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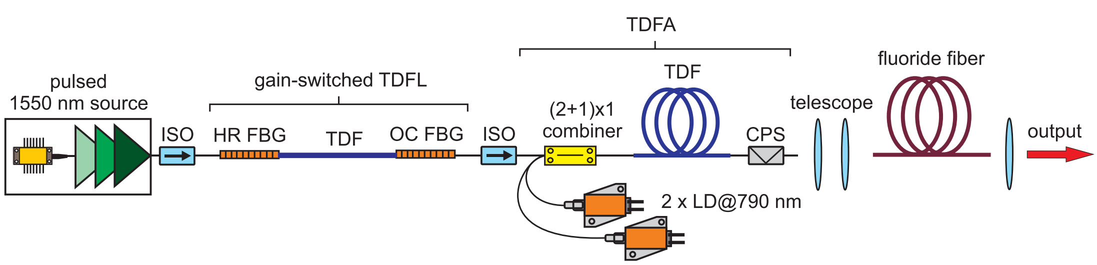

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Gain-Switched 2-μm Fiber Laser System Providing Kilowatt Peak-Power Mode-Locked Resembling Pulses and Its Application to Supercontinuum Generation in Fluoride Fibers

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Abstract: A fast gain-switched Tm-doped fiber laser and amplifier system providing stable 17-ns pulses with a 0.64-mJ energy and 35.6-kW peak power at 25 kHz is demonstrated. Then, self-starting mode-locked resembling pulses with duration of $<$200 ps, recorded within the gain-switched pulse envelope, were achieved in the same laser cavity. By amplifying the pulse train in a Tm-doped fiber amplifier, an average output power of 6.8 W at a $\sim$15-ns full width at half maximum gain-switch envelope and a $\sim$36.9-μJ subpulse with a peak power of up to 115.6 kW were demonstrated. To the best of our knowledge, this is the shortest gain-switched and mode-locked-like pulse as well as the highest peak-power that has been demonstrated in this type of laser system. A mid-infrared supercontinuum generation with a total output power of 2.45 W and a cutoff wavelength at 4.4 μm is also reported.

Index Terms: Fiber lasers, laser amplifiers, supercontinuum generation.

1. Introduction

Gain-Switched Tm-doped fiber lasers (GS-TDFLs) and amplifiers (GS-TDFL&As) operating in the 2-μm spectral region have recently attracted much attention mainly due to their low complexity, power scalability, and their ability to emit short nanosecond pulses, while being very reliable and cost effective. When these features are combined with a wide range of practical applications, such as in medical treatment, communication, remote sensing, supercontinuum (SC) generation, and nonlinear frequency conversion [1]–[6], these laser sources are the focus of many research groups.

Gain-switching of fiber lasers is an alternative pulsing method characterized by an all-fiber integration, and does not require the alignment of free-space components. Compared with Q-switching and mode-locking, they do not require the application of modulating devices inside the cavity, thus ensuring higher efficiencies and simplicity during construction. Furthermore, because the repetition rate and pulse duration of the pump can be well controlled, the characteristics of the output signal pulse train can be easily predicted and adjusted, if necessary. In particular, fast gain-switching and the simultaneous in-band pumping of TDFLs ($^3H_6$ - $^3F_4$ transition) can provide stable and regular 2-μm Gaussian-like pulses of short ($<$100 ns) duration [7]. In the case of resonant-pumped

GS-TDFLs, the cross-relaxation and excited state absorption effects are neglected, which results from the nearly instantaneous building up of the upper laser energy level. As a result, the cavity gain is switched on and off in the same time scale as the pump pulse. Such laser systems have been recently presented, including those that are followed by an amplification section, which deliver pulses as short as 1.5 ns [8], output pulse energies in the microjoule [7], [9] and even single millijoule [10]–[12] ranges, pulse repetition frequencies from single kHz to hundreds of kHz [7], [10] and even providing wide wavelength tunability [13]–[16].

