High power all fiber mid-IR supercontinuum generation in a ZBLAN fiber pumped by a 2 μm MOPA system

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Abstract: High power all fiber mid-IR supercontinuum (SC) generation in a ZBLAN fiber pumped by a 2 μm master oscillator power amplifier (MOPA) system is demonstrated. A semiconductor saturable absorber mirror (SESAM) passively mode-locked laser with pulse width of 26 ps at 1960 nm is used as the seed of the MOPA system. A laser spectrum extending from ~1.9 μm to beyond 2.6 μm is generated in a subsequent thulium-doped fiber amplifier (TDFA). Then, the spectrum is further broadened to the mid-IR region in the ZBLAN fiber. A mid-IR SC extending from 1.9 to 3.9 μm with 7.11 W average output power is obtained based on a large mode area TDFA, the SC power for wavelengths longer than 2.5 μm is 3.52 W with a power ratio of 49.5% with respect to the total SC power. The overall optical conversion efficiency from the 790 nm pump of the large mode area TDFA to the total SC output is 10.4%. To the best of our knowledge, both the 7.11 W total average power and 3.52 W average power in wavelengths beyond 2.5 μm are the highest power ever reported for a mid-IR SC generation in ZBLAN fiber pumped by 2 μm fiber lasers and TDFAs.

OCIS codes: (060.4370) Nonlinear optics, fibers; (320.6629) Supercontinuum generation; (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers.

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1. Introduction

Supercontinuum (SC) generation in optical fibers has attracted significant attention in the past decade owing to its usefulness in a variety of applications such as optical communication [1], frequency metrology [2], spectroscopy [3], and optical coherence tomography [4]. The majority of SC sources developed are based on silica fibers, especially silica photonic crystal fibers (PCFs). The advent of PCF in the late 1990s, together with developments in efficient high power and short pulse fiber lasers, have led to a revolution in the generation of ultra-broadband high brightness spectra through the process of SC generation. Visible and near-IR SC generation in silica PCFs have been widely demonstrated [5–7]. Recently, we demonstrated flat SC generation in an Er/Yb-codoped double-clad fiber amplifier (EYDFA) [8] and high-power SC generation in an Yb-doped fiber amplifier (YDFA) [9]. In those

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systems, the rare-earth doped fiber amplifiers exhibited an excellent performance for high power and spectral flatness SC generation. A 70 W SC spanning from 1.06 μm to beyond 1.7 μm with spectral flatness better than 12 dB and 67.3% optical to optical conversion efficiency was generated in a nonlinear YDFA using an all fiber master oscillator power amplifier (MOPA) configuration [9]. Thulium doped fiber amplifiers (TDFAs) have lately become of great interest for SC generation with wavelengths longer than 2 μm [10–13]. For example, a 2.17 W SC laser spanning from 1.95~2.75 μm was generated in a TDFA [10]. However, the SC range stopped at the wavelengths shorter than 3 μm, due to the intrinsic absorption loss of fused silica. SC sources in the mid-IR spectral region may push the application further in medical, biologic and sensing systems [14]. Recently, there has been an increasing interest in using soft-glass fibers (e.g., fluoride [15–21], tellurite [22, 23], and chalcogenide [24, 25] fibers) for mid-IR SC generation due to their high nonlinearity and low transmission loss in the mid-IR region. However, at present only heavy metal fluoride fibers, especially ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) fibers are considered to be the most stable and technologically mature for high power applications [15, 21].

