Supercontinuum generation in seven-core photonic crystal fiber pumped by a broadband picosecond pulsed fiber amplifier*

Ning Su(苏宁), Ping-Xue Li (李平雪)†, Kun Xiao(肖坤), Xiao-Xiao Wang(王晓晓), Jian-Guo Liu(刘建国), Yue Shao(邵月), and Meng Su(苏盟)

Institute of Laser Engineering, Beijing University of Technology, Beijing 100124, *China*

(Received 15 November 2016; revised manuscript received 16 March 2017; published online 6 June 2017)

We report a supercontinuum source generated in seven-core photonic crystal fibers (PCFs) pumped by a self-made all-fiber picosecond pulsed broadband fiber amplifier. The amplifier's output average power is 60 W at 1150 nm with spectral width of 260 nm, and its repetition rate is 8.47 MHz with pulse width of 221 ps. With two different lengths of seven-core PCF, different output powers and spectra are obtained. When a 10 m long seven-core PCF is chosen, the output supercontinuum covers the wavelength range from 620 nm to 1700 nm, with the output power of 11.7 W. With only 2 m long seven-core PCF used in the same experiment, the wavelength of the supercontinuum spans from 680 nm to 1700 nm, with the output power of 20.4 W. The results show that the pulse width is 385 ps in the 10 m long seven-core PCF and 255 ps in the 2 m long one, respectively, due to the normal dispersion of the PCF.

Keywords: photonic crystal fiber, seven-core, supercontinuum, all-fiber

PACS: 42.55.Wd, 42.60.Da, 42.62.Fi **DOI:** 10.1088/1674-1056/26/7/074210

1. Introduction

Recently, the supercontinuum source has played an important role in a wide area, such as spectroscopy,[1] multi-wavelength pulse source,[2] frequency metrology,[3] and so on. Good results are obtained by different kinds of fiber lasers: continuous lasers,[4,5] nanosecond pulse lasers,[6,7] and picosecond/femtosecond pulse lasers.[8–11] Some of them have reached hectowatt scale.[4,8,9] Compared with continuous laser, picosecond/femtosecond pulsed laser has more advantages because it has much higher peak power to induce stronger nonlinear effects for wider spectrum. However, the nonlinear effects resulting from the femtosecond pulsed laser are always too strong to keep the pulse trains stable. Besides this, the output pulses are mired in a mess caused by the soliton self-frequency shift and modulation instability.[12] They have serious distortion even breaking into lots of small pulses. Picosecond pulsed laser has not only high single pulse energy and peak power, but also high nonlinear effects mainly of self-phase modulation (SPM) and stimulated Raman scattering (SRS). The output supercontinuum source has orderly pulsed trains with good time coherence and wide flat spectrum simultaneously. These features are beneficial for practical applications, such as photo detection[13] and military interference.[14] Recently, there has been plenty of specific research in supercontinuum pumped by picosecond pulsed laser generated in single-core photonic crystal fibers (PCFs)[15,16] and multi-core PCFs.[17,18] Chi *et al.*[19] used a 100 W picosecond laser source to pump two different kinds of single-core nonlinear PCF to produce a supercontinuum source and obtained 30 W and 36 W output powers corresponding to spectral broadening ranges from 550 nm to 1650 nm and from 500 nm to 1650 nm, respectively. Single-core nonlinear PCF has thin core and strong nonlinear effects, but its mode field diameter is small and the welding efficiency is very low due to the mode field mismatch between single-core nonlinear PCF and laser source. In order to solve these problems of mode field mismatch and low coupling efficiency, multi-core PCF is generally applied. It also assures strong nonlinear effects to bring out high power supercontinuum at the same time. Modotto *et al.*[20] reported supercontinuum of mW scale generation in a multi-core PCF pumped by a 600 ps Q-switched germanium-doped Nd:YAG pump laser. But space coupling system is unstable and the input face of the PCF is easily damaged by laser. Therefore an all-fiber system is more favorable for supercontinuum. Wei *et al.*[21] investigated a supercontinuum source produced in 20 m seven-core PCF pumped by a 20 ps fiber amplifier at the repetition rate of 480 MHz. The generated supercontinuum covers the wavelength range from 720 nm to beyond 1700 nm, with an output power of 42.3 W. Huang *et al.*[22] demonstrated a gain-switched all polarization-maintaining fiber laser system with pulse width of 160 ps and average output power of 4.5 W utilized to pump 35 m seven-core PCF, allowing the supercontinuum source with output power of 2.443 W covering wavelength from 500 nm to 1700 nm. Chen *et al.*[23] reported a 104.2 W supercontinuum spanning from 750 nm to beyond 1700 nm generated from a 20 m long seven-core PCF pumped by a 141.6 W picosecond fiber laser. The high output power embodies the superiorities of the multi-core PCF for the su-

