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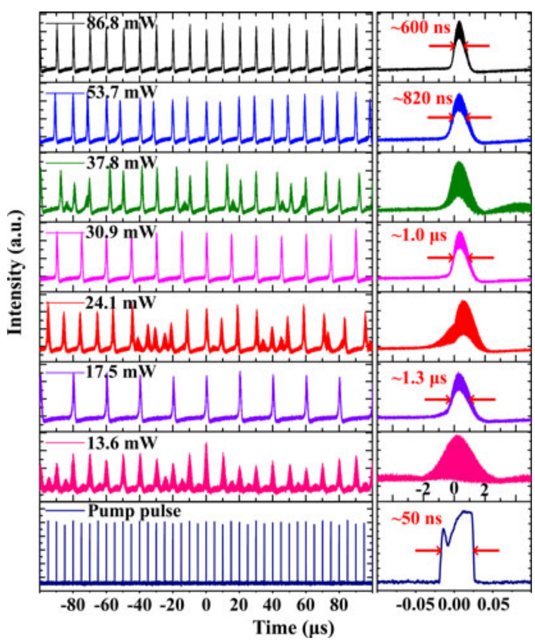

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Repetition-Rate-Switchable and Self-Mode-Locked Pulses Generation From a Gain-Switched Thulium-Doped Fiber Laser and Their Amplification Properties

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Abstract: We report on repetition-rate-switchable and self-mode-locked pulses generation from a gain-switched thulium-doped fiber laser. Stable pulse trains were gain-switched by a home-made, pulsed Erbium/Ytterbium codoped fiber amplifier. The pulse repetition rate (PRR) of stable output pulse trains can be switched as 1/4, 1/3, and 1/2 times of that of the pump pulse train. Besides, the gain-switched mode-locked pulses were also achieved in the same cavity. By following three-stage thulium-doped fiber amplifiers, the average output power of the stable gain-switched pulses was scaled to 115 W with the PRR of 100 kHz, corresponding to a pulse energy of about 1.15 mJ. The amplification properties of the gain-switched mode-locked pulses were also characterized and discussed.

Index Terms: Thulium-doped fiber lasers, gain-switching, pulsed lasers, laser amplifiers, fiber optics.

1. Introduction

Due to the wide emission bandwidth, which is located in eye-safe wavelength band and atmospheric window, thulium-doped fiber lasers (TDFLs) have attracted much attention in the applications of mid-infrared frequency conversion, biomedicine, polymer material processing, and so on [1]–[9]. The output power of TDFL has reached a high level both with the continuous and pulse operations. Stutzki *et al.* in Jena University demonstrated a high power thulium-doped chirped-pulse amplification (CPA) system with average output power of 152 W and pulse peak power of 4 MW [10]. Liu *et al*. achieved an average power of 120.4 W, 16 picoseconds pulsed TDFL with the pulse repetition rate (PRR) of 333.75 MHz [11]. But the single pulse energy was low due to the high PRR. To increase the single pulse energy, the PRR should be decreased. Our group reported a 110 W, all-fiber, thulium-doped master oscillator power amplifier (MOPA) system [12]. The master oscillator was actively Q-switched by a fiber-coupled acousto-optic modulator (AOM). However the insert loss of fiber coupled AOM is very high (about 6 dB) and the cost is very high. By contrast, gain-switching is an efficient way to realize low PRR, nanosecond pulses. The gain-switched fiber laser has advantages in flexible PRR, simple geometry, narrow line width, especially the high pulse energy [13]–[15]. Therefore, lots of attention has been paid to the GS-TDFLs in recent years.