G. Qin *et al*. presented an ultra-broadband low power (<20 mW) SC generation from ultraviolet to 6.28 um in a centimeter-long ZBLAN fiber pumped by a 1450 nm femtosecond laser [16]. C. Xia *et al*. reported a SC extending up to 4 μm in a single mode ZBLAN fiber with 10.5 W average output power using an amplified nanosecond pulsed laser diode at 1550 nm [17], this is the highest average output power SC generation from a single mode ZBLAN fiber to date. However, a limited amount of power is generated beyond 2.5 μm (~3 W with 28.6% power ratio) which is the relevant spectral window for many applications. Recently, Tm-doped fiber lasers operating at an eye-safe wavelength range around 2 μm have attracted significant attention [26, 27]. For efficient mid-IR SC generation, 2 μm pulsed fiber laser is proved to be an attractive pump choice [18–21]. Compared to the 1.55 μm pump scheme, the SC generation efficiency for wavelengths longer than 2.5 μm can be improved by pumping a ZBLAN fiber at 2 μm [18]. M. Duhant *et al.* reported a mid-IR SC extending up to 3.8 μm with 490 mW average output power in a ZBLAN fiber by direct pumping in the anomalous dispersion region at 2 μm [18], the power ratio of SC for wavelengths longer than 2.5 μm is 47% with respect to the total SC power, which is 1.5 times larger than that reported by [17]. O. P. Kulkarni *et al.* used TDFA to improve the mid-IR SC generation efficiency [19]. A continuous spectrum extending from ~1.9 to 4.5 μm was generated with ~2.6 W total average output power and ~0.7 W in wavelengths beyond 3.8 μm. Up to ~2.5 times higher optical conversion efficiency to wavelengths beyond 3.8 μm was achieved by replacing an EYDF with a TDFA. More recently, M. Eckerle *et al.* reported a simultaneously actively Q-switched and actively mode-locked 2 μm Tm-doped fiber laser, and used it for SC generation in a ZBLAN fiber [20]. Over 1080 mW of SC from 1.9 μm to beyond 3.6 μm was obtained. J. Swiderski *et al*. reported a novel method of mid-IR SC generation with the use of a 2 μm gain-switched self-mode-locked thulium-doped fiber laser [21]. The output SC has a wide spectrum range from ~1.9 to 3.8 μm and an average output power of 0.74 W with 0.27 W at wavelengths longer than 2.4 μm. However, in those 2 μm pump schemes [20, 21], the average output power of the mid-IR SC is only around 1 W.

In this paper we demonstrate a high power all fiber mid-IR SC generation in a single mode ZBLAN fiber pumped by a 2 μm MOPA system. A semiconductor saturable absorber mirror (SESAM) passively mode-locked fiber laser with pulse width of 26 ps at 1960 nm is used as the seed of the MOPA system. The laser spectrum is firstly broadened in the fiber amplifiers, and then further broadened to mid-IR region in the ZBLAN fiber. A mid-IR SC extending to 3.65 μm is generated with 1 W average output power based on a small core TDFA. In order to increase the mid-IR SC generation efficiency and further scale up the total average output power, a large mode area (LMA) TDFA and a pulse repetition rate increasing system are used. At last, a mid-IR SC extending from 1.9 to 3.9 μm is generated with 7.11 W total average output power and 3.52 W average power in wavelengths beyond 2.5 μm.

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2. Small core TDFA based mid-IR SC generation

2.1. Experimental setup

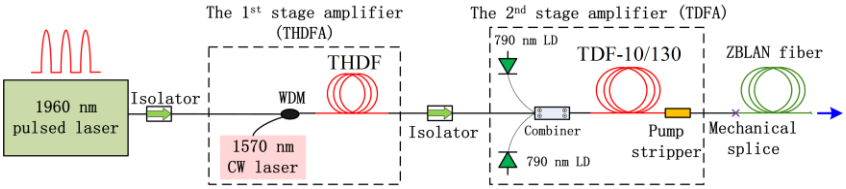

Fig. 1. Experimental setup of the all fiber integrated mid-IR SC generation system.

Figure 1 illustrates the small core TDFA based mid-IR SC generation system. The pump of the mid-IR generation system is a three stage MOPA laser. A SESAM passively mode-locked fiber laser is used as the master oscillator, which is comprised of a 1.5 m long thulium/holmium codoped fiber (THDF), a wavelength division multiplexer (WDM), a SESAM and a fiber Bragg grating (FBG). The FBG has a reflectivity of 80% at 1960 nm with a bandwidth (FWHM: full-width at half-maximum) of 0.5 nm. The THDF has a core/cladding diameter of 8/125 μm and an absorption coefficient of ~20 dB/m at 1570 nm. The pump source of the seed laser is a continuum wave (CW) single-mode fiber laser with a central wavelength of 1570 nm. The first stage amplifier is a THDF amplifier (THDFA), which consists of a 1.5 m long 8/125 μm THDF forward pumped by a 1.02 W 1570 nm CW single mode fiber laser. The second stage amplifier is a TDFA where a 7 m long double clad thulium-doped fiber (TDF) is used as the gain medium with a core/cladding diameter of 10/130 μm, an effective core/cladding numerical aperture (NA) of 0.15/0.46 and a peak cladding absorption of ~3 dB/m at 790 nm. A (2 + 1) × 1 pump combiner is used to deliver pump light to the gain fiber from two fiber-pigtailed multimode diodes with a total pump power of 18.8 W at 790 nm. The output of the double clad TDF is spliced to a 0.8 m long single mode fiber, which has a 7/125 μm core/cladding diameter and a core NA of 0.2, allowing for convenient coupling to the ZBLAN fiber. The single mode ZBLAN fiber used in the experiment has a length of 10 m, a high NA of ~0.27 and a core/cladding diameter of 8/130 μm. Using experimentally derived Sellmeier coefficients [28], the calculated material zero dispersion wavelength (ZDW) of ZBLAN fluoride glass is about 1.62 μm and the ZDW of ZBLAN fiber is around 1.49 μm [29]. The ZBLAN fiber has a transmission range of 0.35-4.5 μm, and the fiber attenuation in 2-3.5 μm wavelength range is less than 0.1 dB/m. The 7/125 μm single mode fiber is mechanically spliced to the input end of the ZBLAN fiber with angle-cleaves on both fibers to prevent reflections in the system. The mechanical splicing loss is about 27%.

