PHOTONICS Research

30-W supercontinuum generation based on ZBLAN fiber in an all-fiber configuration

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We report an all-fiberized 30-W supercontinuum (SC) generation in a piece of ZrF_4-BaF_2-LaF_3-AlF_3-NaF (ZBLAN) fiber. The pump source is a thulium-doped fiber amplifier (TDFA) with broadband output spectrum spanning the 1.9 to ∼2.6 μm region. The used ZBLAN fiber has a core diameter of 10 μm, and was directly fusion-spliced to the pigtail of the TDFA without using a traditional mode field adapter (MFA) or a piece of transition fiber. Such a low-loss and robust fusion splice joint, together with a robust AlF_3-fiber-based endcap, enables efficient and high-power SC generation in the ZBLAN fiber. An SC with an average power up to 30.0 W and a spectral coverage of 1.9–3.35 μm with 20-dB bandwidth of 1.92–3.20 μm was obtained. Moreover, an SC with a broader spectrum was achieved by raising the pump pulse peak power (via reducing the duty ratio of the pump laser pulse). An SC with an output power of 27.4 W and a spectral coverage of 1.9–3.63 μm (with 20-dB bandwidth of 1.92–3.47 μm) was obtained, as well as an SC with output power of 24.8 W and a spectral coverage of 1.9–3.70 μm (with 20-dB bandwidth of 1.93–3.56 μm). The power conversion efficiency was measured as >69%. To the best of the authors' knowledge, this research demonstrates the record output power of SC lasers based on ZBLAN fibers, paving the way for broadband and efficient multi-tens-of-watts SC generation in soft-glass fibers.

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1. INTRODUCTION

High-power supercontinuum (SC) laser sources have a variety of potential applications including active hyperspectral imaging [1], long-range environmental sensing [2], homeland security [3], and so on. Silica fibers support the low-loss transmission of visible to short-wave infrared wavebands and have been widely used in high-power SC generation [4,5]. However, an SC with spectra extending beyond 2.8 μm cannot be obtained in silica fibers due to the large phonon energy of silica (∼1100 cm^{-1}) [6]. Non-silica fibers such as fluoride (ZBLAN and InF_3) [7,8], tellurite (TeO_2) [9], fluorotellurite [10], and chalcogenide [11,12] fibers have been intensively exploited for high-power SC generation [13]. Xia *et al.* reported the first 10-W-level SC generation in a ZBLAN fiber, with a spectral coverage of 0.8–4.0 μm [7]. In such an experiment, a 1550-nm master oscillator power amplifier (MOPA) system was used as the pump source. Later on, the record output power was boosted to 13 W [14] and 21.8 W [15] by Yang *et al.* and Liu *et al.*, respectively, where a thulium-doped MOPA system is used in each experiment. In the above experiments, the used ZBLAN fiber was mechanically spliced (or, butt-coupled) to a silica fiber. The development of a fusion splicing technique makes low-loss and robust fusion splicing between ZBLAN fibers and silica fibers possible. Benefiting from such a technique, Zheng *et al.* and Yin *et al.* achieved an all-fiberized 10.7-W [16] and 15.2-W [17] SC generation in a ZBLAN fiber, respectively. Besides, Yin *et al.* demonstrated a 30.1-W SC with a spectral coverage of 2–3 μm in a piece of germania fiber, but further spectral extension towards a longer wavelength was blocked by the sharply increasing the transmission loss of the germania fiber [18]. Recently, Yao *et al.* reported a 10.4-W SC generation in a piece of fluorotellurite fiber, which was pumped by a femtosecond thulium-doped MOPA system via lens coupling [10]. In such an experiment, the full spectral coverage of the generated SC was 0.9–3.9 μm. Very recently, our group achieved a 11.3-W SC generation in a piece of InF_3 fiber with an overall spectral coverage of 0.8–4.7 μm [19]. Though InF_3 fibers have a much wider transmission window than ZBLAN fibers do, we found that InF_3 fibers are more fragile than ZBLAN fibers under high pump power and need more delicate protection measures [8]. Furthermore, as can be seen from the literature [14–17], the power-handling potential of ZBLAN fibers has not been fully explored yet.

