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Microsecond gain-switched master oscillator power amplifier (1958 nm) with high pulse energy

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Abstract. **An all-fibre master oscillator power amplifier (MOPA) emitting high-energy pulses at 1958 nm is presented. The seed laser is a microsecond gain-switched thulium-doped fibre laser (TDFL) pumped with a commercial 1550-nm pulsed fibre laser. The TDFL operates at a repetition rate f in the range of 10 to 100 kHz. The two-stage thulium-doped fibre amplifier is built to scale the energy of the pulses generated by the seed laser. The maximum output pulse energy higher than 0.5 mJ at 10 kHz is achieved which is comparable with the theoretical maximum extractable pulse energy. The slope efficiency of the second stage amplifier with respect to the pump power is 30.4 % at f = 10 kHz. The wavelength of the output pulse laser is centred near 1958 nm at a spectral width of 0.25 nm after amplification. Neither nonlinear effects nor significant amplified spontaneous emission (ASE) is observed in the amplification experiments.**

Keywords: *all-fibre master oscillator power amplifier, thulium-doped fibre laser, high pulse energy, gain-switching.*

1. Introduction

In recent years, thulium-doped fibre lasers emitting in the so-called ‘eye-safe’ regime have attracted significant attention [1 – 3]. Thulium-doped fibres (TDFs) have a wide gain spectrum from 1.8 to 2.1 μm and have been demonstrated to be an efficient gain medium for high power and high energy laser sources near 2 μm [4 – 6]. The output power of the cw thulium-doped fibre laser (TDFL) has exceeded the 1-kW level [7]. High pulse energy lasers operating in the pulsed regime are often more attractive than cw lasers in many scientific and technical applications, such as material processing [8], biomedical treatment [9], spectroscopy [10] and nonlinear wavelength conversion [11]. However, amplified spontaneous emission (ASE) and nonlinear phenomena such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) and self-phase modulation (SPM) proved to be the main limitations on the pulse energy scaling in rare earth doped fibre lasers [12]. As a rule of thumb, gain fibres with a large mode area and a low numerical aperture (NA) are beneficial for fibre-based pulse energy extraction. If the pump power is constant, the pulses with a lower repetition rate will correspond to a higher pulse energy output; however, for laser operation at a repetition rate $f < 10$ kHz, significant ASE noise will be generated between pulses which will sorrowfully limit the scaling of the pulse energy. Pulses with duration of several microseconds are more suitable for pulse energy scaling than nanosecond pulses. Nowadays, high pulse energy fibre lasers with microsecond pulse durations have been commercialised only in the 1-μm wavelength region. Due to the lack of available components, high pulse energy fibre lasers at 2 μm have not been explored sufficiently so far and are still of great interest.

The reported highest pulse energy obtained directly from a high power Q-switched thulium-doped fibre laser was higher than 2.4 mJ at f = 13.9 kHz [13], where a piece of rod-type large-pitch fibre with core diameter of 81 μm was used as the gain medium. However, in order to further scale the pulse energy the development of a master oscillator power amplifier (MOPA) is often needed. Experiments on amplification of 2-μm pulses with an output pulse energy up to 6.4 mJ in a rod-type thulium-doped photonic crystal fibre with 80-μm core diameter at f = 1 kHz was reported [14]. So far the record for the highest pulse energy near 2 μm is still kept by a gain-switched MOPA setup [15], where a gain-switched seed pulse two-stage amplifier was built with step-index gain-fibres, and the corresponding maximum output pulse energy was higher than 10 mJ. Note that all the experimental setups [13 – 15] contain bulk elements and, therefore, have a limited stability and are sensitive to the environment, which eventually limits their applicability. Therefore, the use of all-fibre components is more attractive owing to their compactness, ease of use and long term stability.

In this paper, we report an all-fibre high pulse energy gain-switched MOPA operating at 1958 nm. Seed pulses with a pulse repetition rate f in the range of 10 – 100 kHz are obtained from a gain-switched seed oscillator. Amplification of seed pulses with different f is investigated in the two-stage fibre amplifier. The output performance of the MOPA at different repetition rates is compared and discussed. The maximum output pulse energy exceeded 0.5 mJ at a pulse duration of nearly 1.6 μs at 10 kHz, which is comparable with the maximum extractable pulse energy stored in the gain fibre. The thus obtained peak power was about 300 W, which is far less than any nonlinear threshold; in addition, no nonlinear spectral components were observed in the measured output spectra.

