launching the power-amplified pulses into the PCF via the MFA, an SC with the output average power of 30.6 W is generated, which is also shown in Fig. 7 (red line with triangles). Considering the 80% coupling efficiency of the MFA, the optical-to-optical conversion efficiency of the PCF at the highest pump power level is estimated to be ∼60%.

The SC spectra measured by two different optical spectrum analyzers (AQ6373 and AQ6375) with spectral resolution of 1 nm are clearly shown in Fig. 7. At the output power of 30.6 W, a wider and flatter SC spectrum ranging from 385 nm to beyond 2400 nm is obtained. The longer wavelength cannot be measured due to the limitation of the optical spectrum analyzer AQ6375 (1200–2400 nm). The short wavelength edge of 385 nm is clearly seen in the inset of Fig. 8, which shows the SC output spectrum in the range of 350 nm to 780 nm (including the whole visible

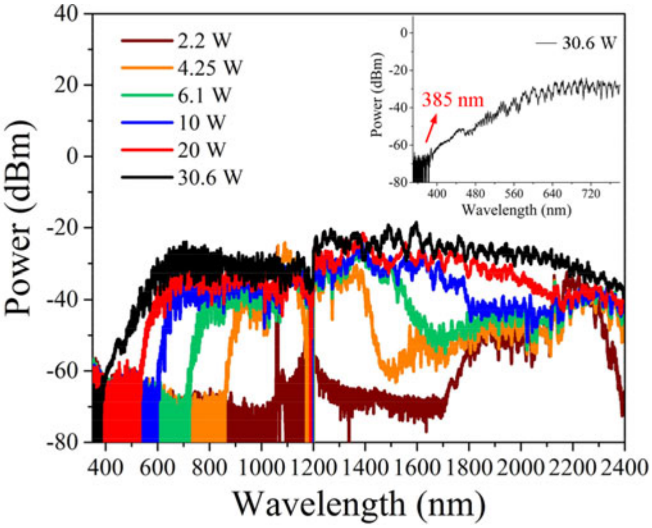


Fig. 8. SC spectra at different power. (Inset) Enlargement of SC output spectra with output power of 30.6 W (from 350 to 780 nm).

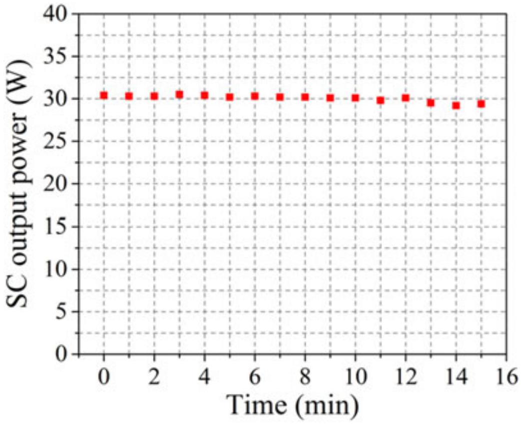


Fig. 9. Measurement of SC power stability.

region). Nevertheless, in order to increase the PCF facet damage threshold, a piece of 40 cm-long multi-mode fiber with an 8° angle cleaved facet is served as the end-cap, which also causes the generated SC spectra fluctuating in measured region. Because most of the fluctuations can be eliminated by removing the end-cap, an effective method to increase the damage threshold of PCF at a high output power level is highly desired. Under current situation, the 10 dB bandwidth of the generated SC is ∼1500 nm (550∼1150 nm, 1200∼2100 nm). Meanwhile, in order to evaluate the power stability of the generated SC, the output power is recorded every 1 minute for a total lasting time of 15 minutes. The recording time is short because the laboratory is not a clean room, which may lead to a potential risk to the SC source working at a high power level. The power stability curve is shown in Fig. 9 and the root mean square error (RMSE) is calculated as 0.372W. The slight fluctuation of the measured output SC power may be caused by three factors: the variation of the center wavelength of the giant-chirped DS; the accumulation of dust particles on the output end of the multi-mode fiber (end-cap); and the temperature variation which may affect the output power of the pump LDs.

4. Conclusion

In conclusion, we have experimentally demonstrated an all-fiber high power, blue-enhanced SC generation in a piece of uniform PCF pumped by a picosecond Yb-doped MOPA. The MOPA source is seeded by an actively DS mode-locked Yb-doped fiber laser with a fundamental repetition rate of ∼15.33 MHz. The seed pulse duration can be compressed from ∼20.4 ps to ∼7.6 ps through a pair of gratings, indicating that the DS seed pulse has a large chirp. A 3.8 W output power SC spanning from 418 nm to beyond 2400 nm can be obtained using the large-chirped DS as the seed. By further introducing giant chirp to the seed pulses through a piece of 1.19 km-long SMF, and optimizing the pump power in every stage of the MOPA, a SC with 30.6 W output average power and an extremely wide spectrum of 385 nm to beyond 2400 nm is obtained. The generated SC is stable under laboratory condition for a measuring time of 15 minutes. Future work will focus on the generation of wider, flatter SC with higher output average power.

Acknowledgment

The authors wish to thank Prof. P. Wang (Institute of Laser Engineering, Beijing University of Technology) and Dr. D. Lu (Institute of Semiconductors, Chinese Academy of Sciences) for providing optical spectrum analyzers that were indispensable to the experiment.

