Review

Recent developments in high power near-infrared supercontinuum generation based on photonic crystal fiber*

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High power supercontinuum generation witnessed rapid developments in the past few years. The mechanism and the latest achievements in high power supercontinuum generation are reviewed both for the continuous wave pump regime and the pulsed pump regime. The challenges in scaling the average power of supercontinuum generation are analyzed. Some of our works on high power supercontinuum generation are summarized, and perspectives for the future development are discussed.

Keywords: fiber laser, supercontinuum, photonic crystal fiber

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1. Introduction

The supercontinuum (SC) generation is a process with which narrow-band optical pulses undergo strong spectral broadening in a nonlinear medium to yield an output with a strongly broadened spectrum. Since the first observation in bulk media in 1970,[1,2] the SC has attracted the attention of researchers across the world for its spatial coherence, high brightness, and broad bandwidth. Especially after the fabrication of photonic crystal fiber (PCF) in 1996,[3] the research on the SC generation was reinvigorated owing to the high nonlinearity and the flexible dispersion control of the PCF.[4,5] The SC generation has been widely used in spectroscopy, confocal microscopy, and optical coherence tomography.[6−9]

2. State of the art SC generation in continuous wave pump regime

The dominate method used in high power SC generation at present is to utilize a continuous wave (cw) or pulsed fiber laser to pump a piece of PCF. In the cw pump regime, the central wavelength of the cw pump laser usually lies in the anomalous dispersion region of the PCF, and the SC starts from the noise. Typically, the modulation instability (MI) breaks up the cw field and gives rise to the first-order solitons. These solitons undergo intrapulse Raman scattering, which results in the soliton self-frequency shifts (SSFSs) and generates a long-wavelength soliton Raman continuum.[10] The SC in the short-wavelength direction could resort to the four wave mixing (FWM) and the soliton trapping mechanisms. A 29 W SC was obtained by using a 50 W commercial cw ytterbium-doped fiber laser as the pump source.[11] The optical spectrum covered the range from 1.06 μm to 1.67 μm. A 20 m long PCF with two zero dispersion wavelengths was used. The optical glue was utilized to secure the splice point and strip the stray light with only 0.4 dB loss between the PCF and a high numerical aperture (NA) fiber.[11] In another experiment, a 50 W Yb fiber laser produced by the IPG Photonics, centered at 1.071 μm with a linewidth of 0.3 nm, was directly spliced to a 100 m long PCF with zero-dispersion wavelength of

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1.068 μm, nonlinear coefficient of 9.8 $W^{-1}\cdot km^{-1}$, and mode field diameter of 5 μm. A maximum of 32.6 W SC was obtained with no spectral component above 1.38 μm owing to the 130 dB/km high water loss at 1.38 μm.[12] Another paper reported an over 50 W SC extended from 1.06 μm to 2.02 μm with the 10 dB width of spectrum over 900 nm achieved using a 20 m HF840 fiber, and a 28 W SC extended from 0.6 μm to 1.9 μm with over 2 mW/nm spectral power density in the short wavelength side by using a 50 m HF1050 fiber. The pump was a commercial 432 W cw fiber laser produced by the IPG Photonics with the central wavelength at 1.07 μm and a spectral linewidth of 3.6 nm. The single mode output of the laser was first collimated and then coupled into a series of mode matching single mode fibers through bulk lens to reduce the mode field diameter before finally splicing to the PCF. The free-space coupling efficiency was typically greater than 70%, and the total free-space to PCF efficiency was between 30% and 50% depending on the splice loss to the PCF.[13] Using cw pump sources to obtain a high power SC is simple in configuration. However, it requires a long PCF, and special attention should be paid to the splice point when the power of the pump source is high.[14]

