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Chang Sun
Tingwu Ge
Siyuan Li
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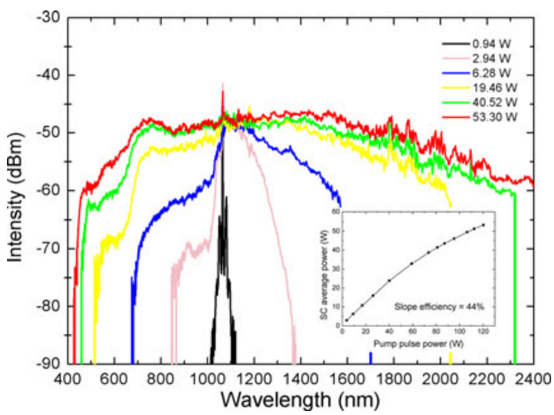
Zhiyong Wang



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53.3 W Visible-Waveband Extra High Power Supercontinuum All-Fiber Laser

Chang Sun, Tingwu Ge, Siyuan Li, Na An, Kang Cao, and Zhiyong Wang

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

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Abstract: A visible-waveband extra high power supercontinuum (SC) all-fiber laser is demonstrated. The laser structure includes a seed laser, master power amplifier, and the SC generation system, which usually adopts photonic crystal fiber (PCF) with small mode area as the nonlinear (NL) medium. A repetition frequency multiplier is utilized in the seed laser to adjust the pulse peak power and suppress the NL effects in the amplification process. Additionally, a homemade all-fiber high power mode field adaptor, which is used to couple the pump pulses into the small mode area PCF, works successfully at the incident pulse power of 120 W with high coupling efficiency of 83%. Eventually, 53.3 W visible-waveband extra high power SC fiber laser is obtained with spectrum ranging from 430 to 2400 nm and spectral width below 10 dB flatness exceeding 1700 nm (except pump wavelength). In addition, the visible-waveband power (below 850 nm) takes up about 22% of the total SC power. To the best of our knowledge, this is the highest average power of visible-waveband extra SC source ever reported in such broad spectrum range and high spectrum flatness.

Index Terms: Super-continuum generation, laser amplifiers, fiber non-linear optics, fiber lasers.

1. Introduction

In recent years, the high power super-continuum (SC) all-fiber laser source has been attracting extensive attention in many areas, including sensors and detection, laser radar, advanced medical imaging, and fiber communication because of its broadband spectrum, high spatial coherence, high brightness, and compact structure [1]–[3]. It has also been developing dramatically in terms of SC average power. For example, 35 W high power SC source was obtained in the photonic crystal fiber (PCF) with spectrum ranging from 600 nm to 1700 nm, which was pumped by a 57.7 W passively mode-locked picosecond pulse fiber laser [4]. In another case, based on a new type of seven-core PCF, the average power of 42.3 W SC pumped with an ytterbium-doped fiber master oscillator power amplifier was generated and it covered the wavelength range from 720 nm to 1700 nm [5]. The report on SC with 116 W output power is the latest record. It employed a repetition rate of 1.9 GHz picosecond fiber laser to pump a piece of multi-core PCF; finally, the high power SC was obtained with spectrum spanning from 800 nm to 1700 nm [6].

The above experimental results indicate that although the SC power has been increased to tens of watts or even over hundred watts, the spectrum range of SC is not further broadened to the visible-waveband and the visible-waveband power occupies only a little part of the whole SC. However, in some special fields such as stimulated emission depletion microscopy and hyper spectral imaging,

