Generation of a compact high-power high-efficiency normal-dispersion pumping supercontinuum in silica photonic crystal fiber pumped with a 1064-nm picosecond pulse*

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(Received 30 October 2012; revised manuscript received 5 December 2012)

Broadband normal dispersion pumping supercontinuum (SC) generation in silica photonic crystal fiber (PCF) is investigated in this paper. A 1064-nm picosecond fiber laser is used to pump silica PCF for the SC generation. The length of PCF is optimized for the most efficient stimulated Raman scattering process in the picosecond pump pulse region. The first stimulated Raman Stokes peak is located in the anomalous dispersion regime of the PCF and near the zero dispersion wavelength; thus the SC generation process can benefit from both a normal dispersion pumping scheme and an anomalous dispersion pumping scheme. The 51.7-W SC spanning from about 700 nm to beyond 1700 nm is generated with an all-fiber configuration, and the pump-to-SC conversion efficiency is up to 90%. In order to avoid the output fiber end face damage and increase the stability of the system, an improved output solution for the high power SC is proposed in our experiment. This high-efficiency near-infrared SC source is very suitable for applications in which average output power and spectral power density are firstly desirable.

Keywords: fiber laser, supercontinuum, photonic crystal fiber

PACS: 42.55.Wd, 42.65.–K, 42.65.Tg **DOI:** 10.1088/1674-1056/22/6/064211

1. Introduction

Supercontinuum (SC) sources have potential applications in a wide market, such as in the areas of display systems, optical communications, spectroscopy, microscopy, and so on. And the SC generation in photonic crystal fiber (PCF) is a very vast research topic.[1–4] Some different parameters, such as spectral bandwidth, spectral flatness, spectral power density, output power, coherence properties, and output beam quality, should be considered to evaluate an SC source. Also different applications put emphasis on different parameters of the SC source. For some applications, such as frequency metrology and coherent spectroscopy, generating a phase-stable SC is essential. For some other applications, however, achieving a high average power or a strong spectral power density is desirable. In recent years, fiber lasers have been utilized as a standard pump source in high power SC generation, owing to their low cost and preferable matching with PCF. A continuous wave (CW) pumped SC source can realize a high power and high spectral power density output,[5] while it requires a long PCF for the spectral broadening. Also the spectral range of the CW pumped SC is relatively narrow compared with the pulse pumped counterpart. Pulse fiber laser is favourable for the SC generation due to its high peak power. The initial SC source is pumped by using a standard femtosecond oscillator system.[6] Whereas the average output power of the femtosecond pulse pumped SC is limited, a suitable high power pump is lacking. The SC with picosecond or nanosecond pulse can be generated in combination with PCF. High power SC sources with average output power up to 50 W and 39 W were reported in Refs. [7] and [8], which correspond to CW and picosecond pulse pumps, respectively. However, bulk-optic designs have been used in both of the two impressive SC sources, which can compromise the stability and practicality. All-fiber architecture is desirable, because it can minimize mechanical vibration and optical reflection, and provide convenience for packaging and application. Recently, an all-fiber picosecond pulse pumped SC source with 49.8-W average output has been demonstrated.[9] A 100-W picosecond fiber master oscillator power amplifier (MOPA), which delivered 350-ps pulse with 16-MHz repetition rate at 1050 nm, was utilized as a pump source. A broadband continuum spanning from 500 nm to beyond 1700 nm was generated in a 5-m-long commercial PCF. The PCF possessed a zero dispersion wavelength (ZDW) of 1040 nm and a mode field diameter of 4 μm. The pump-to-SC conversion efficiency of this SC source was ∼ 50%.

In order to generate the broadest SC, the pump wavelength should be selected within the anomalous dispersion

*Project supported by the International Science and Technology Cooperation Program of the Ministry of Science and Technology of China (Grant No. 2012DFG11470), the State Key Program of the National Natural Science Foundation of China (Grant No. 61235008), the National Natural Science Foundation of China (Grant Nos. 10904173, 11004247, 11274385, 61077076, and 61007037), the Science Foundation for Distinguished Young Scholars of Hunan Province, China (Grant No. 12JJ1010), the Postgraduate Innovation Foundation of Hunan Province, China (Grant No. CX2011B034), and the Postgraduate Innovation Foundation of National University of Defense Technology, China (Grant No. B110704).