The power is measured with a wavelength insensitive thermal power meter, and power distribution beyond 2.5 μm is measured using a cut-off long-pass filter. The output SC spectrum from 1.2 to 2.4 μm is measured by using an optical spectral analyzer (YOKOGAWA AQ 6375) whereas that for longer wavelengths are acquired using a monochromator and a liquid-nitrogen-cooled InSb detector. The ultra-short pulse width is measured by an autocorrelator (Femtochrome Research Inc., FR-103XL). A 20 GHz sampling rate digital oscilloscope with 1.5 GHz bandwidth and an InGaAs detector with <50 ps rise time is used to measure the time characteristics.

2.2. Results and discussion

In our experiment, the fiber oscillator delivers stable CW mode-locked pulses with an output power of 3 mW. The pulse width cannot be characterized by the autocorrelator because of the low average and peak powers of the fiber oscillator. Therefore a pulse autocorrelation trace is measured after the first stage fiber amplifier with an output power of 70 mW, which is shown in Fig. 2(a). The inset of Fig. 2(a) shows the stable passively mode-locked pulse train with a repetition rate of 23.7 MHz. As can be seen in Fig. 2(a), assuming a $sech^2$ pulse profile we

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estimate a FWHM pulse width of 26 ps. The pulse autocorrelation trace has a pedestal which is caused by the detector noise. The photodiode detector used in our autocorrelator is sensitive to both the signal wavelength and the second harmonic wavelength. This pedestal is caused by the 1960 nm signal light, which always exists no matter the nonlinear crystal is phase matched or not. The optical spectrum of the mode-locked fiber laser is shown in Fig. 2(b). The central lasing wavelength is 1960 nm and the spectral bandwidth (FWHM) is ~0.36 nm as measured with resolution of 0.05 nm.

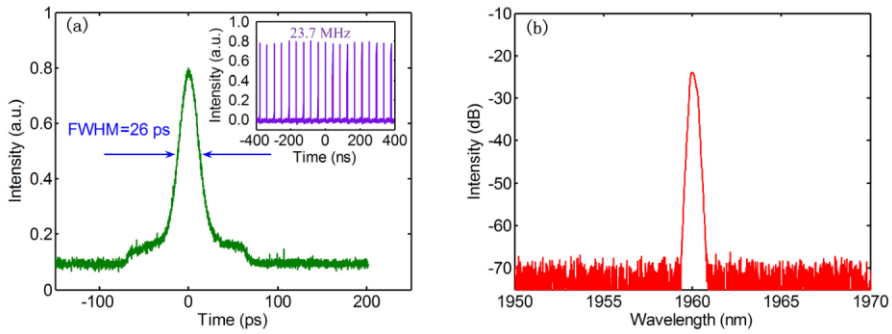

Fig. 2. (a) Pulse autocorrelation trace of the first stage fiber amplifier. Insert shows the stable passively mode-locked pulse train with a repetition rate of 23.7 MHz. (b) Output spectrum of the mode-locked fiber laser.

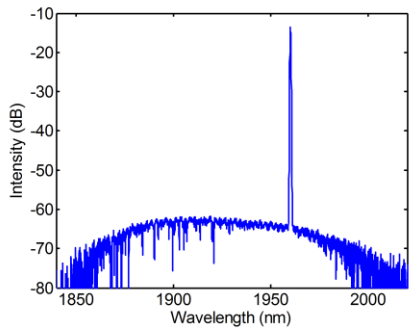

Fig. 3. Optical spectrum of the first fiber amplifier at 110 mW output power.