An interesting issue in the context of GS-TDFLs is the generation of mode-locked-like pulses. It has already been shown that by the suitable selection of pump parameters, it is possible to achieve self-starting mode-locked-resembling (MLR) sub-pulses that are recorded within one gain-switched pulse envelope [17]–[20]. This process starts automatically without any external perturbation that usually has to be applied to modulate the laser losses with a cavity round-trip time. As a result, the peak power of MLR sub-pulses may be higher than in the case of typical gain-switched pulses, thus being very useful for optical parametric generation or SC generation [21], [22]. In our previous works, we demonstrated self-starting mode-locked type pulses in an all-fiber fast GS-TDFL [17]. The laser delivered 100% modulated 1995-nm MLR sub-pulses within the envelope of a 30-ns gain-switched pulse at a repetition rate of 30 kHz and a maximum peak power of 1.1 kW. In another experiment, we also presented GS-TDFL&A emitting MLR pulses with a peak power having the most intense sub-pulse as high as 27.8 kW [22]. In this case, the envelope of the gain-switched pulse was 50 ns. Mode-locked pulsing at 1950 nm with a peak power of 250 W and a pulse duration of 720 ps in a passive GS-TDFL was also demonstrated by Tsao *et al.* [18]. Although the design of the laser is very interesting, the FWHM envelope of the gain-switched pulse was long, i.e., $\sim$0.4 μs, resulting in low peak power of MLR pulses. A mode-locked like operation was also observed by Tao *et al.* [19], who recorded fully modulated $\sim$8-ns MLR pulses in a $\sim$120-ns gain-switched pulse generated by a 1920.26-nm Tm-Ho co-doped single-clad fiber laser. Recently, Ouyang et al. developed a repetition-rate-switchable gain-switched 1.95-μm TDFL&A that delivers an average power of 115 W at a pulse repetition rate of 100 kHz (a pulse width of $\sim$600 ns), which corresponds to a pulse energy of $\sim$1.15 mJ [20]. Self mode-locked sub-pulses recorded within an envelope FWHM of a few hundred nanoseconds were also observed.

In this paper, we present a 2-μm all-fiber resonantly pumped fast GS-TDFL&A system and its use as an effective pump source for mid-infrared SC generation in ZBLAN fibers. It operates at a pulse repetition rate of 25 kHz and delivers a pulse energy of up to 0.64 mJ in 17 ns, corresponding to a peak power of 35.6 kW. Self-started mode-locked type pulses within the envelope of a $\sim$15-ns gain-switched pulse were also reported. The energy of the MLR subpulse with the highest intensity was measured to be 36.9 μJ, corresponding to a peak power of 115.6 kW, which is, to the best of our knowledge, the highest reported peak power of MLR pulses in GS-TDFL&A systems. Furthermore, using this laser source as a pump for ZBLAN nonlinear fibers, we demonstrate a mid-infrared flat SC with an average output power of 2.45 W and which covers the 1.9–4.4-μm band. We believe that this is the highest SC power generated out of a fluoride fiber when applying such a pump system.

2. Experimental Setup

The experimental setup of the GS-TDFL pumped by a pulsed 1.55-μm laser source followed by an amplifier and a section for SC generation is schematically shown in Fig. 1.

A 1.55-μm fiber-based master oscillator power amplifier seeded by a direct current modulated DFB laser providing an average power of up to 3.5 W was applied as a resonant pump. The amplification section consisted of two Er-doped fiber amplifiers (EDFA) and one Er:Yb-doped fiber amplifier (EYDFA). It delivered a train of optical pulses with duration varying from 30 to over 500 ns, which were emitted at a fixed pulse-repetition rate of 25 kHz. The Tm^{3+}-doped fiber laser (TDFL) of the linear cavity consisted of a highly reflective (HR) fiber Bragg grating (FBG) with a reflectivity of 99.3% and a 1.96-nm bandwidth at 2000.1 nm, a Tm^{3+}-doped fiber (TDF), and an output coupler (OC) FBG with a peak reflectivity of 89.3%, a 3-dB reflection bandwidth of 1.04 nm and 24-dB side-mode suppression. In order to decrease the cavity round-trip time, as the active medium, we