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regime near to the ZDW,[10] which has been done in Ref. [9]. By suitably controlling the air-fill fraction and the lattice structure of the air holes in the microstructured cladding, it is possible to fabricate a PCF with the ZDW down to 1 μm, which could match the operating wavelength of the high power ytterbium-doped fiber laser. Generally, the PCF with ZDW at around 1 μm possesses a mode field diameter of ∼ 4 μm. Therefore, it is challenging to couple pump light into the PCF with an all-fiber structure. Also it is prone to suffer optical damage and thermal issues in such a small fiber core at high power operation.

In fact, SC can also be formed with the normal dispersion pumping regime, though the continuous spectral range is relatively narrow.[10] The high coherent SC sources have been demonstrated by pumping all-normal dispersion PCFs.[11,12] Recently, broadband SC was efficiently generated in a meter-length air suspended core single mode tellurite PCF (with a ZDW of 1380 nm and a large mode area of 500 μm^2), which was pumped by a 1060-nm picosecond pulse in the deep normal dispersion region.[13] There are several advantages for the normal dispersion pumping scheme: firstly, the PCF with a larger mode area can be adapted to generate the SC, which can endure more pump power; secondly, it promises to achieve a high pump-to-SC conversion efficiency and high spectral intensity with this pumping scheme.[13]

High power picosecond fiber lasers and SC generation in long silica PCFs pumped by the self-made pulse lasers were demonstrated in our previous work.[14–17] The average output power and the pump-to-SC conversion efficiency of these SC sources were not so promising. In the present paper, broadband normal dispersion pumping SC generation in 3.5-m-length silica PCF is investigated. The PCF possesses a ZDW of 1117 nm and a mode field diameter of ∼ 6 μm. A 57-W picosecond pulse fiber MOPA delivering 14-ps pulse at 1064 nm is used as a pump source. By optimizing the length of the PCF for the most efficient stimulated Raman scattering process in the picosecond pump pulse region, the SC generation process could benefit from both normal dispersion pumping and an anomalous dispersion pumping scheme in our experiment. An average output power as high as 51.7 W is obtained, which correspond to a high pump-to-SC efficiency of up to 90%. The continuum spectrum spans from about 700 nm to beyond 1700 nm. An improved solution for the high power SC output is also proposed in our experiment. The details and a discussion are presented in this paper.

2. Basic idea and experimental setup

According to Ref. [10], the underlying mechanism of broadband SC generation through normal dispersion pumping is as follows: if the pulse duration of the pump is several hundreds of femtoseconds or less, self-phase modulation (SPM) will dominate the pulse broadening and the spectral bandwidth will be narrow due to the approximately symmetric temporal pulse broadening. So the pump pulse duration should be relatively long, e.g., a few picoseconds or longer. In this case, stimulated Raman scattering (SRS) tends to dominate spectrum broadening at the initial stage. Typically, a series of cascaded discrete Stokes lines will appear. Given sufficient pump power being available, the continuum will cross the ZDW and rapidly extend to both sides of the pump wavelength due to nonlinear effects, such as modulation instability (MI) and soliton related mechanism, which now dominate in this dispersion regime. It should be noted that the walk-off effect has a significant influence on the SRS process, especially at normal dispersion.[10] So how to minimize the walk-off effect should be considered in the normal dispersion pumping scheme.

The ZDW of the tellurite bulk glass is around 2.0 μm∼2.3 μm;[1] thus, a tellurite PCF will exhibit high normal dispersion at 1.06 μm. As for the high Raman gain coefficient, large Raman gain bandwidth and high nonlinear refractive index n_2 of the tellurite PCF, a cascade of Raman Stokes orders was initiated in the highly normal dispersion regime.[13] Then the continuum quickly extended to long wavelengths and a broadband SC from 1060 nm to beyond 1700 nm was generated. The whole SC generation process is under the normal dispersion pumping scheme and a continuum has not been formed at the short wavelength side of the pump. Note that the pure silica possesses a ZDW at ∼ 1.3 μm.[18] If we choose a large mode field silica PCF, whose ZDW is longer but not so far from the operating wavelength of the high power ytterbium-doped fiber pump source, as the nonlinear medium, the pump energy could shift to the Raman stokes lines through the normal dispersion pumping regime at the initial stage. Given that the excited Raman Stokes line is just within the anomalous dispersion region and near the ZDW, it can act as the cascaded new SC pump with the anomalous dispersion pumping scheme. As a result, the SC generation process can benefit from both normal dispersion pumping and an anomalous dispersion pumping scheme. In other words, it can obtain a relatively broadband SC with high spectral intensity and high pump-to-SC conversion efficiency output.