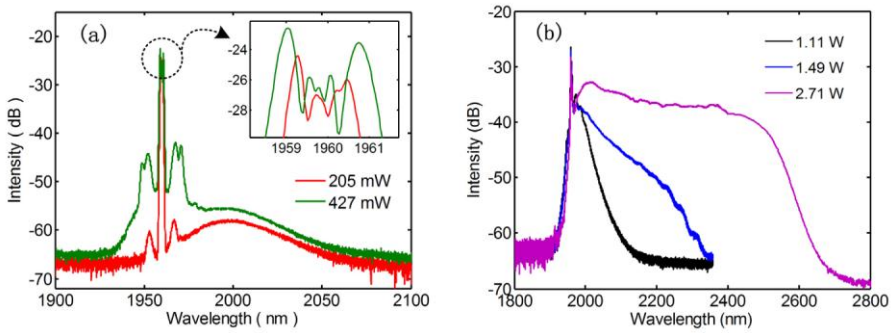

Fig. 4. Output spectra of the second stage fiber amplifier for different output powers of (a) 205 and 427 mW, (b) 1.11, 1.49 and 2.71 W. The inset of (a) provides the detailed SPM induced spectral broadening around the signal wavelength.

The first stage fiber amplifier can provide 110 mW average output power at the pump power of 1.02 W with an output spectrum as shown in Fig. 3. Except for the slightly

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amplified spontaneous emission (ASE), no obviously nonlinear effect induced optical spectrum extension can be seen. However, the laser spectrum is gradually extended in the second stage fiber amplifier during the amplification process. Figure 4 shows the output spectra of the second fiber amplifier for different output powers of (a) 205 and 427 mW, (b) 1.11, 1.49 and 2.71 W. In the second stage fiber amplifier, the initial spectral broadening can be attributed to modulation instability (MI) and self-phase modulation (SPM). Both the characteristic MI side bands and SPM induced spectral broadening with an oscillatory structure [30] can be seen in Fig. 4(a). The MI can induce spectral broadening and break up the picosecond pulses into femtosecond pulse trains to enhance the nonlinear effects. With the increasing of the output power, the spectrum is gradually broadened to longer wavelengths with other nonlinear effects such as intrapulse Raman scattering and soliton self-frequency shift [30]. As can be seen in Fig. 4(b), the long wavelength edge of the output SC already extends to 2.7 μm at the 2.71 W output power.

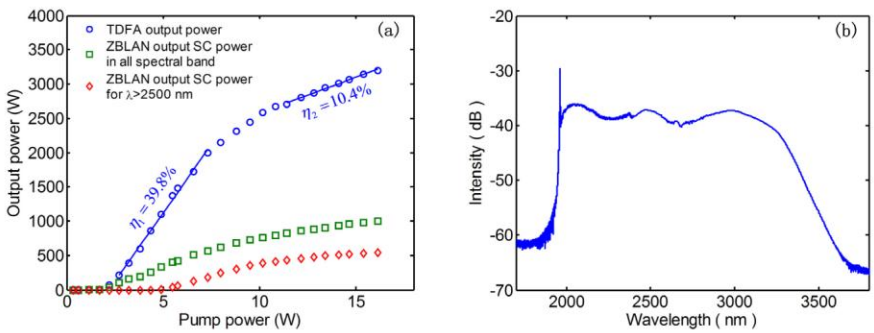

Fig. 5. (a) The TDFA output power, ZBLAN output mid-IR SC power in all spectral band and mid-IR SC power for λ>2500 nm versus the TDFA pump power. (b) ZBLAN output mid-IR SC spectrum at 1 W output power.

The SC spectrum can be further broadened in the following single mode fiber and ZBLAN fiber. The TDFA output power, ZBLAN fiber output mid-IR SC power in all spectral band and mid-IR SC power for λ>2500 nm as a function of the TDFA 790 nm pump power is shown in Fig. 5(a). The TDFA output power is not linearly increased, and the slope efficiency of the TDFA decreases from 39.8% to 10.4% with the increase of the pump power. We think that the slope efficiency decrease is owing to the spectral broadening. Firstly, when the spectrum is broadened in the fiber amplifier, the new generated spectral component which lies spectrally out of the gain band will not be amplified. Furthermore, the silica fiber intrinsic absorption losses beyond 2.4 μm [31] will cause a high transmission loss for the SC with wavelengths longer than 2.4 μm.