2. Experimental setup

Figure 1 schematically depicts the experimental setup of the high pulse energy, gain-switched MOPA. The seed oscillator (1958 nm) and a two-stage amplifier are based on a thulium-

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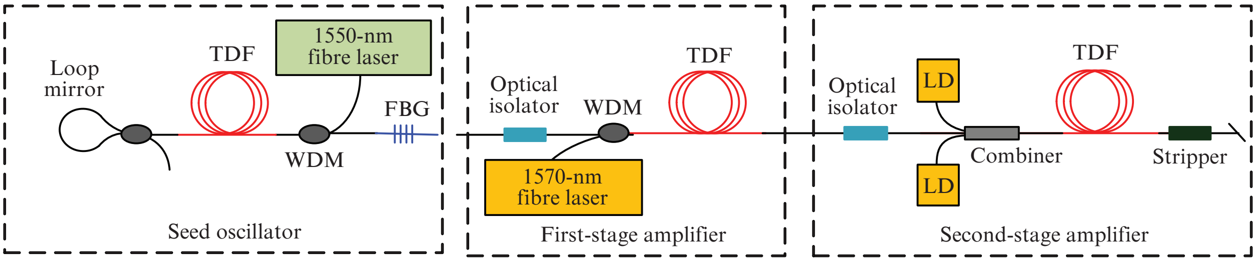

Figure 1. Experimental setup of the gain-switched MOPA laser.

doped fibre. The gain-switched seed oscillator is pumped by a homemade 1550-nm pulsed fibre laser to ensure fast gain-switched operation [16]. The 1550-nm radiation is coupled into the seed oscillator through a 1550/2000-nm wavelength division multiplexer (WDM). The repetition rate of the 1550-nm pulsed source can be tuned from 10 to 100 kHz. The gain fibre is a piece of a single mode TDF which has a core diameter of 9 μm, an NA of 0.15, a cut-off wavelength of 1.75 μm and an absorption coefficient of ~10 dB m^{-1} at 1550 nm. A fibre Bragg grating (FBG) with reflectivity of 50% at 1958 nm with 3 dB bandwidth of 2 nm is spliced to the WDM as the low reflectivity mirror. The left end of the seed oscillator is a fibre loop mirror based on a 50/50 fibre coupler at 2 μm. The length of the gain fibre is 2 m, while the total length of the seed oscillator is 3 m.

In the first-stage amplifier, a 6-m-long single mode TDF is used as the gain fibre, which is pumped in-core through a 1550/2000-nm WDM by an 800-mW Er-doped fibre laser (1570 nm). The second-stage amplifier based on a 7-m-long double clad TDF consists of two fibre-pigtailed 790-nm multimode laser diodes (LDs). The two LDs have a total output power of 18.8 W. Their radiation is coupled into the double clad TDF though the (2 + 1)×1 pump combiner. The double clad TDF has a core/cladding diameter of 10/130 μm, the NA is 0.15 for the core and 0.46 for the inner cladding. The peak absorption coefficient of the inner cladding is about 3 dB m^{-1} at 790 nm. A segment of 20-cm-long standard single-mode fibre (SMF-28) is spliced to the double-clad TDF for stripping the residual pump light. The single-mode fibre end at the output is angle-cleaved to prevent parasitic feedback from Fresnel reflection and two 1-W fibre isolators are used before the two-stage amplifier to prevent the backward light. The measuring system (not shown in Fig. 1) consists of a fast InGaAs photoelectric detector, a power meter and an optical spectrum analyser (Yokogawa AQ6375).

3. Results and discussion

In the first experiment, we studied the temporal characteristics of the gain-switched seed oscillator, which generates stable 1958-nm pulse trains by adjusting the pump energy of the 1550-nm pulsed source. The repetition rate could be varied from 10 to 100 kHz at pulse duration of 1.6 to 2.4 μs. Figure 2 shows the measured spectrum and pulse shape of the 1958-nm seed pulse with pulse energy of 0.5 μJ. One can see from Fig. 2a that the 3-dB spectrum width of the seed pulse is about 0.24 nm with a peak spectral intensity that is 50 dB higher than the background noise. The pulse has a Gaussian shape (Fig. 2b) and a pulse duration of 1.8 μs. Because of the fact that seed pulses with a low repetition rate are more preferable for further pulse energy scaling (see [12–14, 16]), in the two-stage amplification experiments we used seed pulses with repetition rates of 10, 20 and 100 kHz. The chosen seed pulse trains are shown in Fig. 3. One can clearly see that the generated 1958-nm seed pulses are very stable and exhibit no time jitter during the experiments, which is critical for the following pulse energy scaling.