In this paper, high-power SC generation in a short piece of ZBLAN fiber was investigated using a thulium-doped fiber amplifier (TDFA) as a pump source. Owing to the 10-μm core diameter of the used ZBLAN fiber, a direct fusion splicing joint with low loss was fabricated between the ZBLAN fiber and the silica fiber where no mode field adapter (MFA) was necessary. A 30-W SC with spectral coverage of 1.9–3.35 μm was achieved under a pump pulse repetition rate (PRR) and pulse duration of 3 MHz and 3 ns, respectively. By reducing the duty ratio of the pump pulse, a 27.4-W SC with a spectral range of 1.9–3.63 μm and a 20-dB spectral range of 1.92–3.47 μm, and a 24.8-W SC with a spectral range of 1.9–3.7 μm and a 20-dB spectral range of 1.93–3.56 μm were obtained.

2. EXPERIMENTAL SETUP AND RESULTS

Figure 1 depicts the schematic of the SC laser source. The whole SC source is comprised of a TDFA with a broadband output spectrum spanning the 1.9–2.6 μm region as a pump laser and a piece of 2-m-long ZBLAN fiber. The pump laser includes a pulsed seed laser operating at 1550 nm, a two-stage erbium-ytterbium-codoped fiber amplifier (EYDFA) chain, a piece of single-mode fiber (SMF), and a single-mode TDFA. The seed laser is an electrically modulated distributed feedback laser with tunable PRR on MHz scale and pulse duration on nanosecond scale. The first and the second stages of EYDFA were forward and backward pumped, respectively. The 4-m-long EYDF used in each EYDFA has a core/cladding diameter and a core/cladding numerical aperture (NA) of 10/125 μm and 0.21/0.46, while the used TDF has a core/cladding diameter of 10/130 μm and a core/cladding NA of 0.15/0.46, respectively. The 3-m-long TDF is pumped by a pair of multimode laser diodes operating at 793 nm, each of which has a maximal output power of ~50 W. The pigtail of the TDFA is a piece of passive fiber with a core diameter of 10 μm and a core NA of 0.15 which matches the TDF.

The used ZBLAN fiber has a core/cladding diameter of 10/125 μm and a core NA of 0.2, yielding a single-mode cutoff wavelength of 2.61 μm and a zero-dispersion wavelength of 1.56 μm, respectively. Calculations indicated that the fundamental mode area of the ZBLAN fiber around the 2-μm region is pretty well matched with that of the pigtail of the TDFA. Therefore, the ZBLAN fiber was directly fusion spliced to the pigtail of the TDFA with the method introduced in Ref. [20] by an electrode-based fiber fusion splicer. The microphotograph of the fusion splicing joint is shown as the inset of Fig. 1. The splicing loss was measured at 0.25 dB by a 3-W

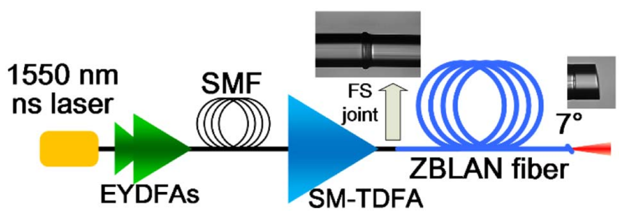

Fig. 1. Experimental setup of the 30-W SC laser source. EYDFA, erbium-ytterbium-codoped fiber amplifier; SMF, single-mode fiber; SM-TDFA, single-mode thulium-doped fiber amplifier; FS, fusion splice.

continuous-wave fiber laser operating at 2000 nm, considering a transmission loss of 0.1 dB/m around 2 μm. The splice joint with the pigtail was tested by a pull strength of 8.1 kpsi and was not damaged. An AlF_3 fiber endcap can reduce the power intensity at the output end and protect the ZBLAN fiber tip from the dissolution of H_2O molecules in the air into the fiber end facet, which is significant for steady and reliable operation of the SC laser. An 80-μm-long endcap was fabricated by fusion splicing a piece of multimode AlF_3 fiber to the ZBLAN fiber and cleaved at 7° to protect the fiber tip from humidity as well as optical or thermal damages during operation, which is also shown as the inset of Fig. 1. The endcap was made with the method described in Ref. [8], which was accomplished with an electrode-based fiber fusion splicer, then angle-cleaved by a fiber cleaver. Such an endcap has a measured loss of 0.06 dB. The whole system was placed on an aluminum plate water-cooled at 17°C for efficient heat dissipation. The SC power was measured by a wavelength-insensitive thermopile power meter. As for spectral characterization, a combination of a grating-based monochromator and a liquid-nitrogen-cooled mercury cadmium telluride detector was used.