Since the first report of GS-TDFL in 1998 [16], lots of investigations have been done experimentally and theoretically. The thulium ion generally has three absorption bands located in $\sim 650-850$ nm (793 nm), $\sim 1000-1300$ nm (1200 nm) and $\sim 1450-1950$ nm (1650 nm) corresponding to the pumping schemes of $^3H_6 \rightarrow {}^3H_4$, $^3H_6 \rightarrow {}^3H_5$ and $^3H_6 \rightarrow {}^3F_4$, respectively. The 1.064 μm pulsed Nd: YAG laser was used as pump source to realize 2 μm GS-TDFL firstly. However, the output pulses contain a series of unstable relaxation spikes because of the excited state absorption (ESA). The existing of ESA would affect the pump efficiency and decrease the accumulation rate of upper level population. Compared with 1.0 μm, semiconductor laser diode (LD) with the wavelength of 793 nm is a superior pump source for high power TDFL due to the high quantum efficiency. However, the relaxation spikes also would appear which attribute to the longer relaxation of $^3H_4 \rightarrow {}^3F_4$ ($\sim 14.2\,\mu$s) as well as cross-relaxation effect (CRE) [13]. By using the 1.6 μm resonant pump scheme, however, the fast gain-switching can be achieved due to the absence of ESA and CRE. Therefore, the population of emission energy level is built up nearly instantaneously following the pump pulse.

In 2007, stable gain-switched pulse was achieved firstly from a TDFL [17]. A modulated 1.55 μm pump laser was used for fast gain-switching to avoid the conventional relaxation spikes pumped by 1.06 or 0.79 μm lasers. Then, Nufern reported a monolithic GS-TDFL with output power, pulse width and PRR of 220 mW, 1.5 ns and 20 kHz, respectively [18]. The pump source was an EYDFA which was seeded by a 1.5 μm modulated semiconductor LD. The narrower pulse width was contributed to short thulium-doped fiber used in the cavity. But the average powers were limited by the available pump powers in the early reports. In 2011, Nikita Simakov reported an efficient, polarized GS-TDFL. The pulse width and PRR were 35 ns and 300 kHz, respectively. The output power was scaled to 8 W at 2.044 μm by a 16 W EYDFA [19]. Furthermore, to produce higher average output powers, a hybrid-pumped structure was reported which was complementarily pumped by a 46 W, 790 nm LD and a 20 W, 1.0 μm pulsed Yb-doped fiber laser [20]. The stable gain-switched pulse was achieved with the average output power of 10 W. However, the pulse width would be elongated by the higher pump power of 790 nm LD. Actually, the high power 790 nm LDs can be used as pump sources to boosting the average output power of the gain-switched seed pulses with MOPA system. In 2013, J. Swiderski reported a GS-TDFL and an amplifier system with an output average power of 9 W with the PRR of 50 kHz [21].

Besides the stable gain-switched pulses operating at 2 μm, self mode-locked pulses were also observed in the GS-TDFL [22], [23]. And, the self mode-locked pulses were amplified to pump fluoride fiber to generate mid-infrared supercontinuum [24]. However, the amplification properties of the self mode-locked operation have not been demonstrated yet. In this paper, we present a hundred-watt level, high pulse energy, all fiber thulium-doped MOPA system operating at 1950 nm. The master oscillator was gain-switched by a home-made, pulse width and repetition rate tunable EYDFA. Stable output pulse train with PRR of quartered (1/4 PRR of pumping pulse), trisected (1/3 PRR), halved (1/2 PRR) with respect to the pump pulse were observed in the experiment. Meanwhile, self mode-locked pulses were also achieved. And, by three-stage thulium-doped fiber amplifiers (TDFAs), the average output power was scaled to 115 W with the PRR of 100 kHz, which corresponding to a pulse energy of 1.15 mJ. Besides, the amplification properties of the gain-switched mode-locked pulse were also characterized and discussed.