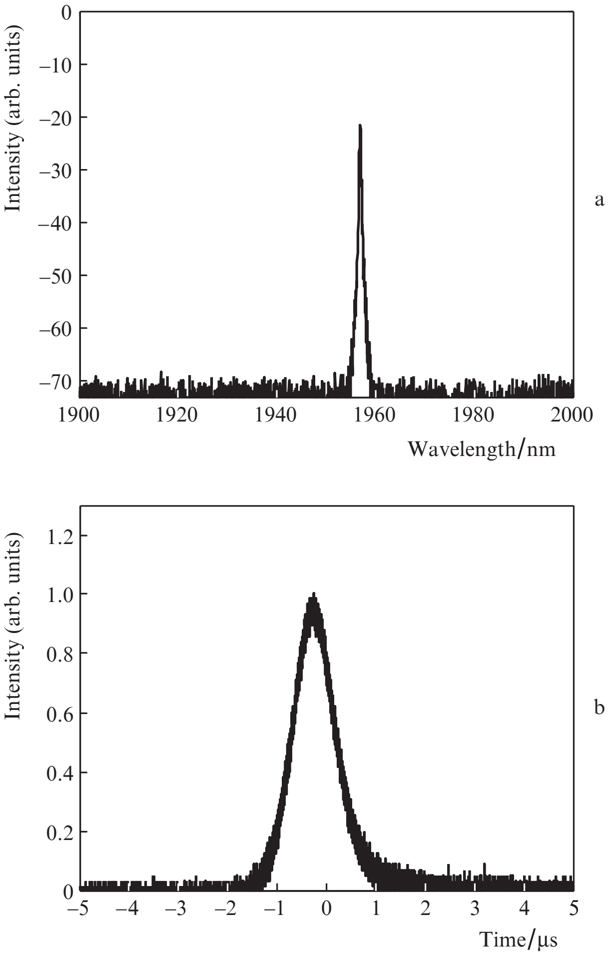

Figure 2. (a) Spectrum and (b) shape of a single seed pulse at $f = 10$ kHz.

In the second experiment, we studied amplification of seed pulses at 10, 20 and 100 kHz (Fig. 3). The first stage amplified the average output power of 1958-nm seed pulse trains up to ~200 mW. Figure 4 presents the average output power and the corresponding pulse energy after the second-stage amplifier as a function of 793-nm pump power. The maximum output powers of 5.06, 5.14 and 6.28 W were obtained

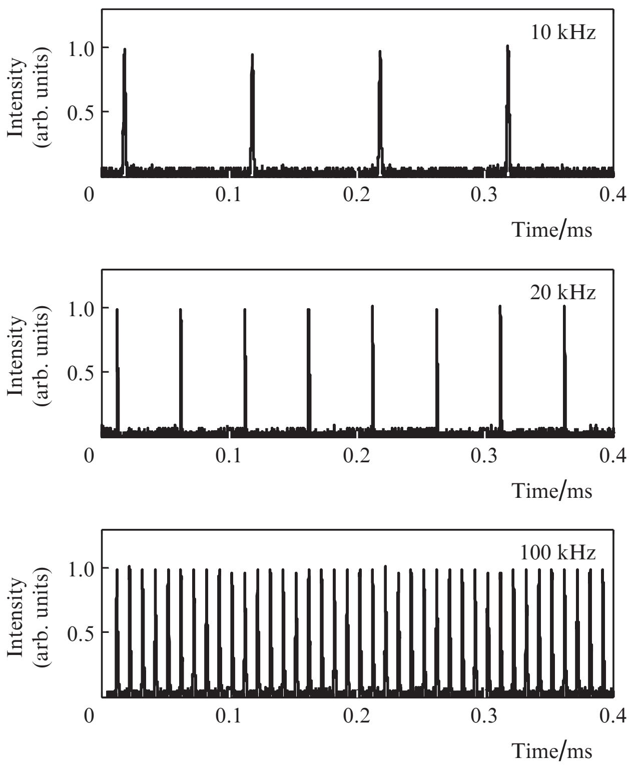

Figure 3. Output pulse trains of the gain-switched seed laser at different *f*.

at repetition rates of 10, 20 and 100 kHz, respectively. The average output power increases linearly with pump power and exhibits the slope efficiencies of 30.4%, 30.7% and 36.5% at 10, 20 and 100 kHz, respectively. Note that the highest output pulse energy of 0.506 mJ is obtained at 10 kHz. The measured pulse duration slightly decreases from 1.8 to 1.6 μs with increasing maximum output pulse energy, which may be caused by the gain depletion in the second-stage amplifier. The corresponding highest peak power is about 300 W.