*Project supported by the National Natural Science Foundation of China (Grant No. 61205047).

†Corresponding author. E-mail: pxli@bjut.edu.cn

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percontinuum. But the supercontinuum spectrum is not wide enough especially in the short wavelength region because of the high repetition rate of 1.9 GHz of the pump laser which caused low single pulse energy of 5.5 nJ and low peak power of 421 W.

To solve these problems, shorter length of seven-core PCF pumped by a picosecond broadband fiber amplifier with wide spectral width of 260 nm, narrow pulse width of 221 ps, high peak power of 32 kW, and high single pulse energy of 7.08 μJ was adopted to get wider supercontinuum. When a 10 m long seven-core PCF was chosen in the experiment, the output power of the supercontinuum was 11.7 W with wavelength range from 620 nm to 1700 nm. In order to enhance the output power, the length of the seven-core PCF was reduced to only 2 m. When a 2 m long seven-core PCF was used, the output power increased to 20.4 W with the wavelength range from 680 nm to 1700 nm. The pulse trains were very stable, simultaneously. We also analyzed the theory of the broad spectra with the influences of nonlinear effects such as the SPM and the SRS.

2. Experiments and results

As shown in Fig. 1, the setup of supercontinuum source system includes three parts: picosecond pulsed laser source, transition fiber, and seven-core PCF. The picosecond pulsed laser source is obtained by master oscillator pulse amplification (MOPA) technology, which consists of an NPR mode-locked picosecond pulse fiber oscillator as a seed source and a two-stage ytterbium-doped all-fiber amplifier. The average output power of the oscillator is 25.8 mW at 1033 nm with repetition rate of 8.47 MHz and pulse width of 567 ps. After the fiber oscillator, a fiber isolator is used to prevent the preamplifier's backward reflection into the seed source. The seed laser is injected into a two-stage ytterbium-doped all-fiber amplifier. The first stage is a cladding pumped fiber amplifier using a 4 m long 10/130 μm core/cladding ytterbium-doped fiber and the second stage uses the same kind of ytterbium-doped fiber with a length of 6 m. The transition fiber is a 10/130 μm undoped core/cladding fiber, which is used to reduce the mode field mismatch between the amplifier and the seven-core PCF. The splice loss between the transition fiber and the seven-core PCF is about 3 dB, so we cool the splice point for heat dissipation to prevent its breakdown. The seven-core PCF consists of seven sold silica cores and five rings of hexagonal-arrangement air holes, and the distance between the two most adjacent holes is about 3.26 μm. The diameters of the innermost layer air holes are 1.2 μm, while the other air holes are 1.47 μm. The zero dispersion wavelength of the fiber is about 1117 nm, and the equivalent mode field diameter is about 18 μm at 1064 nm which can support higher power. Finally, a self-made non-doped fiber mode-expanding end-cap is spliced to the end of the seven-core PCF.