2. Gain-Switched Thulium-Doped Fiber Laser

2.1 Experimental Setup of the Gain-Switched Laser and Three-Stage TDFAs

The experimental setup of the GS-TDFL is illustrated in Fig. 1. The cavity is a linear cavity composed by a fiber coupled high reflection mirror (HR) and a fiber Bragg grating (FBG). The FBG acts as

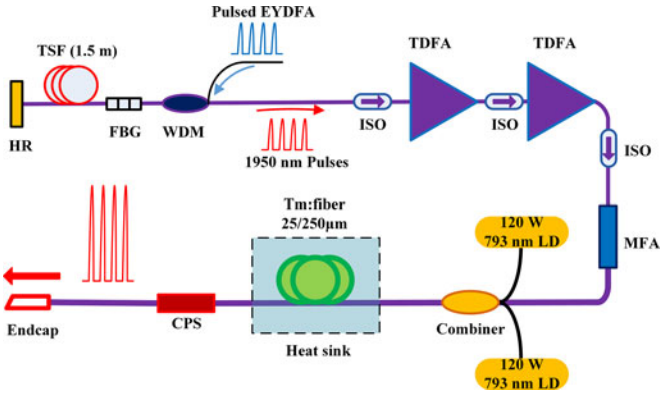


Fig. 1. The schematic diagram of GS-TDFL and three-stage TDFAs.

wavelength selecting component and coupling output port with output ratio of 22%. The 3-dB bandwidth is 0.7 nm at the wavelength of 1950.2 nm. The gain medium is 1.5 meters long single mode thulium-doped fiber (TSF, the core and cladding diameters are 9 μm and 125 μm, respectively) with core absorption about 13 dB @1550 nm. The total cavity length is about 2.5 m.

The pump source is an EYDFA seeded by a 1552 nm electric modulated DFB laser, which was coupled into TSF by a 1550/1950 nm wavelength division multiplexing (WDM). The PRR of EYDFA can be tuned from 10 kHz to 500 kHz, and the pulse width can be tuned from 10 ns to 200 ns. The average output power was confined to $\sim$ 1.2 W to ensure the long-time stability because the EYDFA could be easily damaged by the Yb band parasitic lasing at the higher power [25]. Meanwhile, the spectrum of EYDFA broadened due to the nonlinear effects with a high pulse peak power. The output spectra of GS-TDFL were measured by an infrared spectrometer (Ocean Optics NIRQuest512-2.5) with a resolution about 3.5 nm. The pulses were monitored by a 1 GHz oscilloscope and a 12.5 GHz InGaAs photodetector (EOT, ET-5000). The three-stage TDFAs were the same as illustrated in reference 12. The pump sources of the first and second stage TDFAs are both 793 nm fiber pigtailed multimode diode lasers. The mode field adapter (MFA) between the second and third stage was used to bridge the small core pigtailed fiber of isolator and large core signal fiber of the high power $(2 + 1) \times 1$ pump combiner. An 8° angle polished end-cap was used as the output end to avoid unwanted damage caused by the 4% Fresnel reflection. The total third stage was fixed on a water cooled heat sink to prevent the heat-induced damage.

2.2 Properties of Gain-Switched Seed Laser

Increasing the output power of EYDFA, the 1950 nm signal pulses underwent unstable and stable operation states under different pumping conditions (the pulse width, PRR and pulse energy of EYDFA). And, the PRR of stable gain-switched pulses can be quartered (1/4 of pumping PRR), trisected (1/3 of pumping PRR), halved (1/2 of pumping PRR) and the same with respect to PRR of the pump source. Furthermore, the stable output pulse would develop into sub-pulse envelopes at higher pump energy, which was named as self mode-locked pulse due to self phase modulation (SPM) [26]–[28].

At the pump pulse width and PRR of 50 ns and 30 kHz, the gain-switched pulse train and single pulse profile evolving with the pump power is shown in Fig. 2. At lower pump power, the gain-switched pulses were unstable. Then, it turned into stable operation with the increased pump power, but the PRR was just 15 kHz shown by the red line. Further increasing the pump power, the gain-switched PRR became the same with pump pulse. But, the stable gain-switched pulse starts to form multiple spikes in amplitude with the output power of 12.9 mW. Eventually, the modulation depth was increasing up to 100%. And, the sub pulse interval was 23.6 ns (PRR of 42.4 MHz), corresponding to the laser cavity round-trip time. So, this pulse is always called as self mode-locked pulse. At the maximum output power of 76.4 mW, the full width at half maximum (FWHM) of the sub