The experimental setup of our all-fiber SC source is schematically shown in Fig. 1. It consists of a picosecond source, an SC generation unit (PCF), and a delivery double cladding fiber (DCF). The picosecond source is an all-fiber four-stage MOPA laser. A seed source, which delivers 14-ps pulse with ∼ 480-MHz repetition rate at 1064 nm, is amplified to 110 mW by single mode fiber amplifier 1, then 3.5 W by the DCF amplifier 2. The DCF amplifier 3 is a power amplifier, and two 50-W 976-nm LD pump lasers are combined into a gain fiber through a (2+1) × 1 fiber combiner. The gain DCFs utilized in both amplifier 2 and amplifier 3 are of the same type, and they have 15 μm/130 μm core/cladding diameter. The amplifier 3 provides 57.2-W output with a matched passive DCF.

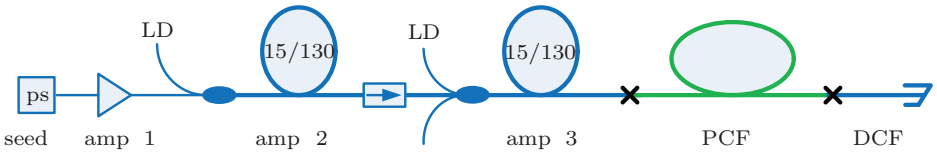


Fig. 1. (color online) Experimental setup of the SC source.

In our experiment, the silica PCF is composed of five hexagonal rings of circular air-holes each with a hole diameter $d = 3.54$ μm and a pitch $\Lambda = 5.42$ μm. The diameter of the silica cladding is 125 μm. The calculated ZDW of the PCF is 1117 nm and the mode field diameter is ~ 6 μm at 1064 nm. Readers should refer to Ref. [19] for the micrograph of the PCF. The Raman frequency shift is ~ 13.2 THz in silica glass.[18] Theoretically, the first Raman Stokes order in the silica PCF appears at about 1116 nm for the 1064 nm pump wavelength. The walk-off length L_W, in this case, is calculated to be 3 m between 1064 nm and 1116 nm ($L_W = T_0/|\beta_P(\lambda) - \beta_S(\lambda)|$, where T_0 is the duration of the pulse (14 ps) and $|\beta_P(\lambda) - \beta_S(\lambda)|$ is the separation between the pump and the Stokes wave.[13]) The attenuation of the PCF at 1064 nm is 4.5 dB/km, and the effective fiber length L_{eff} of 3-m-long PCF is 2.987 m ($L_{eff} = [1 - \exp(-\alpha_P \cdot L)]/\alpha_P$, where α_P represents the optical loss of the fiber at the pump wavelength and L is the fiber length.[18]) Since the L_{eff} of the PCF is comparable to the L_W, the walk-off effect will have an influence on the SRS generation, especially for the PCF with a long length. So 3.5-m-long PCF is adopted for the most efficient stimulated Raman scattering process in the experiment.

Stability is important for an SC source with the purpose of practical application. The laser-induced output fiber end face damage and the optical reflection at the fiber end are two key factors to reduce the stability of a high power fiber laser, given that the laser power is still tolerable in the fiber. In order to enhance the stability, splicing an end cap at the output end of the delivery fiber is a routine solution for a high power fiber laser. The main reason that the fiber end face are made susceptible to laser-induced damage is the existence of surface imperfections. It should be noticed that the microstructure of the PCF could be easily contaminated or damaged due to the dust or mist in the air, though the PCF has been carefully polished. Thus more attention should be paid to how to avoid the output fiber end face damage for a high power SC source, though it is difficult to directly splice an end cap with the PCF. In order to avoid the output fiber end face damage and increase the stability of the system, a 0.5-m-long 15/130 delivery DCF arranged an end cap is spliced with the output end of the PCF. The splices between the PCF and the DCF can introduce an additional power loss. However, both ends of the PCF are mode-field expanded by using the selective airhole collapse technique,[19] and the super-low splice loss (~ 0.2 dB) is realized at the splice points. Owing to the low splice loss, the thermal issue caused by the splice points is not serious, which ensures the safety of the splicing points even at a high power level.

