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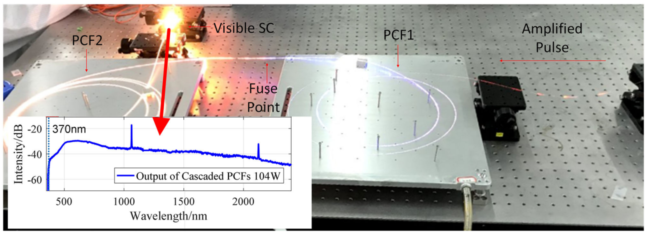

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All-Fiber High Power Supercontinuum Generation by Cascaded Photonic Crystal Fibers Ranging From 370 nm to 2400 nm

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Abstract: 104 W supercontinuum (SC) covering 370 nm-2400 nm is reported. High power visible SC is generated by pumping cascaded photonic crystal fibers (PCF) with 1064 nm picosecond pulse. Cascaded PCFs is fabricated by fusion splicing two different PCFs together with a coupling efficiency of 75%. For the purpose of avoiding fiber fuse phenomenon in PCF, the discharge time and intensity of fusion splicer should be precisely controlled. Two components of cascaded PCFs are pumped separately by 1064 nm picosecond pulse for comparing with the impact of cascaded PCFs. As a result of pumping cascaded PCFs, 104 W SC covering 370 nm−2400 nm is generated. Visible spectra (380 nm−780 nm) accounts for 50.4% (52.4 W) by numerical integration. To best of our knowledge, it's the first time that a visible SC with over a hundred watt output and 370 nm short-wave edge is obtained experimentally.

Index Terms: Fiber laser, Supercontinuum, Cascaded photonics.

1. Introduction

In 1970, R. R. Alfano and S. L. Shapiro proposed “supercontinuum” in his paper firstly, which is defined as the laser with spectrum ranging from tens to hundreds of nanometers. It was produced by using nonlinear medium pumped by high peak power laser [1]. Initially, bulk optical glass was used as nonlinear medium, due to its short interaction distance with the laser, bulk optical glass is not a material that can efficiently produce supercontinuum. In 1996, photonic crystal fibers (PCF) were successfully produced [2]. The zero-dispersion wavelength (ZDW) of the photonic crystal fiber can be easily tuned while maintaining single-mode transmission. These characteristics have accelerated the development of supercontinuum. After more than 20 years of development, SC was applied in a wide range of fields, such as industrial production, biomedical, laser imaging, gas detection and so on [3]–[8]. The increasing application put forward higher requirements for SC laser parameters. Among them, the generation of high-power visible SC is the focus of current research. In the past ten years, many researchers studied it [9]–[21]. In 2010, SC with short wave edge of 320 nm was generated by tapered PCF [22]. Due to fragile structure of tapered PCF, the output power of visible SC increased slowly in the last ten years. By using a single-core PCF pumped by 1064 nm picosecond pulsed fiber amplifier, Zhao Lei *et al.* obtained a SC output with an average

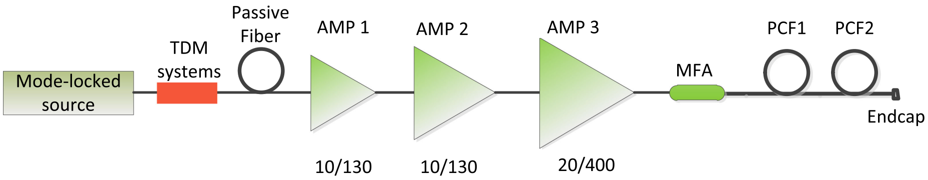

Fig. 1. The scheme of SC generation. The repetition rate is increased by the TDM systems and the pulse duration is stretched by the passive fiber. Three-state amplifiers with increasing fiber core boost the average power above several hundred watts before entering the PCFs. TDM: time division multiplexing systems; AMP: amplifier; MFA: mode field adaptor; and PCF: photonic crystal fiber.

power of 215 W and a spectrum ranging from 480 nm to 2400 nm in 2018 [23]. In the same year, Qi Xue *et al.* acquired SC with an average power of 80W and a spectrum covering from 350 nm to 2400 nm by using a 7-core PCF pumped by 1018 nm picosecond pulse [24].