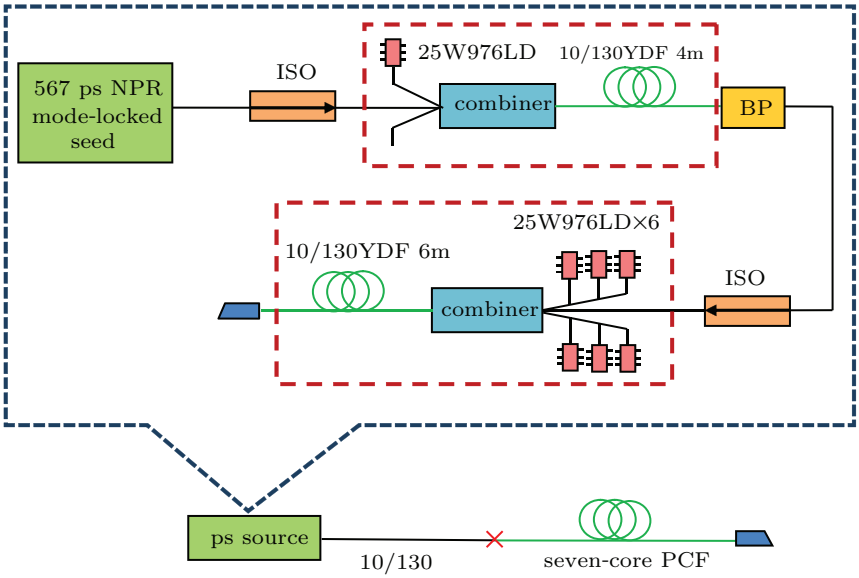


Fig. 1. (color online) The setup of all-fiber picosecond pulse amplifier and supercontinuum source system.

When the average pump power of the master amplifier is 86 W, the output power of the amplifier is 60 W, as shown in Fig. 2. The output spectrum of the amplifier at this time is observed by an optical spectrum analyzer with measurement ranges from 900 nm to 1700 nm (Ocean Optics Spectrometer-NIRQ512, resolution: 3 nm), as shown in Fig. 3. We can find that the central wavelength is 1150 nm with the spectral width of 260 nm. The gain medium (ytterbium-doped fiber) has a strong emission band around 1064 nm, which provides obvious advantages in the mode competition. The central wavelength red shifts to 1064 nm firstly. With the increasing power, the strong nonlinear effects in the amplifier (SPM and

SRS) will play an important role to broaden the spectrum to the long wavelength region. So there is long central wavelength red shifting finally. The repetition rate is 8.47 MHz and the pulse width is 221 ps measured by a high-speed digital oscilloscope (LyCroy, band-width: 13 GHz) with an ultrafast photodetector (ALPHALAS, band-width: 10 GHz, rise time: 35 ps), as shown in Fig. 4. Normally, the pulse width of the amplifier should be larger than that of the oscillator, which is caused by positive dispersion of the amplifier system. This opposite phenomenon may be caused by gain saturation. The gain saturation for pulse frontier edge is weaker than pulse trailing edge due to the time dependence of gain effect, which can result in pulse narrowing in time domain.[24,25]

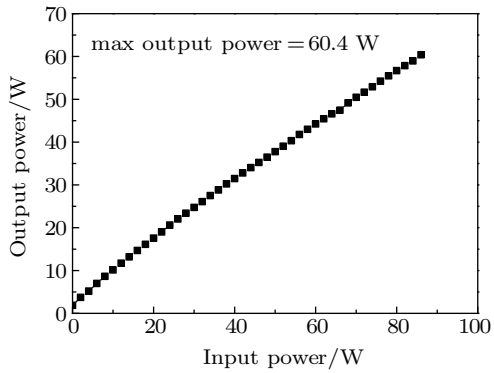


Fig. 2. The input–output power curve of the amplifier.

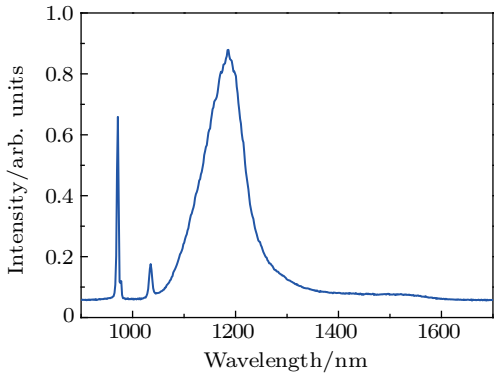


Fig. 3. (color online) The spectrum curve of the amplifier.