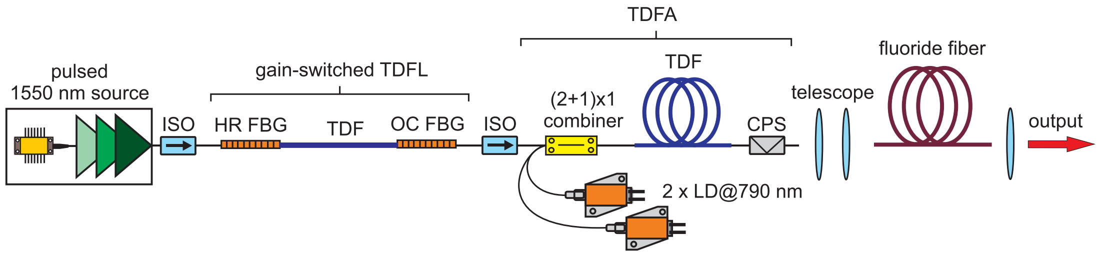


Fig. 1. Schematic setup of gain-switched Tm-doped fiber laser and amplifier followed by a section for supercontinuum generation in fluoride fibers. TDF – Tm-doped fiber, TDFL – Tm doped fiber laser, TDFA – Tm-doped fiber amplifier, ISO – optical isolator, CPS – cladding power stripper, HR FBG – high reflector fiber Bragg grating, OC FBG – output coupler fiber Bragg grating, LD – laser diode.

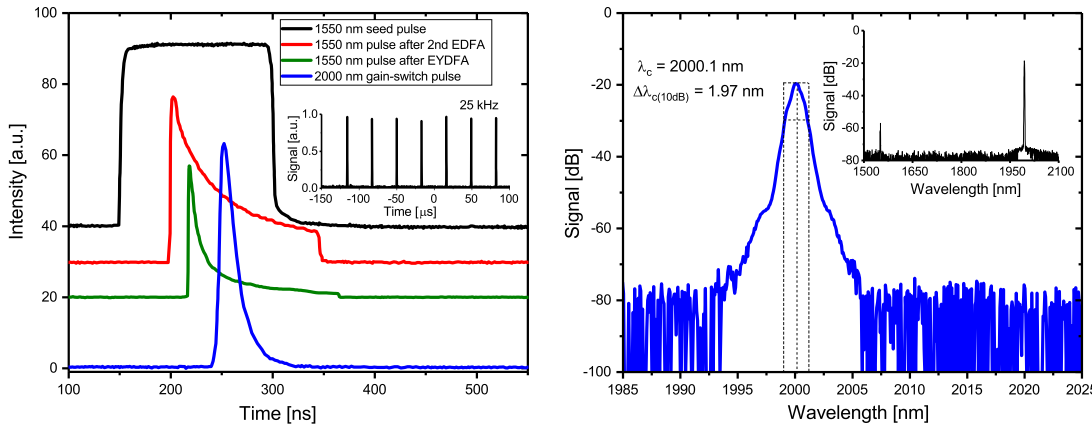
used a 12-cm-long single-mode, double-clad silica TDF with a core/clad diameter of 12/127 μm (0.13 NA) and peak cladding absorption of 19.5 dB/m at 790 nm, which was spliced in-between the FBGs. The total length of the resonator was 36.5 cm. In order to increase the peak power of generated pulses, a single Tm-doped fiber amplifier (TDFA) was applied. It was built using a $\sim$3-m long TDF with a core/clad diameter of 25/250 μm and corresponding NAs of 0.09/0.46. The fiber clad absorption at 793 nm was 9 dB/m. It was cladding-pumped in a co-propagating configuration via a $(2 \times 1) + 1$ pump power combiner with a signal feedthrough, using two 793-nm laser diodes (LDs) emitting a total continuous wave (CW) power of up to 60 W. To eliminate the unabsorbed pump power, a cladding power stripper (CPS) with an output-fiber end angle cleaved at $\sim$8° (to eliminate any back reflections), was applied. Besides, to characterize the laser output, dichroic mirrors were used at the output end to separate the generated 2-μm pulses and the residual 1.5-μm signal as well as unabsorbed 793-nm power. Owing to the quasi-three-level nature of thulium dopant, active fiber cooling is critical to achieve a high conversion efficiency. Therefore, both pieces of active fibers were placed on a water-cooled aluminum plate that was kept at $\sim$18 °C. Furthermore, all of the system components were fusion spliced, thus making it all-fiber. Finally, the emitted 2-μm pulse train was launched into a fluoride nonlinear fiber by a telescope, allowing for launch efficiencies of over 60%.