At present, high peak power short pulse pumping PCF is widely used in generation of high power visible SC, but this method has its limitations. Firstly, in order to generate SC covering the full visible range, it is necessary to shift the ZDW of PCF as short as possible. For example, in the literature [10], [24], The ZDW of PCF are 780 nm and 910 nm respectively. Secondly, in order to match the ZDW of PCF, the pump wavelength is also moved to the short-wave direction, so that the dispersion wave can be captured by the long wave soliton generated by the Raman effect. They are synchronized in the time domain and the interaction of them further produce nonlinear effects which spread spectrum. However, according to the absorption cross section and the emission cross section of gain fiber, it is difficult to generate all-fiber high power short pulse with lower wavelengths, such as 780 nm or 910 nm.

In this paper, cascaded PCFs are pumped by a 1064 nm picosecond pulsed fiber amplifier to enhance short wave SC generation as well as SC output power. The parameters of the cascaded PCFs are different. The nonlinear coefficient of first-stage is 11 (W$*$km)-1and the ZDW is 1040 nm. The nonlinear coefficient of second-stage is 20 (W$*$km)-1and the ZDW is 900 nm. The first segment of the PCF achieves an initial broadening of the spectrum. Through the initial broadening, the spectrum is extended to the ZDW of the second-stage PCF, so the spectrum can be broadened further in the second PCF. As the method is capable of solving the difficulty of mismatch between the pump wavelength and ZDW, it breaks up the SC output limitation caused by the pump power. By this way, a high power visible SC output with an output power of 104 W and a spectrum ranging from 370 nm to 2400 nm is achieved experimentally.

2. Experimental Details

2.1. The Scheme of SC Generation

The scheme of SC generation is shown in Fig 1. It is consist of a home-made mode-locked seed source, time division multiplexing (TDM) systems, passive fiber (Hi 1060), a three-stage amplification and cascaded PCFs.

The home-made mode-locked seed source has a center wavelength of 1064 nm, a repetition frequency of 60 MHz, and a pulse width of 12 ps. The time division multiplexing (TDM) system consists of two 50/50 Optocouplers (OC), which divide the pulse into two equal parts. After the pulses pass through well-designed optical paths of different lengths, the pulses exhibit different delays. The pulse is synthesized by the second OC to achieve frequency multiplication. After three time division multiplexing (TDM) systems, the pulse frequency reaches 480 MHz. The 1 km Hi 1060 passive fiber is set behind the TDM to stretch pulses to 75 ps, which would increase the duty cycle and reduce the peak power compared to the unstretched pulse in the process of amplification.

A three-stage backward amplification structure is used for amplifying the 1064 nm pump pulse. The Nufern 10/130 ytterbium-doped double-clad fiber (YDF) is used as gain fiber in the first two stages of amplification with the length of 1 m and 2 m respectively. The Cladding Absorption of

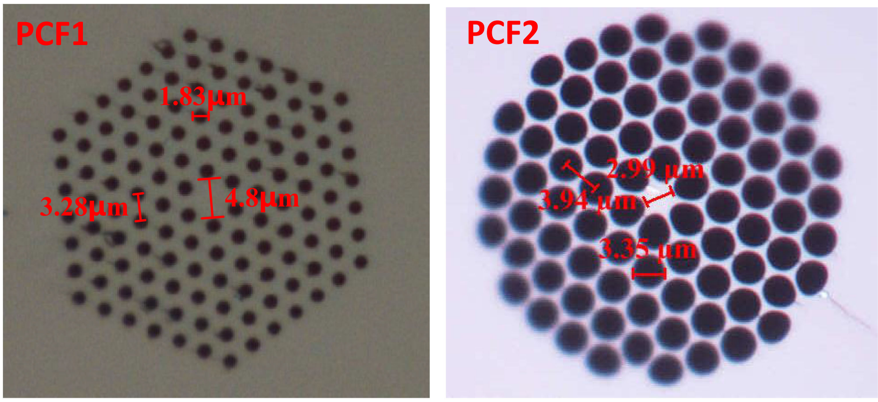

Fig. 2. The measurement data of PCF1 and PCF2.