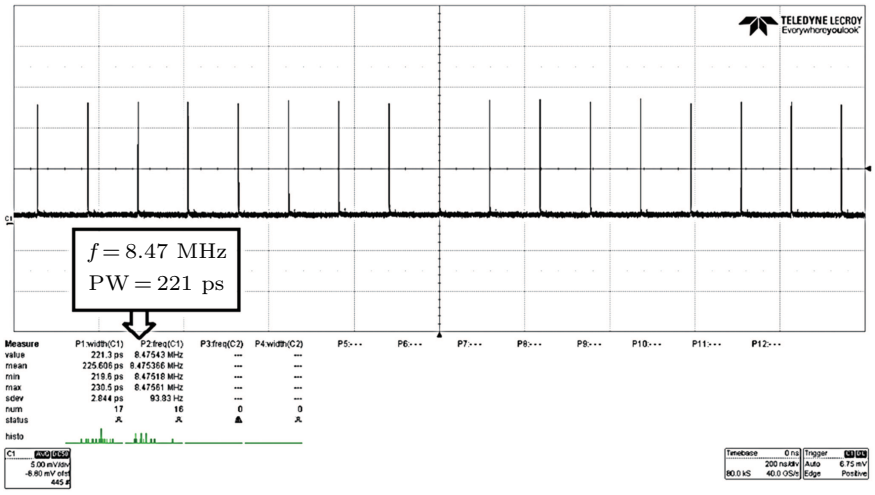


Fig. 4. (color online) The mode-locked laser pulse trains and the pulse width of the amplifier.

Firstly, we choose a 10 m long seven-core PCF in our supercontinuum experiment. When the output power of the amplifier is 44.3 W, the output power of the supercontinuum is 11.7 W as shown in Fig. 5. If we continue to increase the pump power of the amplifier, the output power of the supercontinuum will increase slowly. The reason is that there are very strong nonlinear effects (especially SPM and SRS) in the seven-core PCF to help to broaden the spectrum. The spectral width of the amplifier is 260 nm, covering both the normal dispersion region and the negative dispersion region of the seven-core PCF. When the central wavelength of the amplifier locates in the anomalous dispersion region, modulation instability works firstly and produces Raman solitons to spread the spectra to long wavelength region due to the soliton self-frequency shift. With the increasing pump power, the high-energy solitons move to the normal dispersion region in the form of a dispersive wave. Then the dispersive wave interacts with the high-energy solitons in the long-wavelength region to spread the spectra to the short-wavelength region because of cross phase modulation (XPM) and four-wave mixing (FWM). When the central wavelength of the amplifier locates in the normal dispersion region, SPM plays its role firstly to widen the spectra to both regions of long and short wavelength. Then SRS appears and cascaded Raman broadens the spectra of the long-wavelength region. When the spectra cover the zero dispersion point finally, it will be similar to the situation of anomalous dispersion on the broadening mechanism. Further increasing the injected power would generate

further spectral components, thus giving rise to the evident broadening of spectra and slow increasing of output power. The spectrum of supercontinuum generated from the 10 m long seven-core PCF is observed by an optical spectrum analyzer (YOKOGAWA-AQ6370D, resolution: 0.02 nm, detector range: 600 nm–1700 nm). Figure 6 shows that the flat spectrum covers from 620 nm to 1700 nm at the average output power of 11.7 W. The spectrum range can be judged clearly, although there is some noise in the figure. Strong injected power to the optical spectrum analyzer will lead to the oversaturation in the long wavelength region. The pulse width of the supercontinuum is 385 ps measured by the high-speed digital oscilloscope (LyCroy, band-width: 13 GHz), as shown in Fig. 7. It is obviously much wider than the pulse width of the amplifier. The main reason is the functions of the normal dispersion and the accumulated nonlinear chirp which is equivalent to the normal dispersion in the PCF. Figure 7 also indicates that the supercontinuum laser pulse trains are very stable and uniform without pulse distortion or pulse splitting. The pulse shape and the repetition rate of the supercontinuum laser are no different to that of the signal laser from the amplifier while the spectrum is broadening.

The supercontinuum generated in the 10 m long seven-core PCF has very wide spectrum and quite high peak power but high average power. So in order to obtain high average output power, high single pulse energy, and wide spectrum simultaneously, the length of the seven-core PCF is cut down to 2 m. The result of the 2 m long seven-core PCF indicates that the output power rises to 20.4 W with the same injection power of 44.3 W, just as shown in Fig. 8. Figure 9 shows that the output spectrum spreads from 680 nm to 1700 nm at the average output power of 20.4 W measured by an optical spectrum analyzer (YOKOGAWA-AQ6370D, resolution: 0.02 nm, detector range: 600 nm–1700 nm). Although the power is higher, the spectrum is narrower than the result of the 10 m long seven-core PCF because that shorter PCF has less nonlinear effect and needs more energy to stretch its spectrum. The high-speed digital oscilloscope (LyCroy, band-width: 13 GHz) shows that the pulse width of the supercontinuum is 255 ps shown in Fig. 10 when the output power is 20.4 W. Less normal dispersion and accumulated nonlinear chirp in the 2 m long seven-core PCF cause a pulse width narrower relative to the 10 m long seven-core PCF.