When the 790 nm pump power reaches 16.15 W, the ZBLAN output SC power is 1 W. The overall optical conversion efficiency from the 790 nm pump to the total SC output is 6.2%, which is comparable to recent results of 2 μm pumped mid-IR SC generations [19–21]. When the average output power of the mid-IR SC at the end of ZBLAN fiber reaches 1 W, the power for λ>2500 nm is 546 mW with a ratio of 54.6% with respect to the total mid-IR SC power, and the output spectrum ranges from 1.9 to 3.65 μm, which is shown in Fig. 5(b).

It should be noticed that, there exists a high splicing loss (~25%: estimated by power measured ~5 cm after the splicing point) between the 10/130 μm double clad TDF and the 7/125 μm single mode fiber mainly owing to the mode field mismatch, as well as a high mechanical splicing loss (~27%) between the single mode fiber and the ZBLAN fiber. Therefore, the mid-IR SC generation efficiency would be improved by reducing those losses e.g. the splicing loss caused by mode field mismatch can be reduced with the thermally expanded core technique [32], and the mechanical splicing loss can be reduced by using the fusion splicing method instead of the mechanical splicing. However, the efficiency decrease

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caused by spectral broadening is still a problem to be solved. The LMA TDFA which has a lower nonlinearity may be a good choice to alleviate the declining rate of the slope efficiency.

3. LMA-TDFA-based mid-IR SC generation

3.1. Experimental setup

In the small core TDFA based mid-IR SC generation experiment, the spectral broadening in the TDFA causes the slope efficiency decrease, which will limit the power amplification capability. The small core TDFA system is also limited in its average power scaling capability owing to its small core diameter. Therefore a LMA TDFA is used for the high power operation. The high power mid-IR SC generation system is presented in Fig. 6. The LMA TDFA consists of a (2 + 1) × 1 high-power pump combiner, two 50 W multi-mode laser diodes operating at 790 nm and 3 m LMA TDF. The LMA TDF exhibits 25/250 μm core/cladding diameter, 0.10/0.46 NA and a cladding absorption of ~9.5 dB/m at 790 nm. The mode conversion from LMA TDF to single mode fiber is achieved by a mode adapter with a 25/250 μm passive fiber (0.11/0.46 NA) at the input and a 7/125 μm single mode fiber (0.2 NA) at the output. Then, the 7/125 μm single mode fiber is mechanically spliced to the ZBLAN fiber. In order to improve the mid-IR SC generation efficiency, in this experiment the length of the single mode ZBLAN fiber is reduced to 6.8 m and the mechanical splicing loss is reduced to ~20% by optimization.

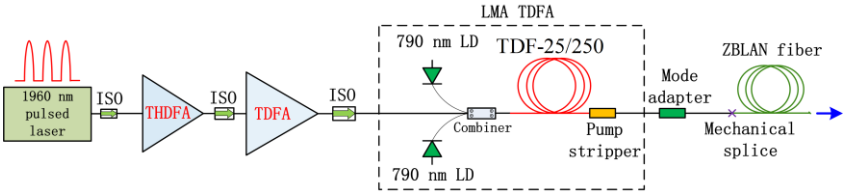

Fig. 6. Experimental setup of the high power mid-IR SC generation system. ISO – isolator.

3.2. Results and discussion

In this experiment, the pump power and the output power of the second stage fiber amplifier is 4.89 and 1.11 W, respectively. The input spectrum of the LMA TDFA is shown as the black line in Fig. 4(b). Similar with the small core TDFA based mid-IR SC generation, the laser spectrum firstly extends in the LMA TDFA, then in the following passive fiber, and finally the spectrum extends to mid-IR region in the ZBLAN fiber. The LMA TDFA output power, mode adapter output power, ZBLAN output mid-IR SC power in all-spectral band and mid-IR SC power for λ>2500 nm versus the LMA TDFA pump power at 790 nm is shown in Fig. 7. Figure 8 shows the evolutions of the output SC spectrum for different 790 nm pump powers of the LMA TDFA.