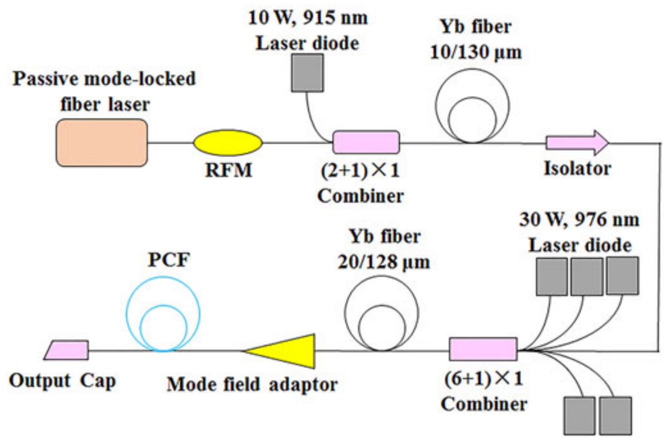

Fig. 1. Schematic of visible-waveband extra high power SC all-fiber laser.

the application of visible-waveband SC is becoming increasingly more important [7], [8]. Thus, it is of great significance to generate visible-waveband extra high power SC source, but in fact, it is difficult to achieve the SC like this. On one hand, to generate visible-waveband SC, the PCF with high nonlinear (NL) coefficient is usually adopted as NL medium to obtain high NL effects in the process of SC generation, but high NL coefficient usually means that the PCF has small mode area. On the other hand, generating high power SC requires high power pump pulses to pump PCF; therefore, a large mode area active fiber is required in pump pulse laser to suppress the NL effects during the amplification process. Thus, the need for a high power mode field adapter (MFA) which can reduce the mode field mismatch between pulse laser fiber and PCF is of great importance. However, there are no high power MFA products in market. At present, most commercial MFA can realize mode matching from large core diameter fiber to small core diameter fiber. Only a handful of MFA products can obtain reverse mode matching, but they can only operate at tens of watts, which is not enough for high power fiber laser. Additionally, in practice, the mode area of the active fiber in amplifier is limited, and therefore, we need to explore other effective methods to control the NL effects in the amplification process, and further enhance the pump pulse power to increase the average power of visible-waveband extra SC source.

In this paper, the thermally expanded core technique is adopted to fabricate a home-made all fiber MFA with 20/125 μm input fiber and 6/125 μm output fiber, and it can work successfully under the incident pulse power of 120 W with coupling efficiency of 83%. Additionally, by employing a self-made repetition frequency multiplier (RFM), the NL effects in the pulse amplification process can be suppressed and 120 W high power pulse laser is obtained. Eventually, 53.3 W high power visible-waveband extra SC fiber laser is achieved with spectrum ranging from 430 nm to 2400 nm, spectral width below 10 dB flatness exceeding 1700 nm (except pump wavelength). The visible-waveband power (below 850 nm) also takes up about 22% of the total SC power.

2. Experimental Setup

The experimental schematic of visible-waveband extra high power SC all-fiber laser is shown in Fig. 1. It consists of a seed laser, fiber master power amplifiers and a SC generation system.

The seed laser is a semiconductor saturable absorber mirror (SESAM) passively mode-locked fiber laser including an oscillator and one stage preamplifier. The SESAM (from BATOP) is used as a mode-locked device with relaxation time of 2 ps, modulation depth of 50%. The oscillator gain is from a core-pumped highly Yb^{3+} doped fiber (YDF) with core absorption of 1200 dB/m at 975 nm, a length of 50 cm. The pump source is a 976 nm single mode laser diode with 6/125 μm pigtailed fiber. The parameters of optics in the preamplifier are about the same as the oscillator.

A homemade all-fiber RFM follows the seed laser, which is used to adjust the pulse peak power appropriately and reduce the NL effects in the amplification process. The RFM system consists of several 50:50 single–mode fiber couplers. These couplers are connected in sequence; the first one divides the pulses into two sequences, then each following one combines the pulses and doubles the repetition frequency (RF) of the input pulses. Therefore, this system can make the RF of input pulse increase exponentially according to the experimental requirements.