10/130 YDF is 4.2dB/m@975 nm. The 976 nm pump power of the two stages is 3 W and 24 W respectively and the amplified signal power is 1.2 W and 10.7 W. 20/400 YDF with a length of 12 m is set in the third stage amplification due to higher 976 nm pump power and output signal power. The Cladding Absorption of 20/400 YDF is 1.15 dB/m@975 nm.A 10/130-20/400 mode field adapter is applied to bridge the fiber for avoiding mode field mismatch. $(6+1)*1$ combiner is used in the third stage amplification, almost 120 W of 976 nm pump light is injected into each pump fiber.

1064 nm Pump pulses need to be coupled into the PCF with high efficiency for generating SC. However, the core diameter of the pre-stage fiber is 20μm and the core diameter of PCF1 is 4.8μm. The high-efficiency mode field coupler is designed and manufactured for the purpose of avoiding mode field mismatch. The coupling efficiency is about 63.7% through the method of taper, thermal expansion, and segmental coupling. The manufacturing method of the coupler used here is shown in [23]. PCF1 has a core of 4.8 μm, a outer diameter of 125 μm, a ZDW of 1040 nm, a nonlinear coefficient of 11 (W$*$km)-1, and a length of 3 m. PCF2 has a core of about 3 μm, a outer diameter of 125 μm, a ZDW of 900 nm. The nonlinear coefficient is 20 (W$*$km)-1and the length is 5 m. Both of the PCFs are provided by Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences.

2.2. Coupling Details of PCF1 and PCF2

The efficient coupling of PCF1 and PCF2 is an important step for the fabrication of cascaded PCFs. The different core sizes and structures of the PCF1 and PCF2 pose great challenges for efficient coupling. In this paper, the Fujikura 100P+ fusion splicer is used to obtain a PCF melting point with a coupling efficiency of 75% by precisely controlling the discharge time and intensity. However, the rest power isn't coupled into the core of PCF2. The cladding light stripper is fabricated in PCF2 for preventing the fiber from burning. It is worth noting that if the PCFs are not well coupled, the mode field mismatch of the PCFs will cause heat accumulation at the coupling point. The fiber fuse phenomenon of the PCF will appear with heat accumulation. Fig 3 shows the fiber fused phenomenon in PCF caused by bad coupling. Fig 3(A) is a cross section of PCF1 before damage. It can be seen from Fig 3(B) that at the output position of PCF1, the core has burned holes. PCF1 is cut off at a distance of 40 cm from the output position. There are also burned holes as Fig 3(C) shows.

In this paper, Yokogawa AQ6373 (350 m–1200 m) and AQ6375 (1200 m–2400 m) are used as spectrometers. After measuring the SC spectra separately, the results are spliced to obtain the final spectral data. Mercury lamp is used to calibrate the spectrometer.

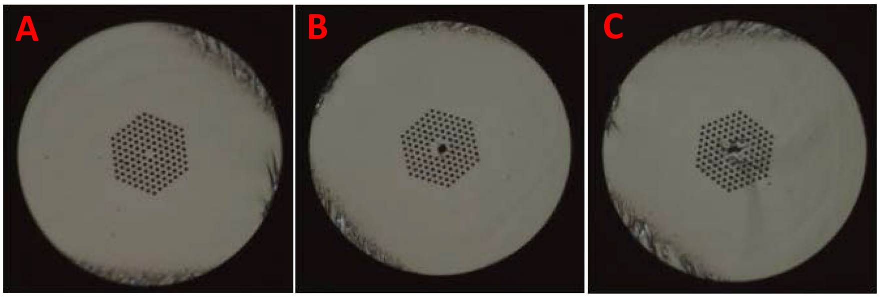

Fig. 3. Cross sections of PCF1 under different conditions: (A) end face with intact solid fiber core; (B) end face after fiber fused; and (C) 40 cm prior to the output end face after fiber fused.