3. State of the art SC generation in pulsed pump regime

In the pulsed pump regime, the SC starts from the MI if the central wavelength of the pump source lies in the anomalous dispersion region of the PCF, or from the self-phase modulation (SPM) if the central wavelength of the pump source lies in the normal dispersion region of the PCF. The stimulated Raman scattering (SRS) effect generates new frequencies of long-wavelength, and when the soliton is produced, its function in the long-wavelength continuum formation is the same as that in the cw pump regime. The FWM and the soliton trapping mechanisms could produce new frequencies in the short wavelength if their phase requirements are satisfied. A maximum average output power of 39 W SC covering a spectral range of 0.4–2.25 μm was achieved at an incident pump power of 57 W with a repetition rate of 114.8 MHz.[15] The pump laser was a robust, repetition-rate tunable, Yb-doped fiber master oscillator power amplifier (MOPA) configuration with a 21 ps gain-switched seed. The spectral power density more than 30 mW/nm was relatively uniform across the visible region. The peak power density could be increased to 26.9 W/nm by reducing the repetition rate to 28 MHz. The optical-to-optical conversion efficiency was up to 74%.[15] However, the configuration is not an all-fiber structure, which greatly comprised the stability and the practicality of the system. Over 100 W picosecond pump power with the central wavelength at 1.05 μm was used to pump a 5-m-long commercially available PCF, and a 49.8 W SC spanning from around 0.5 μm to above 1.7 μm was obtained.[16] The PCF SC-5.0-1040 from the crystal fiber had a zero dispersion wavelength (ZDW) around 1.04 μm and a nonlinear coefficient of 11 $W^{-1}\cdot km^{-1}$ at 1.06 μm. The single mode operation across the whole spectral range was verified through the quantitatively measurement of the beam quality. An end-cap made of pure silica fiber with a length around 200 μm was used to protect the end facet of the PCF. The system could last for one hour under the maximum output power.[16] The pulsed pump regime is attractive owing to its high peak power and short length requirement for the PCF. However, due to unavailable of high power ultrafast fiber lasers, the average output power of SC generation is still under the hundred-watt level.

4. Challenges

There are three challenges in scaling the average power of SC in the current method. The first challenge is the conflict between the high peak power needed for the SC generation in the PCF and the low peak power needed for the nonlinear mitigation in the pump laser itself. The second challenge is the heat produced, especially the heat produced at the splicing point. Because even very small splicing loss could result in a disastrous result under high pump power. The third challenge is the control of nonlinear effects both in the pump laser source and in the PCF.

We demonstrated our first high power 100 W all-fiber picosecond laser in 2009.[17] The system was constructed in the four-stage MOPA configuration, and the seed source was a YDF laser passively mode-locked by a semiconductor saturable absorber mirror (SESAM).[18] The nonlinear effects in the fiber amplifiers were effectively suppressed by using a home-made repetition increasing system. The ultimate outputs of