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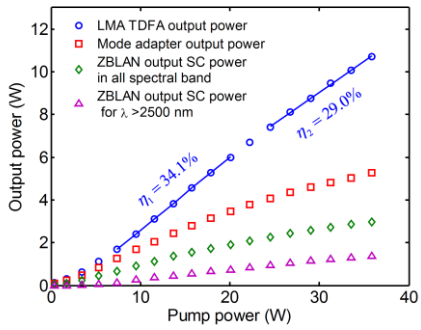

Fig. 7. The LMA TDFA output power, mode adapter output power, ZBLAN output mid-IR SC power in all spectral band and mid-IR SC power for λ>2500 nm versus the LMA TDFA pump power at 790 nm.

As Fig. 7 shows, the slope efficiency of the LMA TDFA decreases from 34.1% to 29.0% with the increase of the pump power. The reason of slope efficiency decrease is the same as that described in section 2.2. Compared with the small core TDFA, the lower nonlinearity of the LMA TDF can reduce the spectral broadening speed, and the shorter gain-fiber length (~3m) of the LMA TDFA can reduce the transmission loss. Therefore, the slope efficiency decrease of the LMA TDFA is not so much as that in Fig. 5(a), where the slope efficiency decreases from 39.8% to 10.4% with the increase of the pump power.

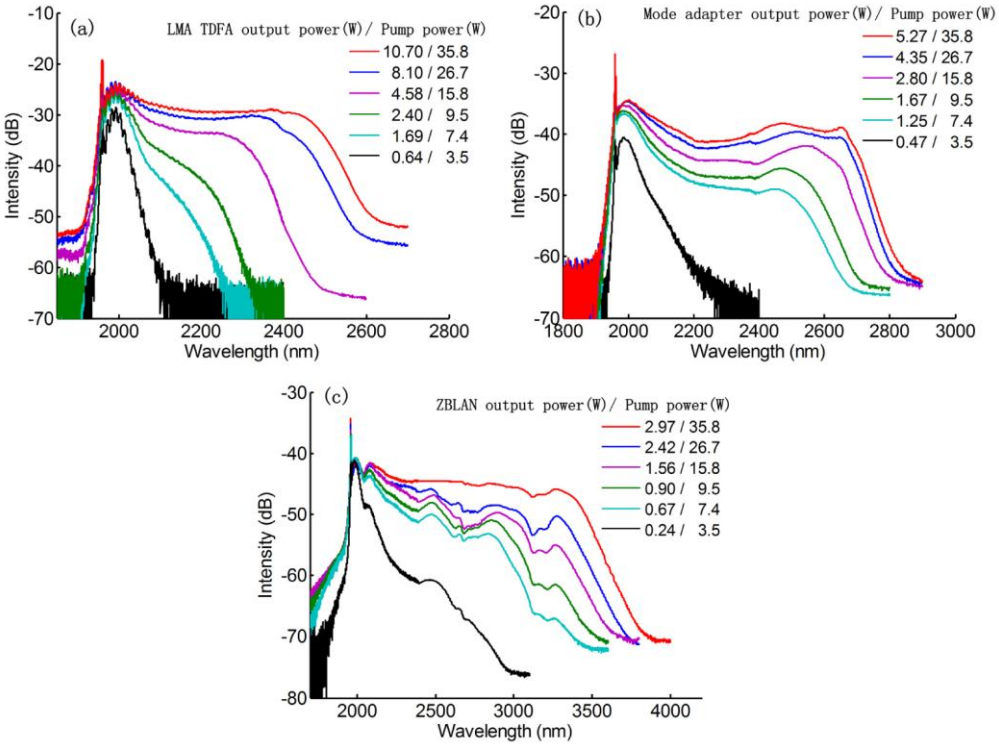

Fig. 8. Evolutions of the output SC spectrum with 790 nm pump power of the LMA TDFA: (a) the LMA TDFA output, (b) the mode adapter output and (c) the ZBLAN fiber output.

By comparing the output power of the LMA TDFA and the mode adapter in Fig. 7, we can see that the loss caused by the mode adapter increases with the augmentation of the pump power. The spectral broadening in the mode adapter is one of the main factors contributing to