The time characteristics of the laser system output were detected by a 12.5-GHz InGaAs photodetector (Electro-Optics Technology, ET-5000) together with a 6-GHz bandwidth, 25-GSa/s oscilloscope (Tektronix, DSA 70604). The output spectrum fluence was monitored by a grating monochromator (SP-2300, Princeton Instruments) equipped with a thermo-electrically cooled mercury cadmium telluride detector (Vigo System S.A.) with a maximum spectral coverage of 1.8–5.6 μm. To avoid the effects of high-order diffraction peaks of the grating, appropriate long-pass filters were placed in front of the detection system. The average output power was measured with an energy meter (LaserStar, Ophir) and a thermal power sensor.

3. Results and Discussion

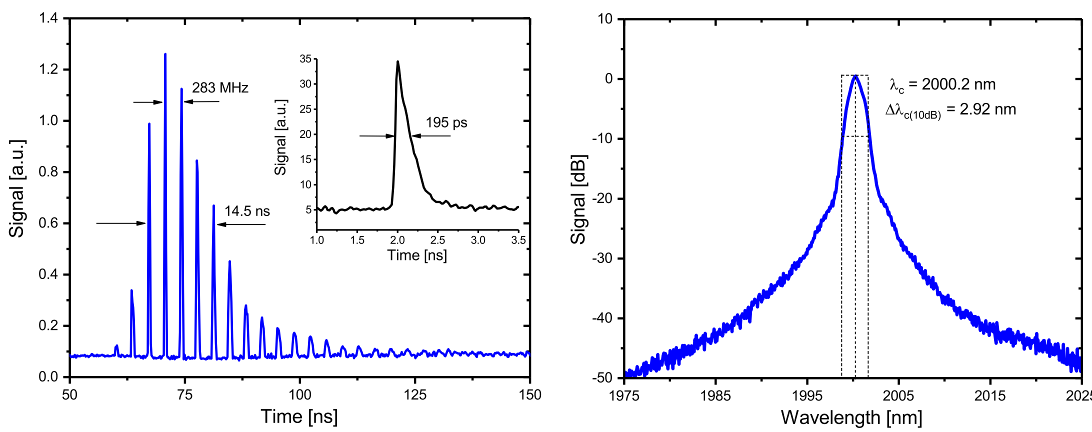
The performance of the GS-TDFL&A was investigated at a fixed pulse-repetition frequency of 25 kHz, and the output characteristics are depicted in Figs. 2 and 3.

We first investigated pulsing in a typical fast gain-switched mode, with the aim of achieving the shortest stable pulse. It can be done in a laser cavity with a short length and with a high-gain active medium. It is clear that the width of pulses emitted by gain-switched fiber lasers is a function of the pump-pulse energy, as the increase in pump energy reduces the pulse build-up time. Shortening the fiber length reduces the round-trip time and consequently the pulse duration; however, it also reduces the medium gain as a result of the lower pump absorption, which can limit the output pulse width. Therefore, the selection of a proper active medium is a key parameter. In our experiment, a core-pumped 12-cm-long TDF with a high Tm^{3+} ion concentration (cladding absorption of 19.5 dB/m at 790 nm) was used. OCs with reflectivity of $\sim$70%, 80%, and 90% were examined



(a) (b)

Fig. 2. (a) Measured pulses from the 1.55-μm pump source and the 2-μm GS-TDFL. Inset shows the pulse train of the GS-TDFL at the pulse repetition rate of 25 kHz. (b) Output spectrum. Inset shows the spectrum measured at a 600-nm span.



(a) (b)

Fig. 3. (a) Measured MLR sub-pulses emitted from the GS-TDFL. Inset, oscilloscope trace of the most intense MLR sub-pulse. (b) Output spectrum.