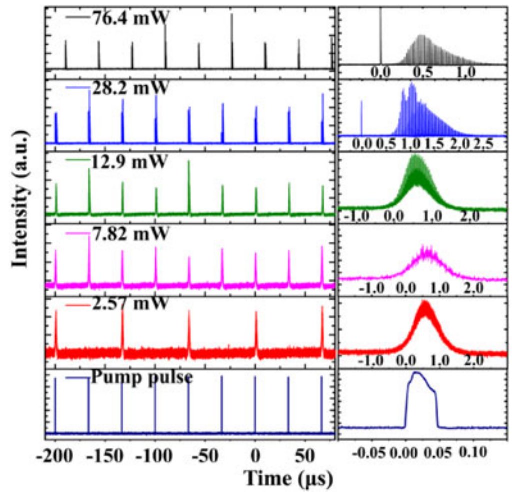


Fig. 2. The gain-switched pulse trains and single pulse profiles with different output power, the pulse width and PRR of EYDFA are 50 ns and 30 kHz, respectively.

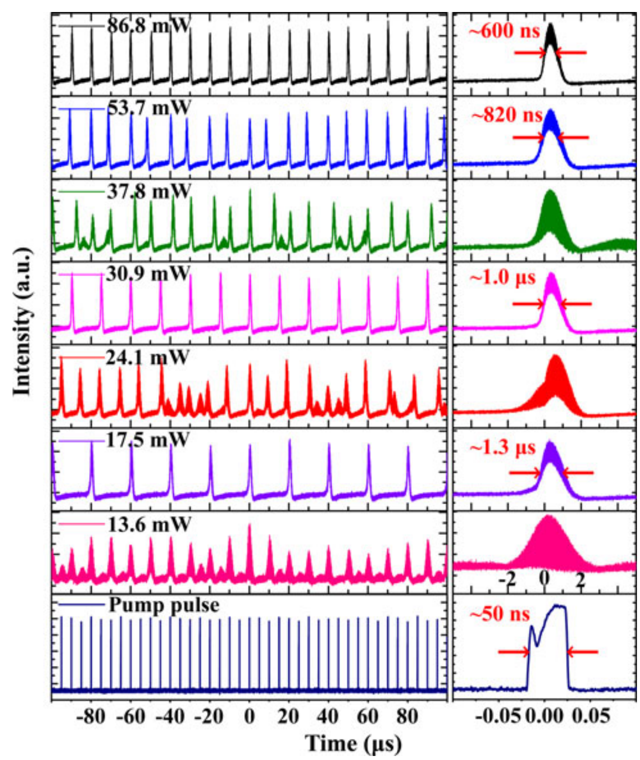


Fig. 3. The gain-switched pulse evolution at the pump pulse width of 50 ns and PRR of 200 kHz.

pulse envelope is about 800 ns. More interestingly, a single pulse with pulse width about 2 ns and PRR of 30 kHz is appeared after 100% modulation of the self mode-locked envelope. Furthermore, the intensity grows quickly and surpasses the self mode-locked envelope. This would be resulted from the amplification of the signal pulses in the pump source [30], [31]. The spectrum of EYDFA broadened beyond 2000 nm due to the nonlinear effects.

For higher PRR of pump EYDFA, the self mode-locked pulses disappeared because of the lower pump pulse energy. And, the gain-switched pulses became more stable. Fig. 3 illustrates the evolution of gain-switched pulses at the pump pulse width of 50 ns and PRR of 200 kHz. It is clearly shown that the gain-switched pulses undergo several unstable-stable statuses with the increasing pump power of EYDFA. With lower pump power, the gain-switched pulse was very unstable. When the output power was 17.5 mW, the gain-switched pulses became stable and the PRR is quartered (1/4 $\times$ 200 kHz) with respect to the pump PRR. Increasing the pump power further, the pulse train evolved unstable again, shown in Fig. 3 at the output power of 24.1 mW. However, the stable pulse reappeared when the output power increased to 30.9 mW. Meanwhile, the PRR became 1/3 $\times$ 200 kHz. Following that, the pulses became unstable once again (such as the output power of 37.8 mW). At last, the pulse became stable gradually. At the maximum pump power, the gain-switched output power was 86.8 mW, with the pulse width of $\sim$ 600 ns and PRR of 1/2 $\times$ 200 kHz.