The average power of the 1550-nm pulses is ~10 mW and then boosted to ~9 W after the EYDFA chain. Herein, no obvious spectral broadening occurs, and most of the pulse energy is located in the spectral peak at 1550 nm. Afterwards, the 1550-nm laser pulses with peak power of several kilowatts are coupled into the SMF, broken into multiple ultrafast pulses, and frequency-shifted towards 2.4 μm. Such spectral evolution is mainly related to nonlinear effects including modulation instability [7] and soliton dynamics, such as soliton fission and Raman soliton self-frequency-shift (SSFS). The output spectrum of the SMF spans from 1.5 to 2.4 μm (with a residual spectral peak located at 1550 nm) and perfectly covers the gainband of the Tm^{3+} ions (1.9–2.1 μm). Next, the broadband ultrafast pulses propagate in the following single-mode TDFA and are spectrally reshaped: the spectral components located in the short wavelength region (1.5–1.8 μm) are absorbed, and those lying in the gainband of Tm^{3+} ions are amplified. Herein, drastic spectral broadening also occurs due to the efficient power-scaling of the broadband ultrafast pulses and nonlinear wavelength conversion dominated by Raman SSFS [21]. As a result, the pigtail of the TDFA emits laser pulses with a spectrum covering the 1.9–2.6 μm waveband. Finally, a pump laser ranging from 1.9 to 2.6 μm is coupled into the ZBLAN fiber and broadband SC is generated in the ZBLAN fiber.

Figure 2(a) shows the power characteristics of the TDFA. Under PRR and pulse duration of 3 MHz and 3 ns, the TDFA output power increases almost linearly with respect to the launched pump power. The slope efficiency of the TDFA is 39.5%, and output power of 41.0 W is obtained when the maximal launched pump power of 100.9 W was launched into the TDFA. For cases of lower pulse duration or PRR, i.e., 3 MHz 1 ns and 2 MHz 1 ns, the slope efficiency is 38.1% and 35.5%, respectively. Herein, a corresponding output power of 39.0 and 35.9 W was obtained. The TDFA output spectrum with maximal launched pump power under different PRR and pulse duration is shown in Fig. 2(b). One could see that a lower pulse duty ratio brings a broader spectrum since the pulse peak

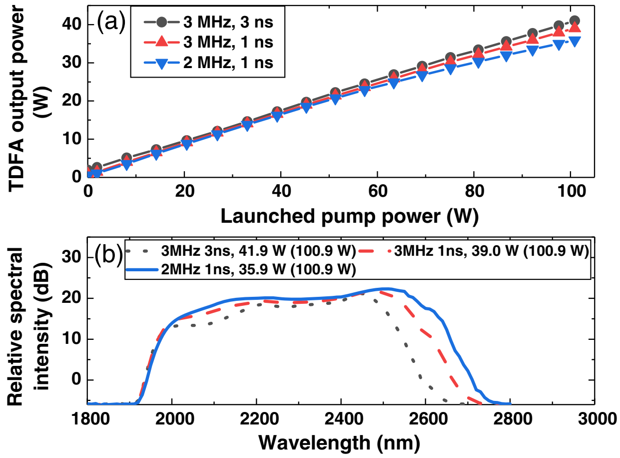

Fig. 2. (a) Power characteristics of the TDFA and (b) spectral characteristics of the TDFA with maximal launched pump power (100.9 W at 793 nm) under PRR and pulse duration of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns. (The measured spectra were not compensated by the detector response.)

power is higher. However, the spectrum is finally limited to ~2.7 μm due to the attenuation-induced loss of silica fiber. In fact, the drop of the slope efficiency for a lower pulse duty ratio when the launched pump power is over 60 W is mainly due to the attenuation-induced loss of silica fiber.

The spectrum evolution of the generated SC under different output powers (under pump PRR and pulse duration of 3 MHz 1 ns) is depicted in Fig. 3(a). Overall, the SC spectrum mainly extended asymmetrically towards the long-wavelength region. It is because the TDFA output spectrum (i.e., the pump laser spectrum for the ZBLAN fiber) was located in the anomalous region of the ZBLAN fiber where the dominant nonlinear effect is the Raman SSFS which mainly contributes to the generation of long-wavelength spectral components. When the TDFA output power was 0.91 W, the spectrum only covered a limited region of 1.95–2.3 μm. Continuous spectral broadening was observed as the TDFA output power increased. When the TDFA output power increased to 11.7 W, the long wavelength edge (LWE) of the generated SC exceeded 3000 nm. A 27.4-W SC with spectral coverage of 1.9–3.63 μm was obtained when the TDFA output power was increased to 39.0 W. The corresponding 20-dB bandwidth was 1.92–3.47 μm. In those spectra pumped with TDFA output power higher than 11.7 W, the spectral dip around 2.7 μm caused by the water vapor in the monochromator could be seen.