The master power amplifier includes two stage amplifiers. In the first stage amplifier, a piece of 11 m long cladding-pumped YDF is adopted as the gain medium, with core diameter of 10 μm and NA of 0.08, inner cladding diameter of 130 μm and NA of 0.46, and cladding absorption of 1.5 dB/m at 915 nm. The gain fiber is pumped by a 10 W, 915 nm central wavelength, 105/125 μm fiber pigtailed laser diode via a $(2 + 1) \times 1$ fiber combiner. A 3 W isolator with 10/130 μm fiber pigtailed follows the gain fiber, which is used to prevent the backward propagation light. In the second stage amplifier, the gain medium is a 2.5 m long large mode area YDF with the core/cladding diameter of 20/128 μm, the core/cladding NA of 0.09/0.46, and cladding absorption of 6.9 dB/m at 975 nm. Five 30 W multimode laser diodes are employed as pump source, with 975 nm central wavelength and 105/125 μm pigtailed fiber. A $(6 + 1) \times 1$ high power fiber combiner with 10/125 μm input fiber and 20/125 μm output fiber is used to deliver pump light into the gain fiber, and its coupling efficiency is about 95%.

A homemade high power fiber MFA following the amplifier is used to couple the high power picosecond pulses into PCF efficiently, and it exhibits an input pigtail of 20/125 μm double cladding passive fiber and output pigtail of 6/125 μm single mode passive fiber. Furthermore, the MFA also can strip the residual pump of the master power amplifier.

The SC generation stage is the final part of this experimental setup. The output fiber of MFA is spliced to a piece of 6 m long PCF (from YSL, SC-PCF-01), which has a core diameter of 4.8 μm, the zero dispersion wavelength of 1040 nm, and the NL coefficient of 11 $(W \cdot km)^{-1}$. A 1 cm long output end-cap with an 8° cleaved facet is spliced to the output end of the PCF; this can decrease the back reflection and enhance the damage threshold of the PCF output facet.

The experimental system is evaluated by measuring average powers, spectra, pulse trains and autocorrelation traces. The average powers are read with power meter (from OPHIR); the spectra are measured by optical spectrum analyzer (from YOKOGAWA, AQ 6373 with measuring range from 350 nm to 1200 nm, AQ 6370C with measuring range from 600 nm to 1700 nm, and AQ 6375 with measuring range from 1200 nm to 2400 nm); the pulse train is taken with oscilloscope (from Tektronix, DPO4054B); the autocorrelation traces are measured with autocorrelator (from Femtochrome, FR-103WS).

3. Experimental Results and Discussions

By adjusting the pump power of oscillator and designing the cavity length, 9.98 mW stable picosecond pulse is obtained, with fundamental RF of 78 MHz, central wavelength of 1064 nm, and 3 dB spectral bandwidth of 0.45 nm. Fig. 2(a) and (b) exhibit the typical shapes of the spectrum and pulses train. The pulse duration is about 12.3 ps if a Gaussian pulse profile is assumed, as can be seen from Fig. 3(a). In the following preamplifier, the average power of picosecond pulse is amplified to 210 mW.

Under the fundamental RF of 78 MHz, the NL effects like Stimulated Raman Scattering (SRS) and Self-phase Modulation (SPM) can be observed in the master power amplifier, when the pulse average power is amplified to 45 W. Fig. 4(a) shows that the peak of SRS occurs at around 1120 nm corresponding to 13.6 THz downshift of 1064 nm central wavelength, and the 3 dB spectral bandwidth of signal light is widen to 13.5 nm due to SPM effect. It means the signal pulse average power cannot be further amplified linearly because the central wavelength of 1064 nm will transfer more pump energy to the peak of SRS with the pump energy increasing, and the inverted SRS back light may damage the fiber devices. In this case, the estimated average power of SC is only about 20 W based on the empirical value of optical-to-optical conversion efficiency of PCF in previous experiment [9].