From above, the output pulse width decreases with the increase of pump power (i.e., output power). Meanwhile, the PRR of stable gain-switched pulses were changed from 1/4 to 1/3 and 1/2 times of the pump PRR. The output PRR of 200 kHz was not realized at this pump condition (50 ns and 200 kHz of EYDFA) due to the lower pump energy. Incorporated with Fig. 2, it can be seen that the output pulse properties are influenced by the pump single pulse energy which would influence the inverse population in the upper energy. When reaching the laser threshold, the unstable and stable pulses appeared one after another. For the particular pump pulse width and PRR (50 ns, 200 kHz), at the lower pump energy, one pump pulse was absorbed by the thulium-doped fiber, and the upper excited level ($^3F_4$) population (N_2) accumulated, but did not reach the threshold. And, the N_2 was consumed by the nonradioactive process until the next pump pulse coming due to the long lifetime of $^3F_4$, which is about 14.2 μs. Then, one gain-switched pulse would be generated in case of the accumulation of N_2 reached the threshold. However, the output pulse was not stable. Increasing the pump energy, relatively stable pulse train was obtained in the experiment. And, the PRR of the output was just a quarter of pump PRR. It can be interpreted as four pump pulses were needed to generate one 2 μm gain-switched pulse. When the pump power increased, three or two pump pulses were needed to generated one stable gain-switched pulse, corresponding to the PRR of 200/3 kHz and 200/2 kHz, respectively. This phenomenon was numerically simulated in reference 29. In addition, our experiment has confirmed that the PRR/4 can also be generated with a relative shorter cavity length.

Even the stable operation pulse width decreases with the increasing pump power, the shortest pulse width obtained in our experiment is about 600 ns, which is larger due to the limited pump power and the cavity length. The gain-switched pulse width would be suppressed further if increasing the pump power and shorting the cavity length. And this would contribute to the output peak power after the power amplifiers. Fortunately, the stable output gain-switched pulses can operate steadily, which would be appropriate for power scaling to get large average power.

The normalized spectrum of the GS-TDFL at different pump conditions are illustrated in Fig. 4. The spectrum baseline was not started from zero point caused by the background noise of the spectrometer. The central wavelength is about 1950 nm and the spectra show no obvious difference in the whole output states. The bandwidth cannot be concreted due to the poor resolution of the grating spectrometer. However, the spectrum bandwidth of gain-switched fiber laser is mainly determined by the FBG (0.7 nm in the experiment).

3. Thulium-Doped Fiber Amplifier

3.1 Amplified Properties of Stable Gain-Switched Pulses

The stable gain-switched pulse was amplified firstly. The pulses with width of 600 ns, PRR of 100 kHz and output power of 87 mW were selected to feed the three-stage TDFAs shown in Fig. 1. The first stage output power is 3.13 W at 16.8 W pump power, and the second stage output power is 8.8 W at 33.5 W pump power. And, the slope efficiencies of the first and second stage are 23.9% and 22.8% respectively. The latter stage is slightly lower caused by the splicing joint between the passive fiber and thulium-doped fiber and different insertion losses of the isolators.

Fig. 5(a) shows the output power of main amplifier versus the pump power. The maximum output power is 115 W at 200 W pump power. The output power increased almost linearly with