3. Results and discussion

At first, the output properties of the SC source are observed directly from the polished output end of the PCF. The output continuum spectra and output power are measured with an Aglient 86142B optical spectrum analyzer (OSA) (using a resolution bandwidth of 5 nm) and a Coherent EPM 2000 power meter.

The output spectrum evolutions of the SC source against different picosecond pump powers are shown in Fig. 2. Two-stage cascaded discrete Stokes peaks appear at about 1120 nm and 1170 nm, respectively, when the pump power is 2.3 W (labeled as S_1 and S_2). Meanwhile, a slight anti-Stokes peak at 1044 nm (labeled as AS_1) is observed. When the pump power is increased to 5.6 W, no more Stokes peak is observed and the output spectrum becomes continuous. And the anti-Stokes peak shifts from 1044 nm to 1024 nm (labeled as AS_2). The SRS dominates the initial process of spectrum broadening, and the most spectrum components extending to the long wavelength side. The anti-Stokes spectral peak can be interpreted with the Raman-assisted frequency mixing process. The MI process is considered, and the corresponding frequency shift for the maximum gain $\Omega = \pm(4\gamma P_0/|\beta_2|)^{1/2}$ is numerically calculated.[18] The pump wavelength $\lambda_p = 1064$ nm, second-order dispersion parameter $\beta_2 = 5.5244$ ps^2/km and the nonlinear coefficient of the PCF $\gamma = 26.9849$ W^{-1}·km^{-1}. When the pump power is 2.3 W or 5.6 W, the spectral pairs corresponding to the maximum parametric gain are calculated to 1040 nm and 1090 nm or 1026 nm and 1105 nm, respectively. The experimental results also show that the anti-Stokes peak relating to the maximum parametric gain varies with launched pump power. Therefore, the MI or degenerate four-wave mixing process is mainly responsible for the generation of the anti-Stokes spectral components. As for the overlap between Raman and MI gain bands in this situation, the Stokes spectral line is no longer fixed at the peak of the Raman gain but depends on the most efficient frequency mixing process.[20]

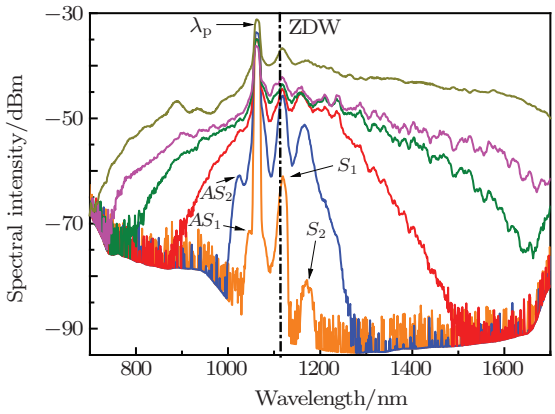


Fig. 2. (color online) Output spectrum evolutions against different pump powers. Form bottom to top, the pump powers are 2.3 W, 5.6 W, 10.5 W, 18.5 W, 27 W, and 57.2 W sequentially.

Note that the ZDW of the PCF is 1117 nm and the first Raman Stokes peak is located in the anomalous dispersion region and near to the ZDW of the PCF. Further increasing pump power, the spectrum quickly broadens to both sides of the pump and evolves to a broadband SC. Under the maximal pump power, the continuum expands from about 700 nm to beyond 1700 nm (spectrum component over 1700 nm is not observed due to the limitation of the OSA). At this stage, soliton fission, dispersion wave generation, and fission trapping are mainly responsible for the broadband SC generation. The SPM and XPM also help to smooth the SC. The numerical calculation of group-velocity matching curve for the nonlinear PCF is shown in Fig. 3. Examining the group-velocity matching curve, it is clear that group-velocity matching is consistent with the output spectral features.

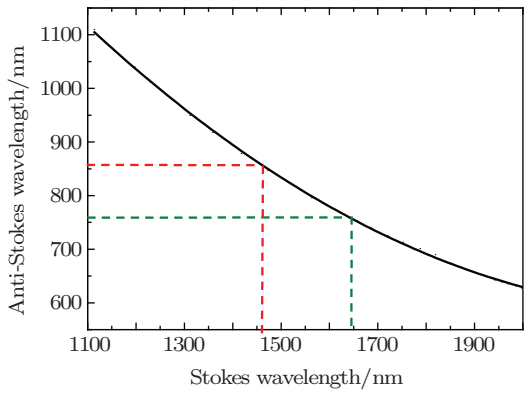


Fig. 3. (color online) Group-velocity matching curve of the PCF.