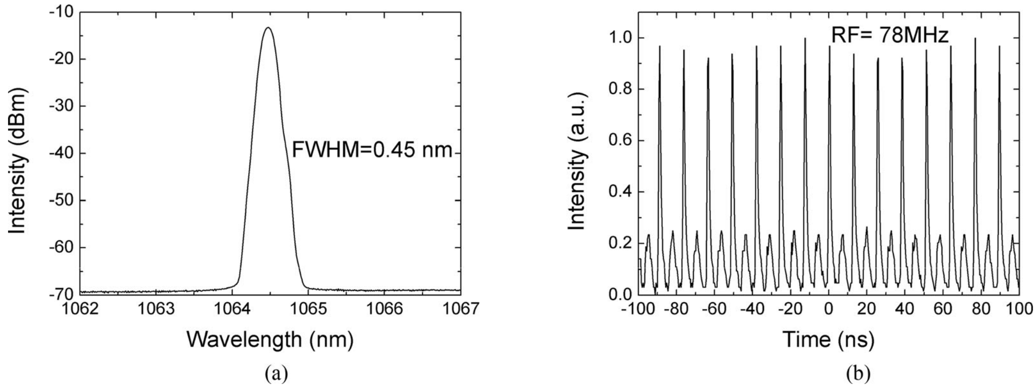

Fig. 2. (a) Output optical spectrum of the oscillator. (b) Picosecond pulse train of the oscillator.

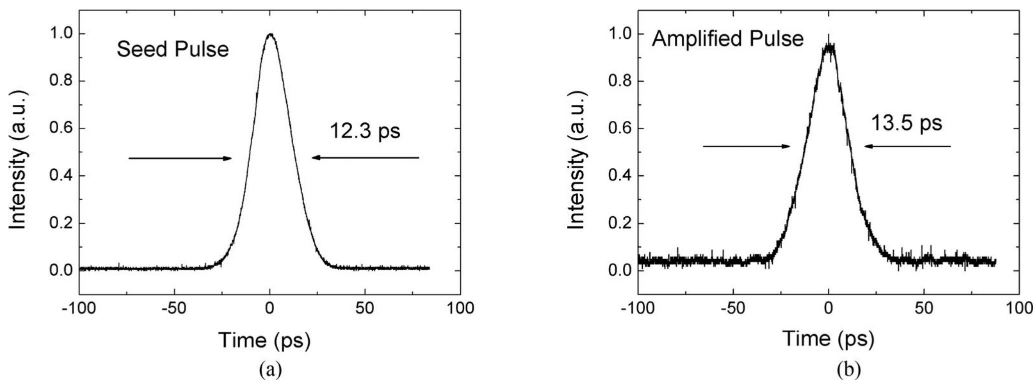

Fig. 3. (a) Autocorrelation trace of oscillator pulse. (b) Autocorrelation trace of the amplified pulse.

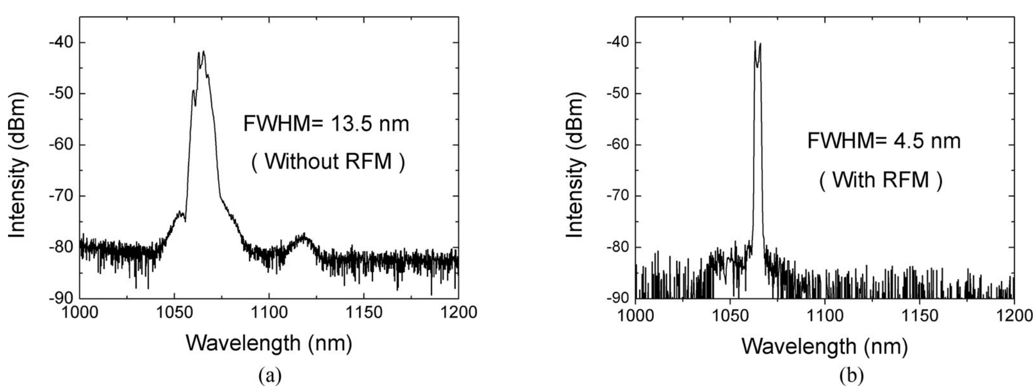

Fig. 4. (a) Spectrum of master power amplifier at average power of 45 W without RFM. (b) Spectrum of master power amplifier with output average power of 120.3 W in the case of using RFM.