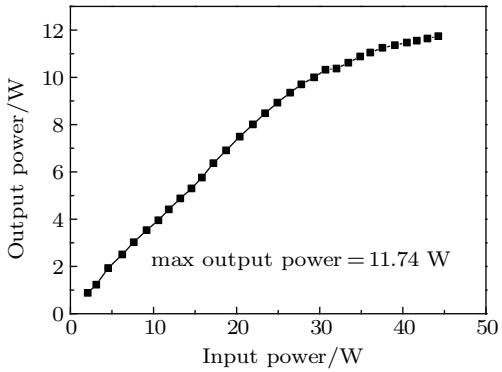


Fig. 5. The input–output power curve of supercontinuum system of 10 m long seven-core PCF.

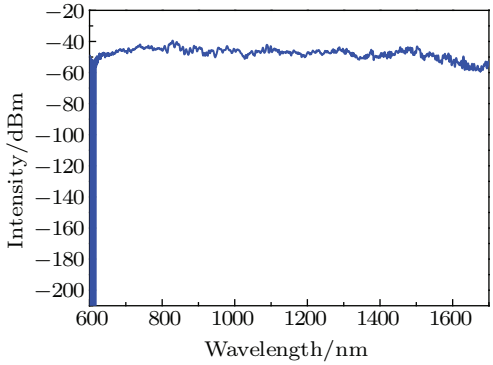


Fig. 6. (color online) The output spectrum of the supercontinuum produced in 10 m long seven-core PCF.

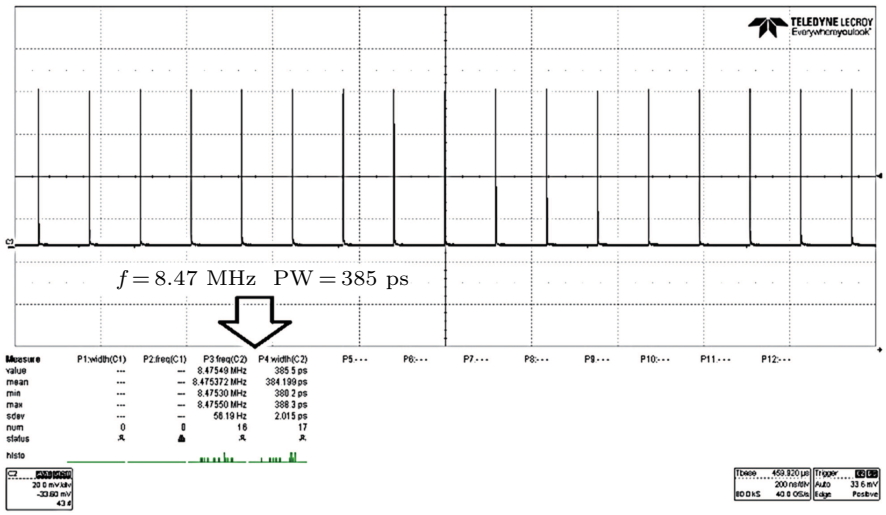


Fig. 7. (color online) The laser pulse trains and the pulse width of supercontinuum produced in 10 m long seven-core PCF.

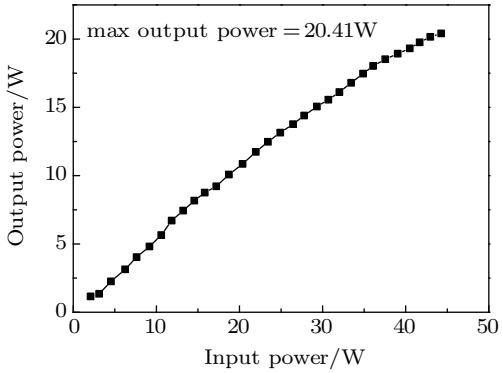


Fig. 8. The input–output power curve of supercontinuum system of 2 m long seven-core PCF.