Figure 5 shows the output spectra of the second-stage amplifier at a maximum output power and f = 10, 20 and 100 kHz. With decreasing repetition rate of the seed pulses from 100 to 10 kHz, a higher portion of the pump power is transferred to the ASE-induced noise, resulting in a relatively higher spectral ASE power. Due to the microsecond duration of the seed pulse and, consequently, a high cycle duty even at f = 10 kHz, the measured spectrum of the 1958-nm laser is still 40 dB higher than the ASE-induced noise. Even after the second-stage amplifier the spectrum does not broaden much and no new spectral components are measured, which indicates the absence of nonlinear effects in our MOPA. According to the calculations, the SRS, SBS and SPM thresholds in the second-stage amplifier for this experimental setup are all at a level of 1 kW, which is much higher than 300 W. The maximum output pulse energy is as high as 0.506 mJ, which is comparable with the calculated maximum extractable pulse energy of 0.6 mJ (limited by ASE) in the TDF with the core/cladding diameter of 10/130 μm [12]. This fact indicates that the output pulse energy of the MOPA has reached the upper limit for the pulse energy scaling within such a gain fibre. If it is needed to continue to scale the output pulse energy of the 1958-nm laser, gain fibres with a much larger core diameter and a higher pump power are required, which will be our future work.

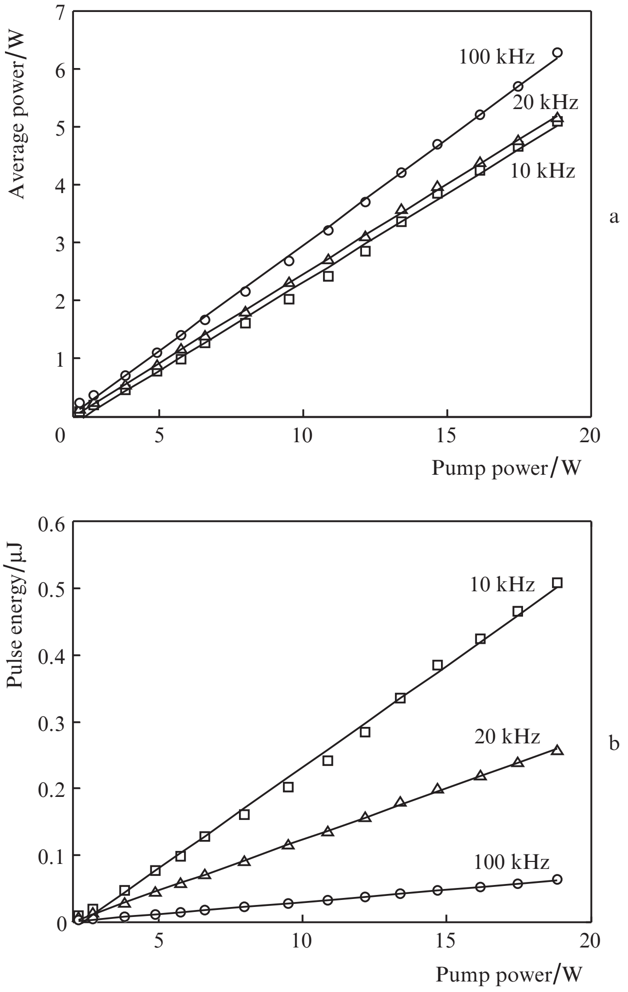

Figure 4. (a) Average output power and (b) pulse energy at the second-stage amplifier vs. pump power (λ_p = 793 nm) at 10, 20 and 100 kHz.

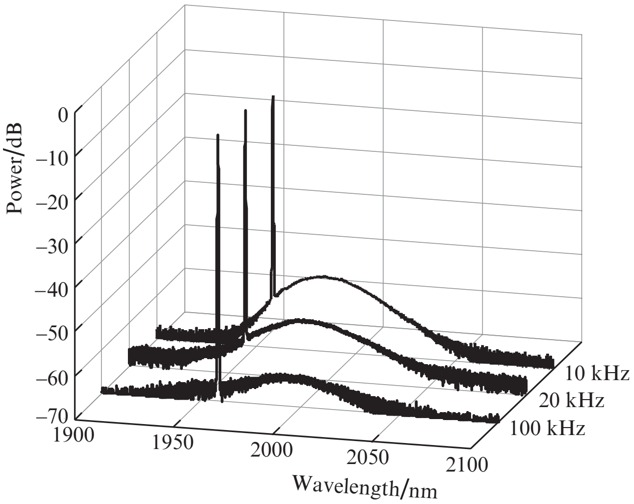

Figure 5. Output spectrum of the second-stage amplifier at f = 10, 20 and 100 kHz.

4. Conclusions

We report an all-fibre high pulse energy MOPA (1958 nm) with maximum pulse energy higher than 0.5 mJ at output pulse duration of 1.6 μs. The corresponding slope efficiency of the second-stage amplifier with respect to the pump power is nearly 30% at 10 kHz. In the amplification experiments, neither nonlinear effects nor significant ASE is observed when we check the output spectrum of the second-stage amplifier in the MOPA. Based on the theoretical estimates, there is still potential to scale the output pulse energy by adopting large-core-diameter gain fibres with sufficient pump powers of 790-nm LDs. In the future we plan to optimise the performance of this gain-switched MOPA and continue to scale the output pulse energy.

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