In order to suppress the SRS effect in the amplification process and further increase the SC average power, a RFM is utilized in front of the master power amplifier, which quadruples 78 MHz fundamental RF of seed laser to 312 MHz. The output spectrum of picosecond pulse after amplification is shown in Fig. 4(b); it can be seen that the SRS effect does not occur with the pulse average power increasing to 120.3 W, and 3 dB bandwidth of the output spectrum is only about 4.5 nm. The duration of amplified pulse is 13.5 ps, as shown in Fig. 3(b); compared with pulse width of the seed

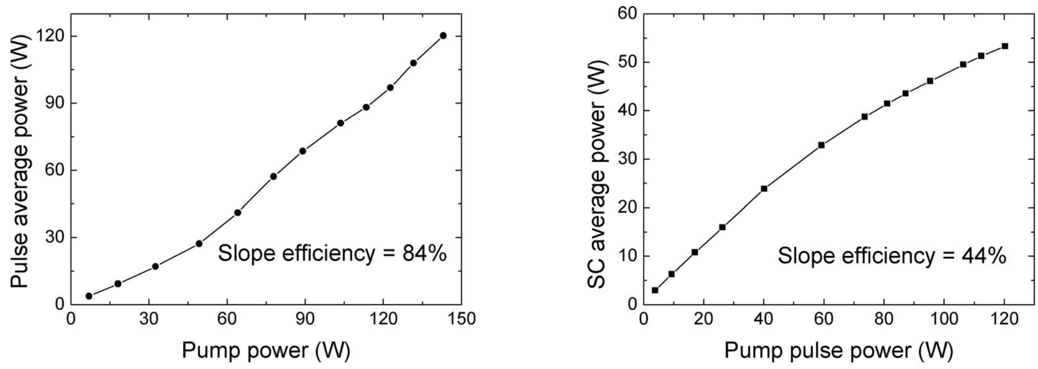

Fig. 5. (a) Curve of picosecond pulse average power versus the incident pump power of the master power amplifier. (b) Curve of SC average power versus the pump pulse power.

laser, it has just a small change, and the pulse is not transform limited. Fig. 5(a) shows the curve of picosecond pulse power versus total incident pump power of the master power amplifier; when the pump power is 143 W, the maximum pulse average power of 120.3 W is obtained with the slope efficiency of 84%, and the average power almost enhances linearly with the incident pump power increasing.

A high power MFA is the key point for the generation of visible-waveband extra high power SC source. In this experiment, we adopt thermally expanded core fibers technique to fabricate the MFA, and fiber fusion splicer Vytran 3400 is employed as the producing equipment. The transmission loss of MFA is caused mainly by mode field mismatch, tapered region length and expanded core shape, if there is only fundamental mode light in the fiber [10], [11]. After optimizing the above parameters by theoretical simulation and experiments, the high power home-made MFA is obtained with high coupling efficiency of 83%, and it can operate stably at the high incident pulse power of 120 W. The splicing point quality between the output fiber of MFA and PCF is also very crucial for generating high power SC. We employ Fujikura FSM-45F splicer, and adopt low current, short-term, multiple-discharge splicing method which can guarantee the air hole of PCF not to collapse to make the splicing point. Eventually, 0.5 dB low splicing loss was achieved.

With the pump pulse power coupled into PCF increasing, the visible-waveband extra high power SC with a maximum power of 53.3 W is obtained. The curve of SC average power versus pump pulse power is shown in Fig. 5(b), and the corresponding slope efficiency is 44.4%. Considering the above-mentioned transmission efficiency of MFA and the splicing loss, the optical-to-optical conversion efficiency of the PCF is estimated as 58%.