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the loss increase. The evolutions of the LMA TDFA output spectrum and the mode adapter output spectrum are shown in Figs. 8(a) and 8(b), respectively. As can be seen from those two figures, the optical spectrum can be further broadened to the longer wavelength in the mode adapter, especially in the 7/125 single mode fiber at the output of the mode adapter. When the pump power reaches 9.5 W, the output powers of the LMA TDFA and mode adapter are 2.4 and 1.67 W respectively, and the mode adapter output spectrum extends to beyond 2.6 μm. In this case, the loss caused by the mode adapter is ~30%. With the increase of the pump power, the mode adapter output spectrum further extends to the longer wavelength but with a slowly spread speed and a limited broadening scope owing to the absorption losses of silica fiber. When the pump power reaches 35.8 W, the output powers of the LMA TDFA and mode adapter are 10.7 and 5.27 W respectively, and the mode adapter output spectrum extends to beyond 2.8 μm. In this case, the loss caused by the mode adapter is 50.7%. Both the spectral broadening and the strong attenuation of silica fiber in the long wavelength region can cause laser power decrease. On the other hand, the insert loss of the mode adapter, which is wavelength dependence, may increase with the spectral broadening. Therefore, the loss caused by the mode adapter increases from 30% to 50.7% when the pump power changes from 9.5 W to 35.8 W.

The optical spectrum is further broadened to the mid-IR region in the ZBLAN fiber. The evolution of ZBLAN fiber output spectrum with the 790 nm pump power of the LMA TDFA can be seen in Fig. 8(c). When the pump power reaches 35.8 W, the mid-IR SC average output power is 2.97 W, corresponding to an output efficiency of 7.8% with respect to the 790 nm pump power of the LMA TDFA. Considering the 20% mechanical splicing loss, the total power coupled to the ZBLAN fiber is 4.2 W (5.27 W mode adapter output power multiplies 80% coupling efficiency) when the pump power is 35.8 W. Therefore, the SC generation and material absorption induced loss in ZBLAN fiber is only 29.3%. When the average output power of the mid-IR SC is 2.97 W, the output spectrum ranges from 1.9 to 3.8 μm, and the average output power of the SC power for λ>2500 nm is 1.38 W with a power ratio of 46.1% with respect to the total SC power.

3.3. Pulse repetition rate increasing to further scale up the average output power

Both the average output power and the optical conversion efficiency of mid-IR SC generation can be increased by increasing the system repetition rate [19]. In order to improve the optical conversion efficiency to get a higher output power, a self-made all-fiber repetition rate increasing system [33] is utilized after the seed laser to double the pulse repetition rate.

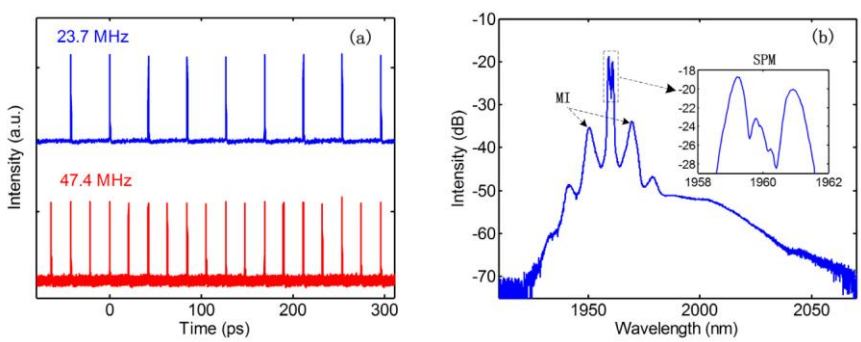

Fig. 9. (a) Seed laser pulse trains before (upper) and after (bottom) the pulse repetition rate increasing system. (b) Output spectrum of the second stage fiber amplifier at 1.33 W output power with 47.4 MHz pulse repetition rate.

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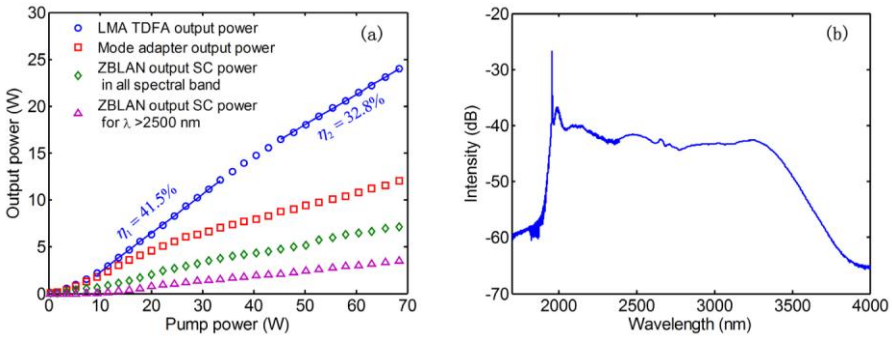

Fig. 10. With the pulse repetition rate increasing system, (a) the LMA TDFA output power, mode adapter output power, ZBLAN mid-IR SC output power in all spectral band and mid-IR SC power for λ>2500 nm versus the LMA TDFA pump power at 790 nm, (b) ZBLAN output mid-IR SC spectrum at 7.11 W output power.