Optimizations for higher SC power or better spectral coverage could be achieved by tuning the pump PRR and pulse duration. Figure 3(b) depicts the SC spectrum comparison with maximal launched pump power under PRR and pulse duration of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns. Under PRR and pulse duration of 3 MHz 3 ns, an output power of 30.0 W was detected (corresponding to a power increase of ~10% compared with 27.4 W), though the LWE of the generated SC was limited to 3.35 μm. For PRR and pulse duration of 2 MHz 1 ns, a better spectral coverage of 1.9–3.7 μm (with 20-dB bandwidth of 1.93–3.56 μm) was achieved, and the SC power was lower (24.8 W). Note that the obtained SC's

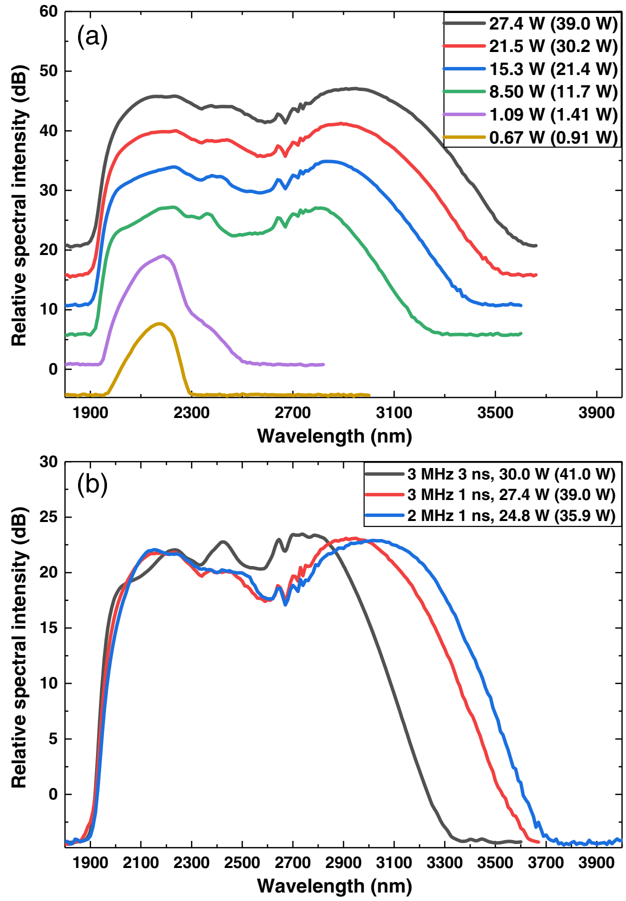

Fig. 3. (a) SC spectrum evolution under different TDFA output power for PRR of 3 MHz and pulse duration of 1 ns. (b) SC spectrum comparison with maximal pump power under PRR and pulse duration of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns.

LWE is shorter than the transmission limit of a ZBLAN fiber (typically ~4.0 μm). We attributed this to the comparatively short length of the available ZBLAN fiber and the larger fiber core diameter compared to those used in the literature [16,17]. Of course, exploiting the pump source with higher pulse peak power (such as a chirped pulse amplification system) could partially make up for such deficiency. The power ratio as well as the average power of >2.4 μm was calculated by a spectral density integral. The power ratios over 2.4 μm under the pulse parameters of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns are 65.0%, 68.0%, and 70.6%, respectively, corresponding to average power of 19.5 W, 18.6 W, and 17.5 W.

Figure 4 shows the output power of the SC laser in terms of the TDFA output power under different PRR and pulse duration of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns. As shown in Fig. 4, the output power of the ZBLAN fiber (i.e., the SC power) increased almost linearly along the TDFA output power for all three cases, which means that the generated SC spectrum has not been extended into the high-attenuation zone of the ZBLAN fiber. SC power of 30.0 W was obtained under TDFA output power of 41 W for the case of 3 MHz 3 ns. For the cases of 3 MHz 1 ns and 2 MHz 1 ns, a lower SC power of 27.4 W and 24.8 W was detected, pumped with maximal TDFA