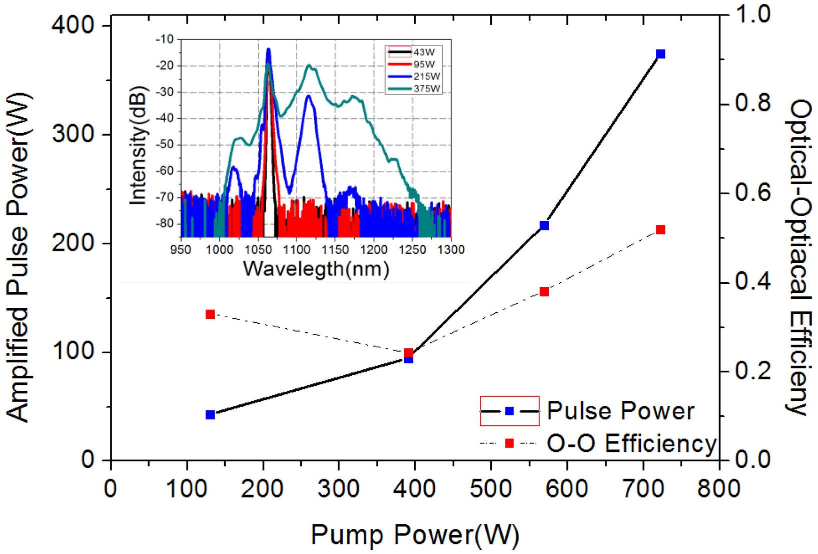

Fig. 4. The output characteristics of the high-power amplifier. The average output power and spectra are measured with different pump power. The optical-optical efficiencies are calculated accordingly, represented in red rectangles.

3. Results

3.1. High Power Amplified Pulse

As shown in Fig 4, the output power of amplified pulse is 375 W and the o-o efficiency is 52% by three-stage amplification. Due to relatively high peak power, a third-order Raman peak is generated. The spectrum extends to 1250 nm at the output power of 375 W.

3.2. SC Generation by Pumping PCF2

In this section, PCF2 is used directly to generate SC by 1064 nm pump pulse. PCF2 has a core of about 3 μm, a ZDW of 900 nm. As a result, the dispersive-wave cannot be trapped by the Raman shifting soliton to extend the blue-edge of the supercontinuum. The spectra are shown in Fig 5.

It can be seen that since the pump wavelength is in the anomalous dispersion region of PCF, the four-wave mixing (FWM) meet the phase matching conditions and modulation instability (MI) generate sidebands on both sides of the spectrum. As the power increasing, the spectrum is continuously spread in the long-wave direction by soliton self-frequency shifting (SSFS) under the action of the Raman Effect. A first-order Raman peak appears at 1114 nm by further increasing the pump

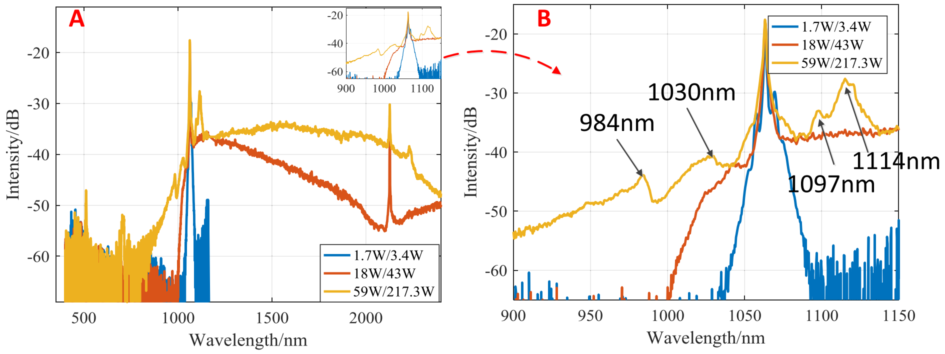

Fig. 5. (A) SC spectra generated by directly pumping PCF2. (B) Zoomed in spectra from 900 to 1150 nm. The labels are presented by output power/input power.