Figure 9(a) shows the seed laser pulse trains before (upper) and after (bottom) the pulse repetition rate increasing system. After the repetition rate increasing system, the seed laser's pulse repetition rate is doubled to be 47.4 MHz. The laser spectrum is gradually broadened in the second stage fiber amplifier during the amplification process. In this experiment the second stage fiber amplifier provides 1.33 W output power with 5.8 W 790 nm pump power. The output spectrum of the second stage fiber amplifier is shown in Fig. 9(b). The characteristic MI side bands and SPM induced spectral broadening with an oscillatory structure can be seen in Fig. 9(b). The spectral broadening process is the same as that described in section 3.2. The spectrum extends in the LMA TDFA and mode adapter, and then, it further extends to mid-IR region in the ZBLAN fiber. Figure 10(a) illustrates the dependence of the LMA TDFA output power, mode adapter output power, ZBLAN fiber output mid-IR SC power in all-spectral band and mid-IR SC power for λ>2.5 μm on the third stage fiber amplifier pump power at 790 nm . Figure 10(b) shows the ZBLAN output mid-IR SC spectrum at 7.11 W output power.

As can be seen from Fig. 10(a), by using the repetition rate increasing system, the slope efficiency of the LMA TDFA is 41.5% at the lower pump power level and 32.8% at the higher power level. The slope efficiency is higher than that in Fig. 7, under the similar pump condition. When the pump power reaches 68.5 W, the ZBLAN fiber output mid-IR SC power in all-spectral band is 7.11 W with an overall efficiency of 10.4% with respect to the pump power of the LMA TDFA, and the SC power for λ>2.5 μm is 3.52 W with a power ratio of 49.5% with respect to the total SC power. Figure 10(b) shows the ZBLAN fiber output mid-IR SC spectrum at 7.11 W average output power, indicating an output spectrum ranges from 1.9 to 3.9 μm.

4. Conclusion

In conclusion, high power all fiber mid-IR SC generation in a single mode ZBLAN fiber pumped by a 2 μm MOPA system is demonstrated. A SESAM passively mode-locked fiber laser, which operates at 1960 nm with pulse width of 26 ps and pulsed repetition rate of 23.7 MHz, is used as a seed source of the MOPA system. The laser spectrum extending from ~1.9 μm to beyond 2.6 μm is generated in the TDFA. Then, the spectrum is further broadened to the mid-IR region in the ZBLAN fiber. A mid-IR SC extending from 1.9 to 3.65 μm is generated with 1 W average output power based on the small core TDFA. The overall optical conversion efficiency from the 790 nm pump to the total SC output is 6.2%. A pulse repetition rate increasing system and a LMA TDFA are used to scale up the average output power. At last, a mid-IR SC with 7.11 W average output power is obtained. The output spectrum ranges from 1.9 to 3.9 μm, and the SC power for wavelengths longer than 2.5 μm is 3.52 W with a power ratio of 49.5% with respect to the total SC power. The overall optical

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conversion efficiency from the 790 nm pump of the LMA TDFA to the total SC output is 10.4%.

Compared with the mid-IR SC generation pumped by 1550 nm pulsed laser, the total mid-IR SC output power of 7.11 W in our experiment is smaller than the 10.5 W result in [17]. However, the 3.52 W output power and 49.5% power ratio of SC for wavelengths longer than 2.5 μm in our experiment are higher than that (~3 W with 28.6% power ratio) reported by [17]. Among the 2 μm and TDFA pump schemes, both the 7.11 W total average power and 3.52 W average power in wavelengths beyond 2.5 μm are the highest power ever reported for a mid-IR SC generation in ZBLAN fiber, to the best of our knowledge.

The average power of the mid-IR SC generated in the single mode ZBLAN fiber can be further scaled up to ~40 W according to the theoretical analysis in [17]. However, the output end of the ZBLAN fiber is susceptible to thermally induced damage at high powers. In our future work, we will try to scale up the average output power by increasing the TDFA output power and end capping the ZBLAN output end to prevent the thermal damage.

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