As noted above, the central wavelength of the amplifier matches well with the zero dispersion point of the seven-core PCF which can generate supercontinuum with high single pulse energy and wide spectrum pumped by the picosecond pulse amplifier with narrow pulse width and high peak power. The output supercontinuum pulse trains are stable without serious distortion and pulse splitting, which is important for the applications of the supercontinuum source. We get 20.4 W supercontinuum source with spectrum range from 680 nm to 1700 nm by using only 44.3 W of the amplifier when the length of the seven-core PCF is 2 m.

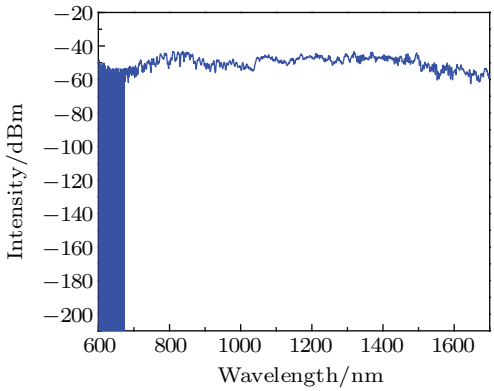


Fig. 9. (color online) The output spectrum of the supercontinuum produced in 2 m long seven-core PCF.

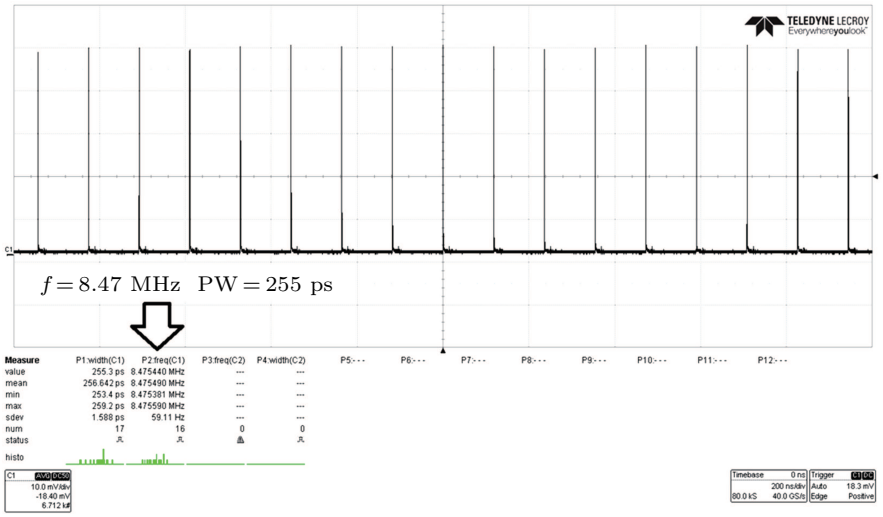


Fig. 10. (color online) The laser pulse trains and the pulse width of supercontinuum produced in 2 m long seven-core PCF.

3. Conclusion

In summary, we demonstrate a supercontinuum source by adopting an all-fiber broadband picosecond pulse fiber amplifier to pump nonlinear seven-core PCF with zero dispersion wavelength covered by the spectrum of the amplifier. The nonlinear effects in normal dispersion region and negative dispersion region can help to obtain wide spectrum. An NPR mode-locked fiber oscillator of 567 ps with repetition rate of 8.47 MHz and average output power of 25.8 mW is used as a seed source to be injected into a two-stage ytterbium-doped MOPA all-fiber amplifier. The central wavelength of this amplifier is 1150 nm with the spectral width of 260 nm, and the output power is 60 W with the pulse width of 221 ps. We analyze two different lengths of seven-core PCF contrastively. When the seven-core PCF is 10 m long, the output supercontinuum ranges from 620 nm to 1700 nm with the output power of 11.7 W and pulse width of 385 ps. When only 2 m long seven-core PCF is used, the output power is enhanced to 20.4 W with a pulse width of 255 ps and a spectrum range from 680 nm to 1700 nm. The pulse trains are uniform without pulse splitting.

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