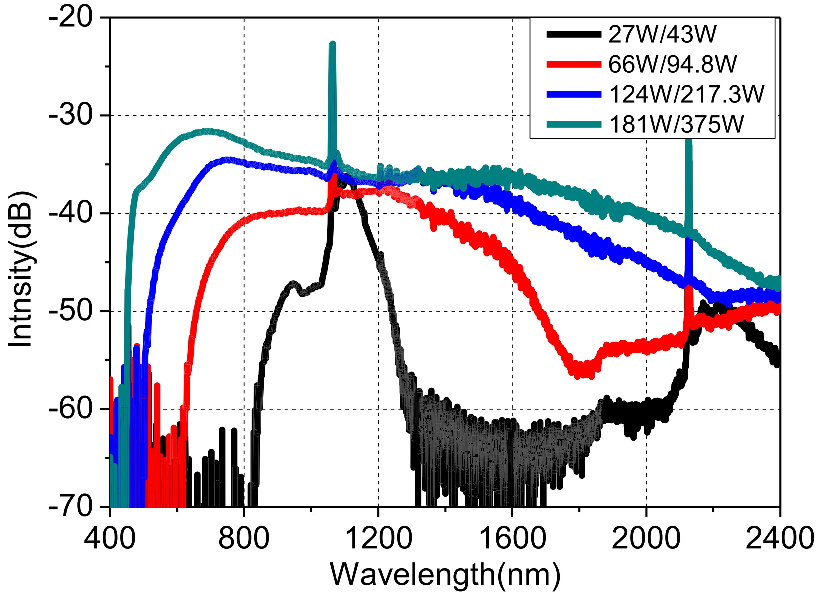

Fig. 6. The evolution of the SC spectra with increasing average power by directly pumping PCF1.The labels are presented by output power/input power.

power. In the short-wave direction, the FWM and cascaded FWM produce multiple sidebands. However, since the pump wavelength (1064 nm) largely deviates from the ZDW (900 nm), poor phase-matching condition leads to strong walk-off. As a result, the generated dispersion wave cannot be trapped in time and is slowly dissipated. Therefore, SC covering the visible light band cannot be realized. It is necessary to point that the sharp peaks appearing around 2120 nm are due to the high-order effects of the spectrometer, which is systematic error. All the peaks around 2120 nm in this paper are for this reason, and will not be mentioned later.

3.3. SC Generation by Pumping PCF1

In this section, PCF1 is used directly to generate SC by 1064 nm pump pulse. PCF1 has a core of 4.8 μm, a ZDW of 1040 nm. Since the pump wavelength is close to ZDW of PCF1, the dispersion wave can be trapped by long wavelength soliton. Through the four-wave mixing, dispersive wave and other nonlinear effects, the spectrum would expands to short-wave direction, the spectra are shown in Fig 6. Due to the high-order effects of the spectrometer, the black curve

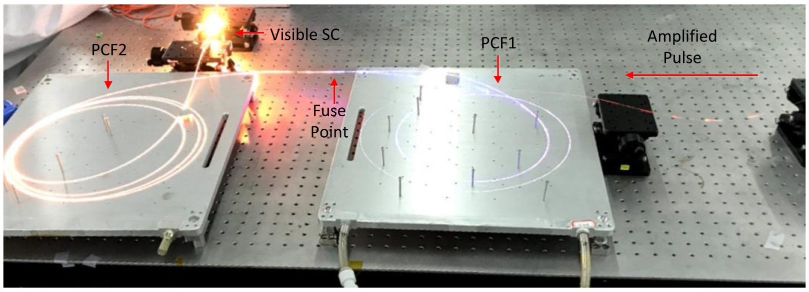

Fig. 7. Experimental device of the cascaded PCFs. Amplified pulses are injected from the right. Different colors are clearly seen along the PCFs, and the output spot exhibits a pretty high brightness.

from 1600 nm to 2400 nm and the red curve from 1800 nm to 2400 nm are the measurement artifacts.