over the course of the experiment, and finally, the FBG with R $=$ 89%, which provides the highest optical feedback, was selected. The GS-TDFL was pumped by $\sim$150-ns 1.55-μm pulses with an average power of up to 1.3 W, of which over 90% was absorbed by the active dopant. The onset of lasing was reached for a low value of pump-pulse energy, $<$1 μJ, which was the result of very high optical feedback. After reaching the threshold, a 2-μm pulse of long duration (delayed to the pump pulse) appeared, and with an increase in pump power, the pulse width shortened rapidly. For the pump-pulse energy of $\sim$45 μJ, the TDFL operated in a stable single-pulse regime, and delivered a train of $\sim$17-ns pulses with an average output power of up 400 mW, corresponding to a peak power of 885 W, as shown in Fig. 2(a). The plot also presents the pump-pulse profile measured after the 1.55-μm seed DFB laser, second EDFA, and final EYDFA. Note that the 150-ns pump-pulse shape is deformed owing to the saturation effect, which occurs during amplification in a long-gain fiber [23]. The laser operated at a central wavelength of 2000.1 nm with a 10-dB linewidth of 1.97 nm [see Fig. 2(b)]. The inset in Fig. 2(b) shows a spectrum measured for a 600-nm span with visible peaks at 1.55 μm and 2 μm, corresponding to unabsorbed pump power and Tm laser emission, respectively. The spectrum was clean, without any signals coming from

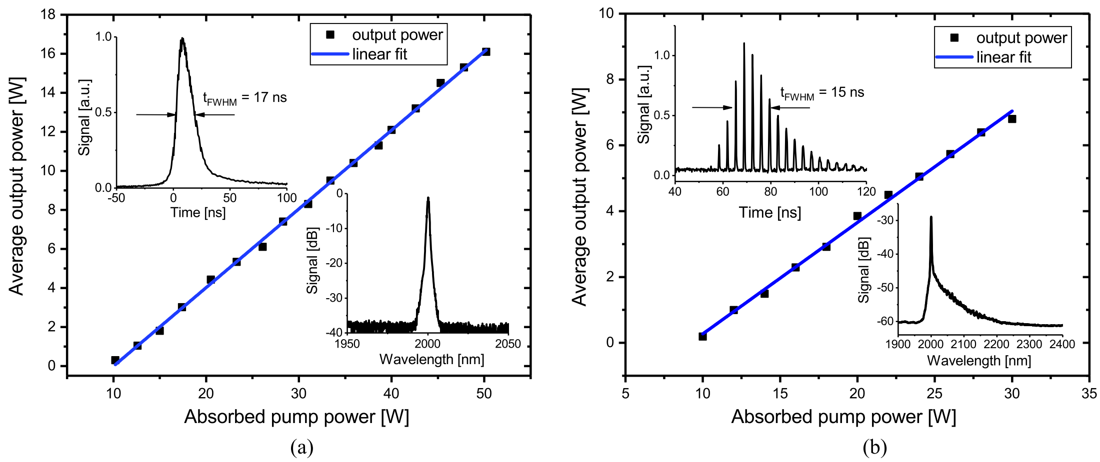


Fig. 4. Average output power of the TDFA versus absorbed pump power for amplification of single gain-switched pulses (a) and gain-switched MLR pulses (b). Upper insets present the time width of amplified pulses, whereas lower insets depict output spectra measured for the maximum output powers.

amplified spontaneous emission (ASE) or nonlinear effects. Furthermore, the dynamic range was over 50 dB, which represents a very good signal-to-noise ratio.

At high pump powers, mode-locked resembling operation with a 100% modulated gain-switched envelope was observed, as was already reported [17]. When the average pump power was set to ~1.6 W and the pump-pulse width reduced to ~50 ns, a train of gain-switched pulses revealing simultaneous mode-locked-like operation with an average power of ~300 mW was achieved. Fig. 3(a) presents a typical output pulse at 25-kHz repetition rate. As can be seen, there are about 15 MLR sub-pulses within one gain-switched pulse envelope. The duration (FWHM) of the sub-pulse envelope is about 15 ns, whereas the width of sub-pulses with the highest intensity was of the order of a few hundred nanoseconds. The shortest MLR pulse width was measured to be 195 ps. The sub-pulse interval was 3.5 ns (frequency of 283 MHz), exactly matching the round-trip time of the 36.5 cm laser cavity. It was difficult to measure the exact pulse width of the shortest MLR sub-pulses as it was limited by the bandwidth of our detection system (6-GHz bandwidth of the oscilloscope). The origin of the MLR operation can be identified as the beating of laser longitudinal modes [17], [24]. The laser operated at the same central wavelength (measured as 2000.2 nm), but compared with the typical gain-switched operation, the spectrum, which measured 10 dB below the peak, was broadened to 2.92 nm [see Fig. 3(b)]. This can be attributed to self-phase modulation (SPM) that occurs when high-peak-power pulses propagate in a small-area core of the gain fiber and passive pigtail of the OC FBG. The duration of the mode-locked type pulses recorded within the gain-switched pulse envelope depends on the number of coupling longitudinal modes circulating in the laser cavity and at this stage of the study it was difficult to determine conditions facilitating this process. It should be also noted that increasing the pump power over 1.7 W resulted in the decrease of stability of the output 2-μm pulse train. Therefore, output average power scaling up was not performed. These issues need to be analyzed more deeply and it will be the subject of our further research.