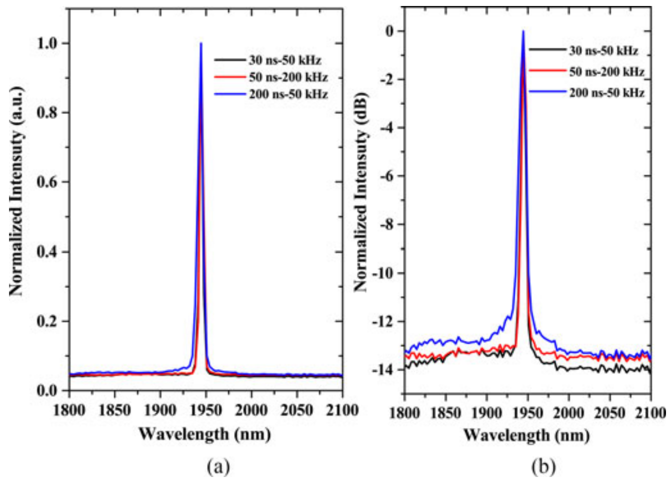


Fig. 4. The output spectra of gain-switched seed laser at different pump conditions (a) linear scale, (b) logarithmic scale.

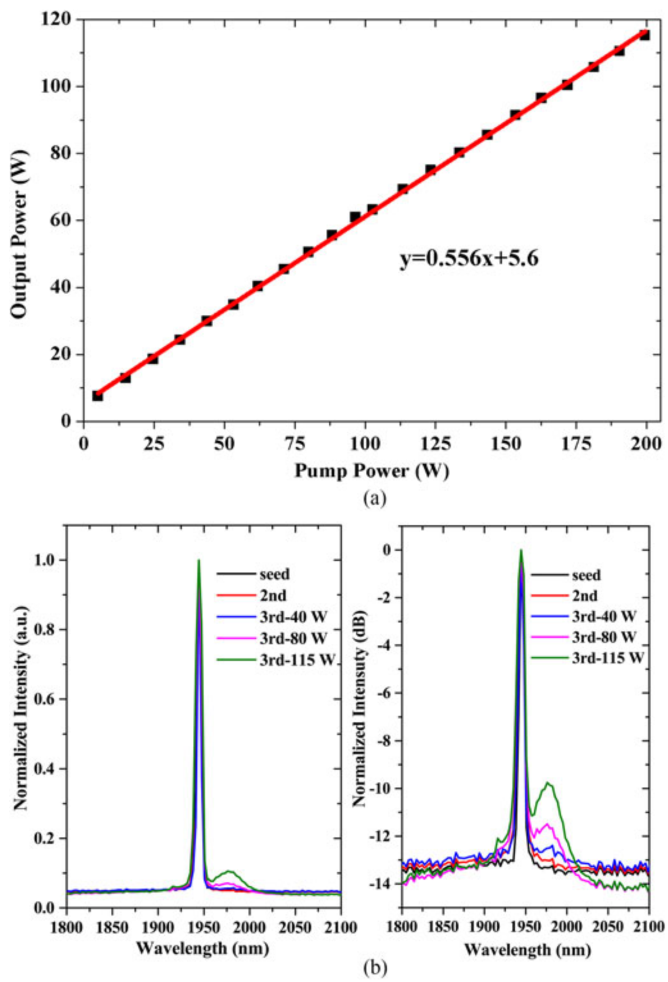


Fig. 5. (a) The output power of main amplifier versus the pump power. (b) The spectrum evolution at different output powers.