It can be clearly seen that output spectra expanded to both the long-wave and short-wave directions by pumping PCF1.The extension of the spectrum to the long-wave direction is due to the combined effects of SSFS, Raman effect, and four-wave mixing. The extension of the spectrum to the short-wave direction is due to dispersion wave trapped by long wavelength soliton. Finally the short-wave spectrum is extended to 450 nm. The ZDW and nonlinear coefficient of PCF2 are more favorable for visible SC generation. Moreover, PCF2 is two meters longer than PCF1, which is more conducive to the generation of non-linear effects .However, due to the large difference between pump wavelength and ZDW of PCF2, PCF2 can't directly generate SC spectrum with wider short-wave coverage compared to PCF1.

3.4. SC Generation by Pumping Cascaded PCFs

The advantage of using cascaded PCFs is that the short pulse is spectrally pre-widened in PCF1, and the broadened spectrum covers the ZDW of PCF2. SC with wider spectral range can be achieved by pumping PCF2 with pre-widened pulse mentioned above. The amplified pulse is utilized to pump cascaded PCFs and the experimental device is shown in Fig 7. The amplified pulse is coupled into PCF1 and the pulse wavelength is broadened to the ZDW of PCF2. Then the pre-widened pulse is used to pump PCF2, which is equivalent to pumping PCF2 by high power pulse close to ZDW of PCF2. The temperature of the fuse point of PCF1 and PCF2 is high, and the temperature gradually increases with the heat accumulation.

SC spectra generated by cascaded PCFs are shown in Fig 8. As the pump power increasing, the short-wave spectra are broadened to 828 nm, 618 nm, 510 nm and 450 nm by direct pumping PCF1. Cascaded PCFs are built by melting PCF2 to PCF1.With Cascaded PCFs, the short-wave spectra are effectively expanded compare to direct pumping PCF1.The short-wave limitation are 786 nm, 535 nm, 425 nm, 370 nm respectively. Spectra of visible light are fully covered with the output power of 104 W. Comparing with direct pumping PCF1 or PCF2, cascaded PCFs could effectively expand the short-wave spectrum.

Spectrum with 104 W output power is plotted in linear coordinate system as shown in Fig 9. Numerical integration of the SC spectrum indicates that the visible spectra component (380 nm–780 nm) accounts for 50.4% (52.4 W) of the total SC power and the residual 1064nm pump light (1060 nm−1068 nm) occupies 5.33%.

Although a supercontinuum output with a power of 104W and a spectral range from 370 nm to 2400 nm is realized, the long-term stability of the system is not guaranteed. After operating at maximum power, the fuse point of PCF1 and PCF2 is damaged due to high temperature. According to the author's analysis, there are several reasons. First, in order to adjust the ZDW to a suitable value, the air hole duty of PCF2 is large. Considering the optical fiber structure, it cannot carry excessive power. Secondly, the low-power coupling efficiency is 75%, and this efficiency needs