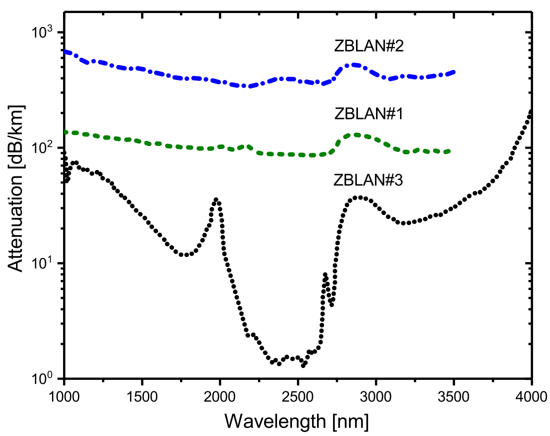
To achieve kilowatt peak powers, the pulse train generated by the TDFL was boosted in a fiber amplifier. The results of the amplification are shown in Fig. 4.

The amplifier was built using a large mode area TDF in order to eliminate nonlinear effects, which are exhibited especially when amplifying short MLR sub-pulses. As can be seen in Fig. 4(a), after reaching the threshold, the average output power increases linearly proportional to the increase in the pump power absorbed by the TDFA. For a pump power of 50.2 W, we achieved a train of single gain-switched pulses with a maximum average power of 16.1 W and a slope efficiency of 40.3%, which corresponds to a pulse energy and peak power of 0.64 mJ and 35.6 kW, respectively. The output pulse width was the same as that before amplification, and was measured to be

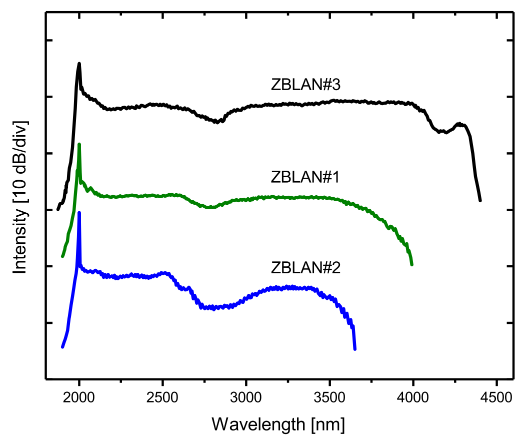
TABLE 1
Main Parameters of the ZBLAN Fibers Used in the Experiment

	Core/clad diameter [μm]	NA	ZDW [μm]	Length [m]
ZBLAN#1	8/125	0.30	1.54	8
ZBLAN#2	7/125	0.30	1.55	8
ZBLAN#3	6.8/125	0.23	1.60	12

NA - numerical aperture, ZDW - zero dispersion wavelength.



(a)



(b)

Fig. 5. (a) Attenuation of the fluoride fibers. (b) Mid-infrared SC output spectra measured out of the three ZBLAN fibers used in the experiment.

17 ns (Fig. 4(a), upper inset). The output spectrum did not reveal any artifacts coming from ASE or nonlinear effects (Fig. 4(a), lower inset).