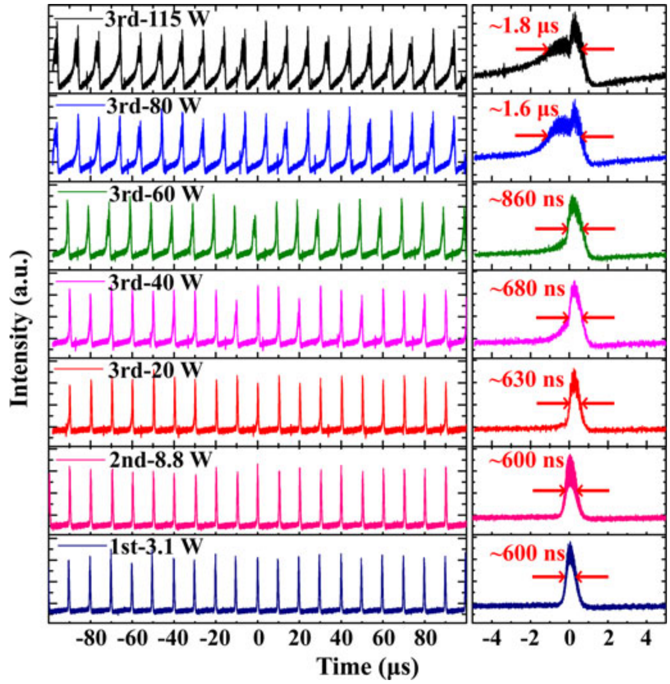


Fig. 6. The temporal properties of the amplified stable gain-switched pulses.

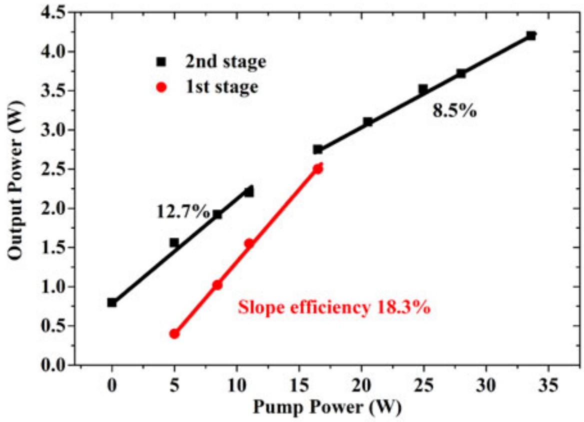
the increase of pump power; correspondingly, the slope efficiency was $\sim$ 55.6%. And no power saturation phenomenon was observed. So the maximum output power can be further scaled by increasing the pump power of LDs. Fig. 5(b) is the optical spectrum of the main amplifier at different output powers. The spectrum shows no obvious nonlinear effects except for the appearance of small amount ASE at the longer wavelength. This also demonstrates that this amplifier has potential ability to scale the average output power to a higher level.

The amplified pulse train and single pulse profile at different output power are illustrated in Fig. 6. It can be seen that the pulse width unchanged after the first and second amplifier. And, the pulse width showed slightly broadening with the output power increasing from 20 W to 60 W after the third power amplifier. The pulse leading edge grew faster than the trailing edge at higher output power, i.e., $>$80 W. Moreover, the corresponding pulse envelope distorted severely. At the maximum output power, the pulse width was about 1.8 μs. Compared with the Q-switched pulse generated by acousto-optic modulator (AOM), the gain-switched pulses do not undergo the amplified spontaneous emission (ASE) process due to the pulse pump scheme [32]. But, the ASE could also appear in the fiber amplifier because of that the amplifier is not operating with great temporal quality at higher output power level [12], [33]. The pulse distortion here was caused by the inter-pulse ASE at such a low PRR. Generally, the ASE can be suppressed mainly by two techniques: one is to increase the PRR, the other one is to adopt pulsed pump.

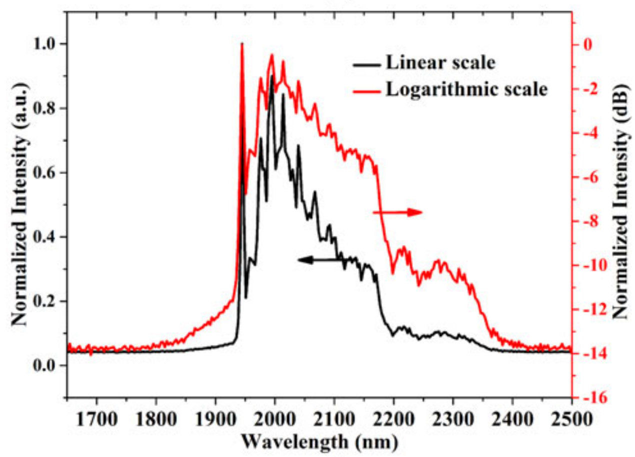
3.2 Amplified Properties of Self Mode-Locked Pulses

The self mode-locked pulse has been amplified to pump fluoride fibers to generate mid-infrared supercontinuum [24]. However, the amplified pulse and spectrum properties were not given in the reference. Here, we give a specific investigation on the amplification of self mode-locked pulses generated in the GS-TDFL. The pump pulse with width and PRR of 30 ns and 50 kHz was used to pump the TDFL. The self mode-locked pulse was generated with an envelope FWHM of 300 ns. Then the self mode-locked pulse was fed to the TDFAs shown in Fig. 7.