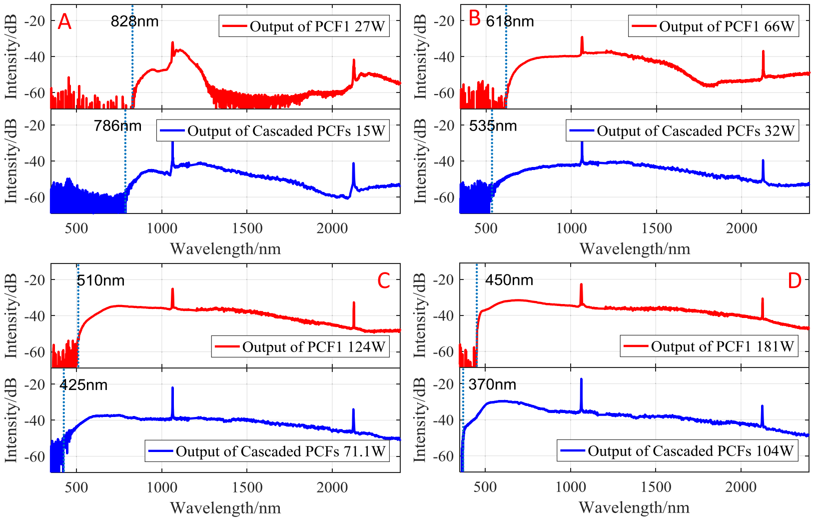

Fig. 8. Comparisons of the output SC spectra generated by directly pumping PCF1 and pumping cascaded PCFs with identical incident power. The output power for each situation is labeled respectively.

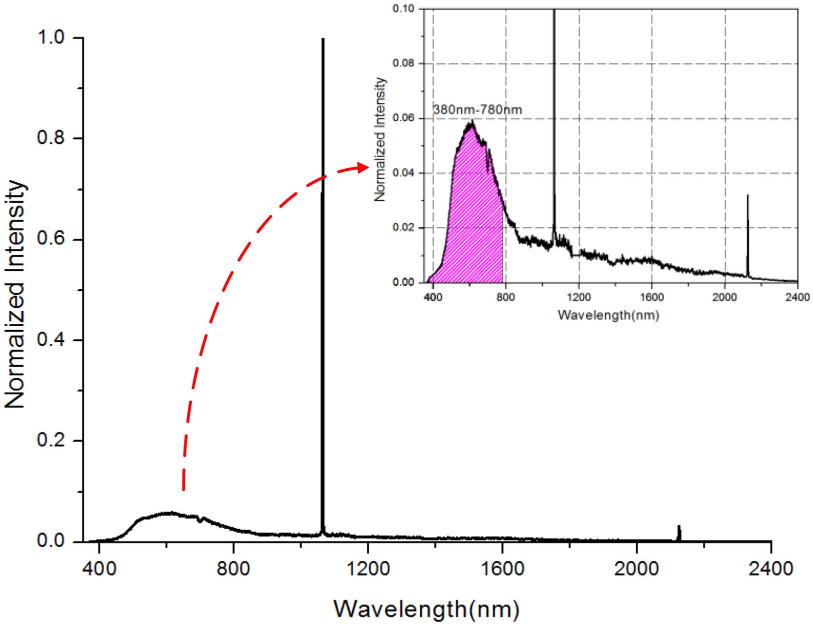

Fig. 9. The SC spectrum at highest output power in linear coordinate system. The spike at 1064 nm stands for the pump laser, and the visible component is shaded in magenta in the inset.

to be further improved. Third, the fuse point is directly exposed to the air without further heat dissipation. After solving the above problems, the output power could be further improved.

4. Conclusions

In this paper, we experimentally obtain an all-fiber SC output with an average power of 104 W ranging from 370 nm to 2400 nm. Cascaded PCFs pumped by 1064 nm high peak power picosecond pulse is applied to generate the SC, which is able to cover wide spectral range especially in visible wavelength.The key technologies could be further optimized. MFA between PCF1 and

PCF2 will be developed to improve the coupling efficiency. The photonic crystal fiber with long tapered region will be developed for adiabatic transition, and the thermal load could be depleted throughout the tapered region to improve the thermal stability of the supercontinuum system. When the thermal management level is improved, the output super-continuous spectrum power can be further increased by increasing the pump power. To further expand the output spectrum, more stages of photonic crystal fibers can be cascaded with decreasing ZDW, which can further enhance the short-wave spectrum.

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