In the experiment, a 51.7-W SC is obtained under a 57.2-W picosecond pump, which corresponds to a high pump-to-SC conversion efficiency of up to 90%. As for its high average output power and relatively narrow continuum spectrum range, the average spectral power density of this SC source is very considerable. The SC output power versus incident pump power is shown in Fig. 4. The SC power increases straightly with the picosecond pump power increasing, which indicates that the output power can be further scaled with higher pump power. Several reasons likely contribute to the high pump-to-SC conversion efficiency: 1) a short piece of PCF is used, and the propagation loss of light in the PCF is very low; 2) with the PCF post-processing techniques, the splice loss between the DCF and PCF is very low; 3) due to the relatively narrow continuum spectrum band, the quantum defect from the pump photons to the generated photons is low.[13]

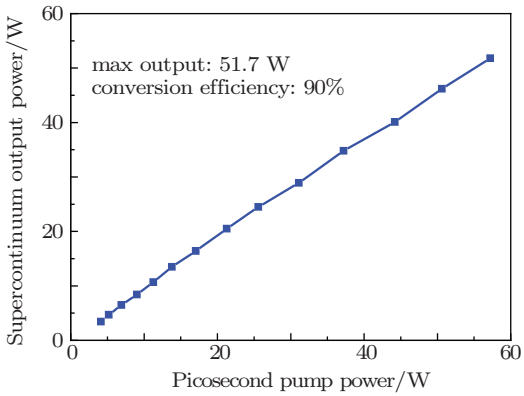


Fig. 4. (color online) The SC output power versus incident pump power.

The SC source is tested for several minutes at ∼ 50-W output power level and no significant change about the output power and the output spectrum is observed. While, due to the dust and mist in the air, the polished output end of the PCF could suffer an optical damage after a long time running. In order to avoid this problem, an additional 0.5-m-long deliver DCF arranged an end cap is spliced following the PCF as shown in Fig. 1. Though the total output power of the SC source drops off to about 47 W after adding the additional delivery DCF, this improved solution for the high power SC output can effectively reduce the optical reflection, avoid the end face damage, and increase the stability of the whole system.

The continuum spectrum of this SC source is wider than that in Ref. [13], which just covers a spectral range from 1100 nm to 1700 nm. The silica PCF with a specially designed ZDW is very crucial for broadband SC generation. Optimizing the length of silica PCF is also important in our experiment. The walk-off effect can significantly affect the SRS process when the pump pulse duration is less than 100 ps,[18] especially at a high normal dispersion. The PCF length should be comparable to the walk-off length for the most efficient stimulated Raman scattering process in the picosecond pump pulse region. Though the continuum spectrum can be extended to a wider range within a long PCF, it also induces a high quantum defect and an additional propagation loss. Meanwhile, the effect on the spectral broadening through increasing the fiber length is limited by the structure of the PCF, which has been testified with experimental results in Ref. [17].

It should be mentioned that the presented SC source can have a good coherence at the initial stage of SC generation, because the spectrum broadening is caused by the Raman Stokes orders and a low one otherwise. However, as for the long pulse duration of the pump, the noise-induced MI and soliton dynamics are mainly responsible for the spectrum broadening at the advanced stage of SC generation. Therefore, the coherence of the SC is degraded. However, this high efficiency near-infrared SC source is very suitable for the applications that the average output power and spectral power density are firstly desirable.

4. Conclusion

In this paper, we experimentally investigate broadband near-infrared SC generation in silica PCF. The PCF is pumped by a 1064-nm picosecond fiber MOPA in a normal dispersion region. A broadband SC spanning from about 700 nm to over 1700 nm is generated with an all-fiber configuration. The average output power of this SC source is 51.7 W and the pump-to-SC conversion efficiency is up to 90%. In order to avoid the output fiber end face damage and increase the stability of the whole system, an additional delivery DCF arranged on an end cap is spliced following the PCF. The experimental results prove that the normal dispersion pump in combination with suitable PCF design is a feasible method to generate the broadband, high-efficiency, and high-spectral power density SC in silica PCF.

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