Fig. 4(b) presents the average output power for gain-switched and mode-locked type operation plotted as a function of the absorbed pump power. The amplified gain-switch pulse envelope contained a train of 15 sub-pulses precisely spaced at the TDFL cavity round-trip time, and its FWHM was ~15 ns. For the absorbed pump power of 30 W, the maximum output power was 6.8 W with a slope efficiency of 33.8%. The duration of the fully modulated, most intense MLR pulse was measured to be ~300 ps. The maximum energy of the gain-switched pulse (calculated by dividing the average output power by the repetition rate) was 272 μJ. The energy of the highest peak in the train was 36.9 μJ, corresponding to a peak power of 115.6 kW (estimated by assuming a Gaussian shape of the subpulse). To the best of our knowledge, these are the highest peak power and average power levels reported in a GS-TDFL&A system with a self-starting mode-locked-type operation. The central wavelength was 2000.2 nm with an FWHM width of 2 nm. Note that the spectrum was significantly broadened towards the red wavelengths, up to 2.2 μm, which can be attributed to nonlinear effects, mainly Raman-induced scattering [25]. This spectral broadening was also the reason for not further scaling up the output average power.

In a second experiment, the GS-TDFL&A system with mode-locked-type operation was used as the pump source for mid-infrared SC generation in fluoride fibers. Three ZBLAN fibers having different parameters [presented in Table 1 and Fig. 5(a)] were used as nonlinear media. The attenuation curves of the fluoride fibers were provided by the manufacturer (Le Verre Fluore).

All ends of the ZBLAN fibers were angle cleaved to avoid light back reflection. To improve the coupling stability and heat dissipation capacity, the fiber ends were put onto an aluminum block with v-grooves. Furthermore, the fiber claddings were covered with a high-refractive index optical glue to remove the residual cladding modes. The results of the SC generation are summarized in Fig. 5(b).

The spectra of the generated SC were recorded after passing through a long-pass filter with a cut-off edge at 1.85 μm, and they were corrected for the detector and grating responsivities. The spectral range was considered according to the noise level of the detection system. The broadest spectrum, spreading to 4.4 μm, was measured when the ZBLAN#3 fiber was pumped with an incident power of 6.4 W at a 2-μm wavelength. The output SC average power was as high as 2.45 W, and the 5-dB spectrum flatness was maintained from 2.05 μm to 4.09 μm. Pumping the ZBLAN#1 and ZBLAN#2 fibers with the same power yielded spectra with a cut-off at 3.95 μm and 3.65 μm as well as a corresponding power of 2.05 W and 1.8 W, respectively. The infrared edges of the spectra were determined by the loss edge of fluoride glass. In the case of ZBLAN#1 and ZBLAN#2 fibers, the less efficient spectrum extension towards the red wavelengths can be attributed to higher attenuation losses, as shown in Fig. 5(a). The observation of the SC evolution at shorter wavelengths ($<$1.9 μm) was not carried out, mainly because of limitations with our detection system. When performing the research on SC generation, we did not optimize the length of the fluoride fibers as it was not within the scope of this study. In this research, we mainly focused on showing the usefulness of the developed GS-TDFL&A system providing self-starting MLR pulses for high-power mid-infrared SC generation.

4. Conclusion

In this paper, we presented an all-fiber 2-μm fast gain-switched thulium doped fiber laser and amplifier system, in-band pumped at 1.55 μm. The proposed system delivered stable 17-ns pulses with an energy of 0.64 mJ and a corresponding peak power of 35.6 kW when operating at a pump power of 50.2 W. The maximum output average power, which was measured at a repetition rate of 25 kHz, was 16.1 W. Self-started mode-locked-type sub-pulses, recorded within a 15-ns gain-switched pulse envelope, was achieved in the same laser cavity. To the best of our knowledge, this is the shortest gain-switched and mode-locked-like pulse. After amplification, the mode-locked resembling sub-pulses with the highest intensity were characterized by a duration of $\sim$300 ps, energy of 36.9 μJ, and a corresponding peak power of 115.6 kW, which is believed to be the highest reported peak power for the applied gain-switched laser system configuration. Using this laser source as a pump for a step-index fluoride fiber, we also demonstrated a broadband, mid-infrared supercontinuum generation with an average power of 2.45 W, a cut-off wavelength at 4.4 μm, and a spectral flatness of 5 dB over a bandwidth of 2040 nm. This represents the highest supercontinuum average power generated out of fluoride fibers pumped by a Tm-doped gain-switched laser and amplifier system revealing simultaneous mode-locked-like operation. The scalability of the pump makes this scheme promising for future high-average-power supercontinuum sources with reduced complexity.

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