Fig. 6 illustrates the SC spectrum evolution with different average powers. In the beginning of the SC generation, a few new spectral components appear on both sides of the central wavelength because of SPM. With the pump pulse power increasing, the spectrum is broadened significantly on the long wavelength direction, and a small quantity of short wavelength components are also generated; these phenomena are caused mainly by the interaction of Modulation Instability (MI) and SRS. When the SC average power is up to 6.28 W, the red light can be observed with naked eyes. Due to MI, the incident pulses will be divided into more ultrashort pulses. In the anomalous dispersion regime of PCF, these ultrashort pulses will convert to higher order solitons and low order solitons under the action of Group Velocity Dispersion (GVD) and SPM, and then, the higher order solitons can generate the red-shift soliton and blue-shift dispersion wave because of intrapulse SRS; In the normal dispersion regime of PCF, the solitons exists as the form of dispersion wave. Therefore, the spectrum will be broadened on the both directions. As the pump pulse power continues to increase, due to the soliton trapping effect, the red-shift soliton and blue-shift dispersion wave can further broaden the SC spectrum, especially at the short wavelength direction. As can be seen from Fig. 6, more visible-waveband energy is generated with the pump pulse power growing. Meanwhile,

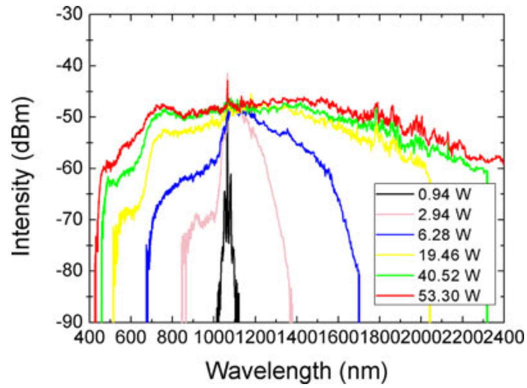

Fig. 6. SC spectrum evolution with different average output power.

the SC spectrum becomes more and more flat and wide. As the pump pulse power reaches 120 W, 53.3 W visible-waveband extra high power SC is achieved with spectrum ranging from 430 nm to 2400 nm, spectrum width below 10 dB flatness exceeding 1700 nm (except pump wavelength), and we can see the white light radiation. In addition, the visible-waveband laser is filtered by an 850 nm short-pass filter plate, and we measure its power. Consequently, the visible-waveband power is up to 12 W, and takes up 22% of the total SC power. This is of great significance for many applications.

4. Conclusions

In conclusion, we have experimentally demonstrated a high power visible-waveband extra SC all-fiber laser source. The difficulties of achieving it mainly lie in two aspects; one is to suppress the NL effects in amplification process to obtain high power pump pulses, and the other one is to efficiently couple high power pulse from large mode area pigtailed fiber of master power amplifier into PCF with small mode area. In our experiment, a home-made RFM is used in the master power amplifier to control the threshold of generation of NL effects, and 120 W average pulse power is obtained eventually. Additionally, we utilize thermally expanded core technique to fabricate a home-made all fiber MFA with 20/125 μm input fiber and 6/125 μm output fiber, and it can operate stably at 120 W high incident pulse power with 83% high coupling efficiency. Both of the two problems mentioned above have been solved effectively in this experiment. Finally, a visible-waveband extra high power SC fiber laser source is obtained with average power of 53.3 W, spectrum ranging from 430 nm to 2400 nm, spectrum width below 10 dB flatness exceeding 1700 nm (except pump wavelength). In addition, the visible-waveband power (below 850 nm) occupies about 22% of the total SC power. To the best of our knowledge, it is the highest average power of visible-waveband extra SC source ever reported, in such broad spectrum range and high spectrum flatness.

In the next step, we will try to further increase the visible-waveband SC power by optimizing the laser system such as designing the PCF with different structures, and this SC source will meet the application requirements in more and more fields.

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