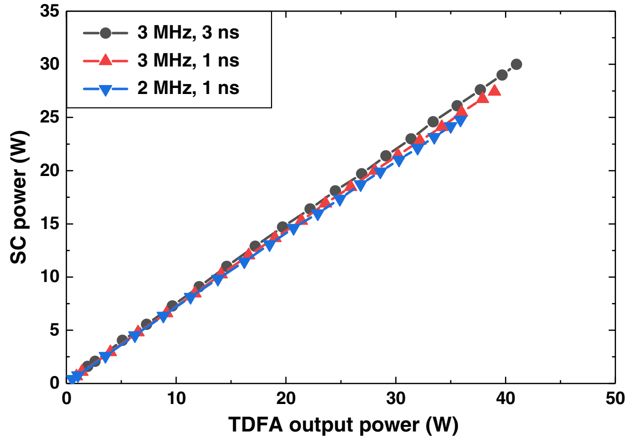

Fig. 4. SC power as a function of the TDFA output power under PRR and pulse duration of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns.

output power of 39.0 W and 35.9 W, respectively. One could see from Fig. 4 that the maximal TDFA output power limited further power scaling of the SC laser.

The power conversion efficiency of the generated SC laser in terms of the maximal TDFA output power, for the cases of 3 MHz 3 ns, 3 MHz 1 ns, and 2 MHz 1 ns, was 73.1%, 70.3%, and 69.0%, respectively. In addition, a simple calculation shows that the optical-optical conversion efficiency from the 793-nm laser diodes of the TDFA to SC output is up to 29.7% and 24.6%, for the cases of 3 MHz 3 ns and 2 MHz 1 ns, respectively. It has to be noted that, the introduction of a large-core ZBLAN fiber and the removal of the MFA (usually with a pigtail having a core diameter of 7 μm) contribute a lot to the high-power and efficient SC generation. In this way, the unpleasant attenuation-induced loss in both pigtails of the MFA, as well as the coupling loss between the ZBLAN fiber and the output pigtail of the MFA, was reduced. The short length of the used ZBLAN fiber is also beneficial to loss reduction though the generated SC has a limited bandwidth. Furthermore, neither power degradation nor obvious temperature rise was observed during the whole experiment which lasted for over 2 h (where the full-power operation period was ~10 min). The literature on high-power (>10 W) SC generation with a spectrum extending beyond 3 μm is summarized in Fig. 5. One could see that this paper represents the most powerful one of SC lasers based on soft glass fibers to date.

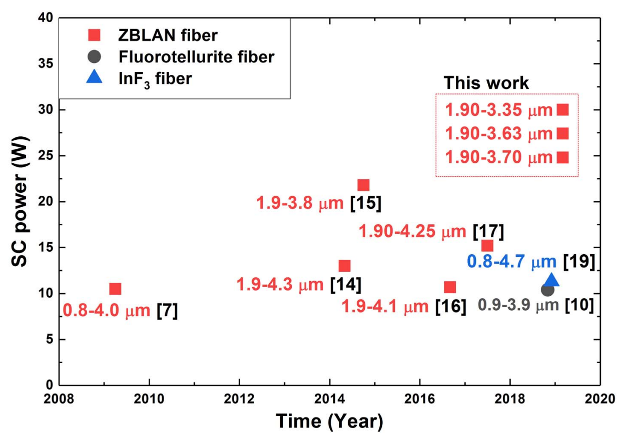

Fig. 5. Summary of the literature on 10 W level SC generation based on non-silica fibers with a spectrum extending beyond 3 μm. The bandwidth in the diagram represents full spectral range.

3. CONCLUSION

In conclusion, a 30-W supercontinuum with full spectral coverage of 1.9–3.35 μm was generated in a short piece of ZBLAN fiber in an all-fiberized configuration. By varying the pump pulse duty ratio, we also obtained an optimized supercontinuum with an output power of 27.4 W and a spectral coverage of 1.9–3.63 μm (with a 20-dB bandwidth of 1.92–3.47 μm), and a supercontinuum with an output power of 24.8 W and a full spectral coverage of 1.9–3.7 μm (with a 20-dB bandwidth of 1.93–3.56 μm). The employment of a large-core ZBLAN fiber made a traditional mode field adapter unnecessary and thus enhanced the power conversion efficiency of the generated supercontinuum. Higher output power and better spectral coverage are expectable by exploiting the pump laser with higher average/peak power, and using a longer ZBLAN fiber. To the best of the authors' knowledge, this research demonstrates record power among ZBLAN-fiber-based supercontinuum lasers to date, paving the way of broadband multi-tens-of-watt supercontinuum generation in ZBLAN fibers with high efficiency.

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