that laser had a pulse width of 16 ps, a beam quality (M^2) of less than 1.5, and an optical conversion efficiency of 61.5%. In the same year, the problem of low splicing loss between the large mode area double clad fiber and the PCF was solved by using the PCF post-processing methods.[19] The mode field of the PCF could be increased up to three times by adiabatic collapsing two-inner-ring air holes, which acted as the transition region between the double clad fiber and the normal PCF. As a result, less than 10% splice loss could be realized. The typical structure is shown in Fig. 1.[20] Our first SC source was constructed in 2010 with an average output power of 7 W. The picosecond pump fiber laser could output a maximum average power up to 20 W at 480 MHz with the central wavelength at 1.064 μm. A 40 m home-made PCF with 7 μm core was used, and the spectrum covered a range more than 1100 nm (from 0.6 μm to beyond 1.7 μm) with an optical-to-optical conversion efficiency of 34%.[21] In order to scaling the average output power of the SC generation, the core of the PCF was enlarged at the input end through a series of PCF post-processing methods to match the output fiber of the picosecond pump laser. With the optimization of the splicing loss between the double clad fiber and the PCF, a 20 W SC was achieved under 29.5 W picosecond pump power, and the optical-to-optical conversion efficiency was improved to 67.8%.[22] The output spectrum covered the wavelength range from 0.65 μm to beyond 1.7 μm, and a 31-m long PCF was used. Further scaling the average output power is mainly limited by the available pump power. So increasing the average output power of the ultrafast pump laser source is a requisite in scaling the average output power of the SC generation. In the same year, a 35.6 W SC was obtained by using a 57.7 W picosecond pump source with the central wavelength at 1.064 μm, the spectrum covered the range from 0.65 μm to beyond 1.7 μm with an optical-to-optical conversion efficiency of 62%.[23] The results are shown in Fig. 2. Further scaling the average output power of SC needs novel designs to overcome the problems of high splice loss, heat treatment, fiber facet damage, and control of nonlinear effects. In 2011, an all-fiber 70 W SC source was achieved with an optical-to-optical conversion efficiency of 67.3%.[24] The spectrum covered the range from 1.064 μm to beyond 1.7 μm, and the spectral flatness was better than 12 dB. The spectrum and the experimental photograph are shown in Figs. 3(a) and 3(b), respectively. Several months later, we realized a 156.6 W high power picosecond laser in the all-fiber MOPA configuration. A home-made repetition increasing system as well as a short gain fiber with high concentration was utilized to suppress the nonlinear effects under the high pump power, and an optical spectrum width of 0.6 nm and a pulse width of 24 ps were obtain in the maximum output power.[25] In the same year, a 177.6 W SC was achieved with its spectrum ranging from 1.064 μm to beyond 2 μm.[26] The 10 dB optical spectrum width was 740 nm, and the optical-to-optical conversion efficiency was 56%. The experimental results are shown in Fig. 4.

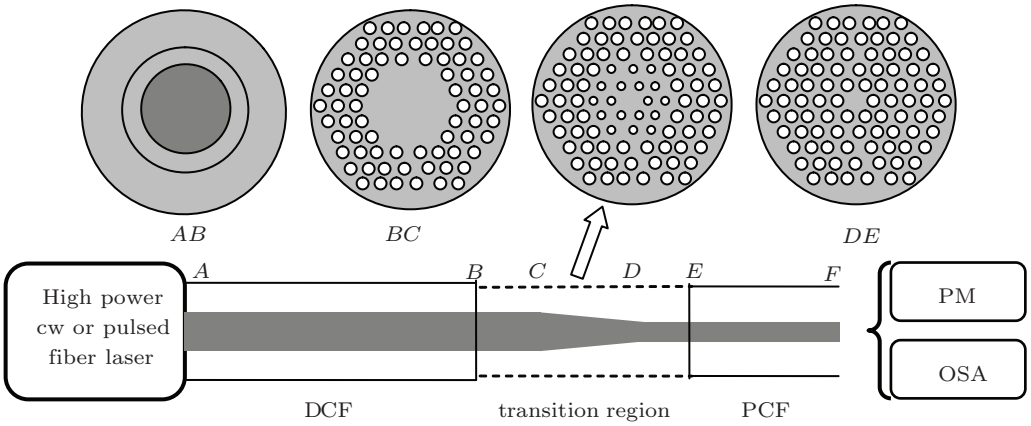


Fig. 1. Typical structure in high power SC generation using PCF, the top panel shows the cross sections in the corresponding regions shown in the bottom panel.[20] The complete hole-collapse region is from B to C, the gradual hole-collapse region is from C to D.