Fig. 7(a) shows the power characteristic of the amplified self mode-locked pulse. After the first stage amplifier, the output power was scaled to 2.5 W. However, the slope efficiency of the second



(a)



(b)

Fig. 7. (a) The amplified power of the self mode-locked pulse versus the pump power. (b) The second stage output spectrum at 4.2 W output power.

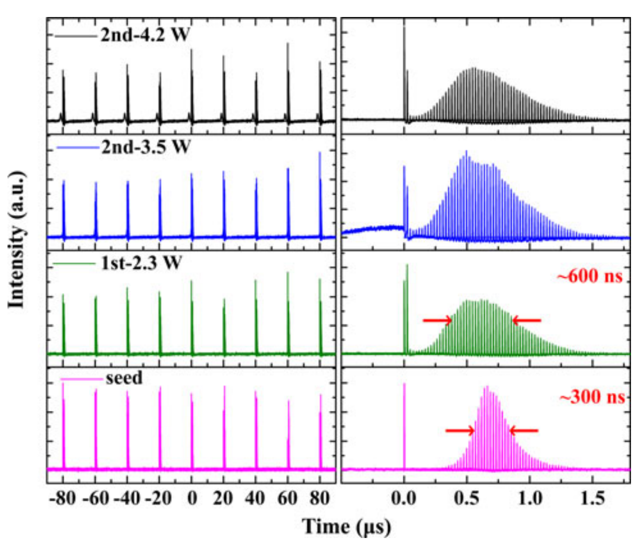


Fig. 8. The evolution of amplified self mode-locked pulse at different amplified power.

amplifier stage decreased sharply from 12.7% to 8.5%. And, the maximum output power was only 4.2 W at the pump power of 33.5 W. By monitoring the output spectrum after the second stage amplifier, it can be seen that the spectrum has been widely broadened caused by the nonlinear effects. It is mainly Raman effect here (shown in Fig. 7(b)). The long wavelength edge was extended to $\sim$ 2400 nm. To increase the pump power further, the nonlinear effects would be enhanced and the spectrum would be red shifted. Meanwhile, the higher loss of silica fiber at this wavelength region would cause the slope efficiency to a very low level. So, we think that the self mode-locked pulses are unsuitable for high power amplification due to the intense nonlinearity appeared in the amplifier. Still, it has the potential to pump mid-infrared fibers to generated supercontinuum as reported in reference 24. But the output power would be limited to a low level.

The evolution of amplified self mode-locked pulse is also given in Fig. 8. The FWHM of pulse envelope increased to 600 ns after the first stage amplifier. And the number of sub-pulses increased. Front pulse also split into two pulses. After the second stage amplifier, the pulse became unstable. Thus both the temporal and spectrum characteristics indicate that the self mode-locked pulses are unsuitable for high power amplification.

4. Conclusion

In summary, the GS-TDFL was achieved by using a pulsed EYDFA in this paper. Stable output pulse trains with PRR of 1/4, 1/3, 1/2 times of that of the pumping pulses were achieved in the experiment. The self mode-locked pulses were also observed at high pump energy. Then the stable gain-switched pulse ($\sim$ 600 ns and 100 kHz) was amplified by three-stage TDFAs, of which the output power was scaled to 115 W. We also confirmed that the self mode-locked pulses were not suitable to power amplification due to the nonlinear effects in the amplifiers. The tens of Watts, kHz PRR TDFL would have some advantages in clear plastics processing. The gain-switched pulses with narrower pulse width, higher average power and higher peak power might be done in our future work as well as their interactions with clear plastics.

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