References

[1] I. Hartl *et al.*, “Ultrahigh-resolution optical coherence tomography using continuum generation in an air-silica microstructure optical fiber,” *Opt. Lett.*, vol. 26, no. 9, pp. 608–610, 2001.
[2] K. Lindfors *et al.*, “Detection and spectroscopy of gold nanoparticles using supercontinuum white light confocal microscopy,” *Phys. Rev. Lett.*, vol. 93, no. 3, p. 037401, 2004.
[3] Y. Sun *et al.*, “Characterization of an orange acceptor fluorescent protein for sensitized spectral fluorescence resonance energy transfer microscopy using a white-light laser,” *J. Biomed, Opt.*, vol. 14, no. 5, p. 054009, 2009.
[4] Z. Zhi, L. An, J. Qin, and R. K. Wang, “Supercontinuum light source enables in vivo optical microangiography of capillary vessels within tissue beds,” *Opt. Lett.*, vol. 36, no. 16, pp. 3169–3171, 2011.
[5] A. Kudlinski *et al.*, “Zero-dispersion wavelength decreasing photonic crystal fibers for ultraviolet-extended supercontinuum generation,” *Opt. Exp.*, vol. 14, no. 12, pp. 5715–5722, 2006.
[6] J. M. Stone and J. C. Knight, “Visibly “white” light generation in uniform photonic crystal fiber using a microchip laser,” *Opt. Exp.*, vol. 16, no. 4, pp. 2670–2675, 2008.
[7] S. F. Gao *et al.*, “Ultraviolet-enhanced supercontinuum generation in uniform photonic crystal fiber pumped by a giant-chirped fiber laser,” *Opt. Exp.*, vol. 22, no. 20, pp. 24697–24705, 2014.
[8] S. F. Gao, R. Y. Sun, D. C. Jin, and P. Wang, “Blue-enhanced supercontinuum generation pumped by a giant-chirped SESAM mode-locked fiber laser,” presented at the *Conf. Lasers Electro Optics*, 2015, paper SF2D.2.
[9] H. W. Chen, S. P. Chen, J. H. Wang, Z. L. Chen, and J. Hou, “35 W high power all fiber supercontinuum generation in PCF with picosecond MOPA laser,” *Opt. Commun.*, vol. 284, no. 23, pp. 5484–5487, 2011.
[10] X. H. Hu *et al.*, “High average power, strictly all-fiber supercontinuum source with good beam quality,” *Opt. Lett.*, vol. 36, no. 14, pp. 2659–2661, 2011.
[11] H. F Wei *et al.*, “A compact seven-core photonic crystal fiber supercontinuum source with 42.3 W output power,” *Laser Phys. Lett.*, vol. 10, no. 4, p. 045101, 2013.
[12] R. Song, J. Hou, S. P. Chen, W. Q. Yang, and Q. S. Lu, “High power supercontinuum generation in a nonlinear ytterbium-doped fiber amplifier,” *Opt. Lett.*, vol. 37, no. 9, pp. 1529–1531, 2011.
[13] W. Zhao *et al.*, “The recent progress on all-fiber supercontinuum source,” *Chin. J. Lasers*, vol. 11, p. 225, 2011.
[14] L. Zhao *et al.*, “Generation of high average power supercontinuum involve visible spectrum,” in *Proc. SPIE Int. Symp. High-Power Laser Syst. Appl.*, 2015, vol. 9255, p. 925513.
[15] C. Sun, T. W. Ge, S. Y. Li, N. An, and Z. Y. Wang, “67.9 W high-power white supercontinuum all-fiber laser source,” *Appl. Opt.*, vol. 55, no. 14, pp. 3746–3750, 2016.
[16] C. Sun *et al.*, “53.3 W visible-waveband extra high power supercontinuum all-fiber laser,” *IEEE Photon. J.*, vol. 8, no. 6, Dec. 2016, Art. No. 1504407.
[17] J. Gao, T. W. Ge, W. Y. Li, H. S. Kuang, and Z. Y. Wang, “GHz high power Yb-doped picosecond fiber laser and supercontinuum generation,” *Appl. Opt.*, vol. 53, no. 36, pp. 8544–8548, 2014.
[18] J. Gao *et al.*, “All-fiber tunable supercontinuum laser source,” *IEEE Photon. Technol. Lett.*, vol. 27, no. 14, pp. 1553–1556, Jul. 15, 2015.
[19] P. S. Teh, R. J. Lewis, S. Alam, and D. J. Richardson, “200 W Diffraction limited, single-polarization, all-fiber picosecond MOPA,” *Opt. Exp.*, vol. 21, no. 22, pp. 5426–5432, 2013.
[20] W. Y. Li, Z. S. Yin, J. F. Qiu, J. WU, and J. T. Lin, “Tunable active harmonic mode-locking Yb-doped fiber laser with all-normal dispersion,” *IEEE Photon. Technol. Lett.,* vol. 25, no. 23, pp. 2247–2250, Dec. 1, 2013.
[21] H. Zellmer, A. Tuennermann, H. Welling, and V. Reichel, “Double-Clad Fiber Laser with 30 W Output Power,” presented at the *Optical Amplifiers and Their Applications, vol. 16 of OSA Trends in Optics and Photonics Series*, 1997, paper FAW18.