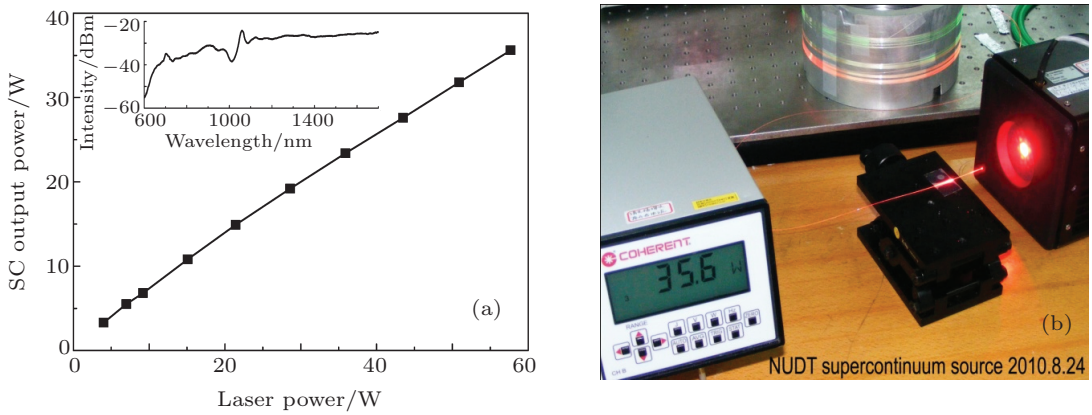


Fig. 2. (colour online) (a) Output power versus ps laser pump power in an SC.[23] The inset is the spectrum of the SC. (b) Photograph of the SC.

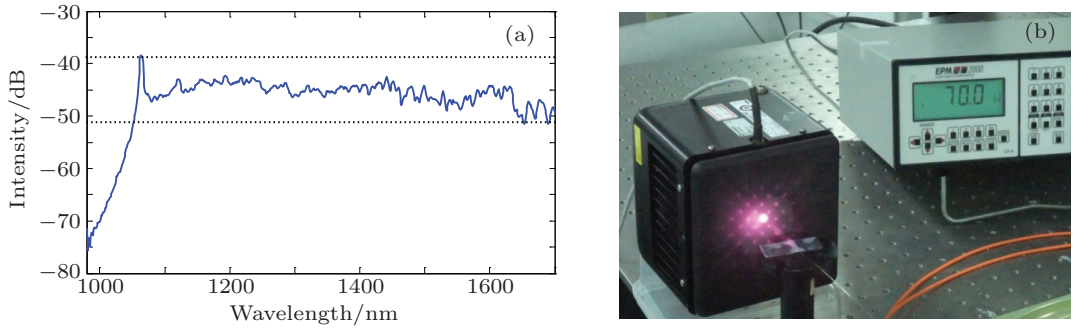


Fig. 3. (colour online) (a) Output spectrum of an SC, (b) photograph of the SC.[24]

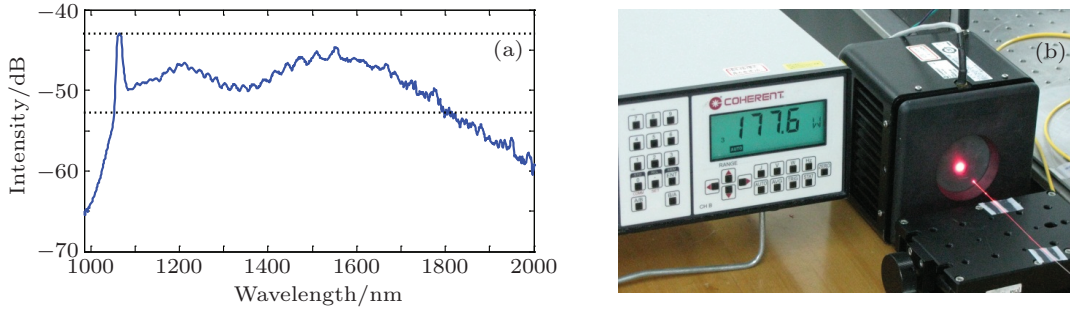


Fig. 4. (colour online) (a) Output spectrum of an SC, (b) photograph of the SC.[26]

5. Conclusion

In conclusion, although the high power SC generation has witnessed rapid progress in recent years, there is still a long way to go, and a great improvement is still possible compared with the 36 kW power limit of single mode fiber lasers with diffraction-limited quality.[27] The SC generation with higher average output power is still under investigation, and we believe some new breakthroughs could occur in the near future.

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