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Linearly polarized and narrow-linewidth pulse generation at high repetition rate from an all-fiber gain-switched Thulium-doped fiber laser

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ABSTRACT

Narrow-linewidth and linearly polarized operation at high repetition rate of an all-fiber gain-switched Thulium-doped fiber laser is presented. The laser produces stable 135 ns pulses with maximum average output power of 960 mW at repetition rate of 500 kHz, corresponding to maximum pulse energy of 1.92 μJ and a slope efficiency of 55.1% with respect to 1.55 μm pump power. The center wavelength of 1926.7 nm with a spectral bandwidth of < 50 pm is achieved.

1. Introduction

There is considerable interest in 2 μm Thulium-doped fiber lasers for use in many important fields such as remote sensing, laser induced breakdown spectroscopy, medical care and frequency conversion to mid-infrared [1–7]. In order to generate 2 μm pulsed laser sources with high average power, compact size and high beam quality, much research in recent years has focused on the Q-switched Thulium-doped fiber laser (TDFL) system [8,9], the Q-switched Ho:YAG laser system pumped by TDFL [10] and the gain-switched TDFL system [11–14]. Maximum pulse energy of the Q-switched system has been reported to be 325 μJ with a 200 ns at 20 kHz [9]; however, use of waveplates, lens and mirrors in this system not only required precise alignment but also increased system complexity and energy loss. With some optimization to the Ho:YAG system, Lippert et al. have extracted more than 42 W of output power from Ho-laser pumped by TDFL [10], but this system can hardly achieve good beam quality at high average power because of thermal beam distortions on gain medium [15].

Gain-switched TDFL pumped by pulsed 1.55 μm source is considered to be the most charming choice because its possible all-fiber configuration provides an efficient method for achieving high beam quality, narrow pulse width and high pulse energy. Jiang et al. obtained a stable 10 ns, over kilowatt peak-power pulse generation from a gain-swtiched Tm-doped fiber laser [11]. Moreover, with the development of Thulium-doped fiber and fiber Bragg grating (FBG), gain-switched TDFLs with linearly polarized output pulses have been demonstrated. For example, Smakov et al. established a monolithic, robustly polarized thulium fiber laser which produced pulses with 25 ns duration and energy of up to 35 μJ [13].

Although the majority of recent research efforts were invested into scaling the pulse energy and the peak power of gain-switched TDFL, little attention has been paid to stability control on the temporal behavior of the gain-switched TDFL system, especially the TDFL system operating at repetition rate as high as 500 kHz. According to the mechanism of gain switching [15,16], stable pulses output at high repetition rate can be achieved by increasing the pump power; however, high pump power may lead to optical damage in the fiber laser system. Therefore, a cavity design for increasing intracavity power and ensuring the stable pulses output at high repetition rate is needed. Our approach is to realize a TDFL system with stable narrow-linewidth output pulses at high repetition rate which can be used as the seed laser source for remote sensing.

In this paper, we present an efficient all-fiber gain-switched TDFL which produce linearly polarized pulses with narrow linewidth at high repetition rate. Pumped by a pulsed 1.55 μm source and spectral narrowed by FBGs, the gain-switched TDFL has generated a linearly polarized output pulses at 1926.7 nm with an average output power of 960 mW and a narrow linewidth of < 50 pm at repetition rates up to 500 kHz.

2. Experiment

The experimental setup of our gain-switched TDFL system is depicted in Fig. 1. The pump source of the TDFL included a single-mode 1.55 μm Erbium-doped fiber laser (Amonics) driven by square pulse signal produced from a function signal generator (Agilent).

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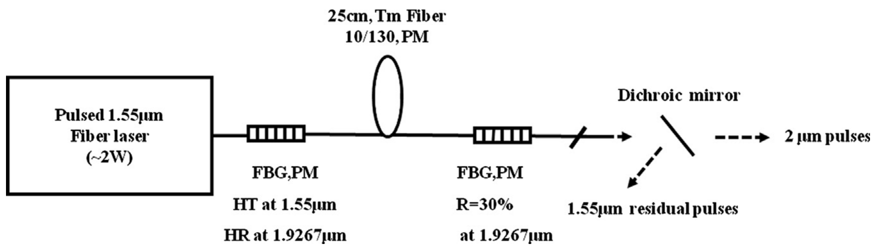

Fig. 1. The experimental setup of the gain-switched Thulium-doped fiber laser pumped by 1.55 μm fiber laser.

Stable 1.55 μm square pulses with average power up to 2 W were generated from the pump source and their pulse widths were 100 ns controlled by the function signal generator. The pump power was injected into a double-clad polarization-maintaining (PM) Thulium-doped fiber (Nufern) through an FBG (AFR). The input FBG which is written into PM passive fiber has high reflectivity ($R>99\%$) at 1926.7 nm (fast axis); it was used as the input cavity mirror. The length of Thulium-doped fiber was designed to be 25 cm and its doping concentration was 2 wt%. It was believed that more than 95% of the pump power could be absorbed by the Thulium-doped fiber with the total fusion loss measured to be 0.1 dB. The end of the Thulium was spliced to another FBG (AFR) which was also written into PM passive fiber and served as an output coupler. The reflectivity of the output FBG was designed to be 30% at 1926.7 nm (slow axis). It was optimized by our numerical model, for the sake of increasing the intracavity power to realize the stable pulses output with low pulse energy at high repetition rate. The splice of the Thulium-doped fiber and the output FBG was shown in Fig. 1 using a similar method of Smakov et al. [13] in order to enable single polarization operation. However, both of our FBGs had narrow bandwidth of 0.1 nm for the purpose of achieving narrow-linewidth output, so the splice with 90° rotational offset was precisely aligned as well as the temperature control of both FBGs were considered. All of those PM fiber used above (including PM Thulium-doped fiber and PM passive fiber) had a 10/130 (core/cladding, units: μm) structure with their core $NA=0.15$; their optical losses both at the pump and laser wavelengths are much smaller than the fusion loss, less than 0.01 dB. The total length of the laser cavity was 55 cm due to pigtail lengths of both FBGs. The whole TDFL cavity was attached to a piece of aluminum block for not only avoiding the thermal effects on Thulium-doped fiber [15] but also controlling FBGs temperature mentioned above. A dichroic mirror was located after the end of TDFL cavity in order to separate the residual power of 1.55 μm pump source and the 2 μm output power. The experiment was conducted at a room temperature of 20 °C.

3. Results

2 μm output powers of our gain-switched TDFL operated at repetition rate of 100, 300 and 500 kHz are presented in Fig. 2. The average output power was measured by a laser power meter (Molectron Detector, Incorporated) whose detectable power ranges from 1 mW to 100 W; as indicated in Fig. 2, the character of the output power with respect to the pump power and the threshold of the laser were found to be extremely similar at different repetition rate, with slight fluctuation. The threshold of the TDFL at repetition of 500 kHz was 254.5 mW and the slope efficiency of the laser output at repetition rate of 500 kHz was 55.1%, corresponding to the 1.55 μm pump power. The sudden drop in the output power and in the slope efficiency recorded by other authors [14] did not exist in our results ascribed to the temperature control of the Thulium fiber and FBGs mentioned above. For the repetition rate of 500 kHz, a maximum output power of 960 mW was obtained when the 1.55 μm pump power was 2018 mW; it is believed to be limited by the available pump power. Moreover, no residual 1.55 μm pump power could be detected in the laser output and the optical-to-optical conversion efficiency of 1.55 μm pump power to 2 μm is 47.65%.

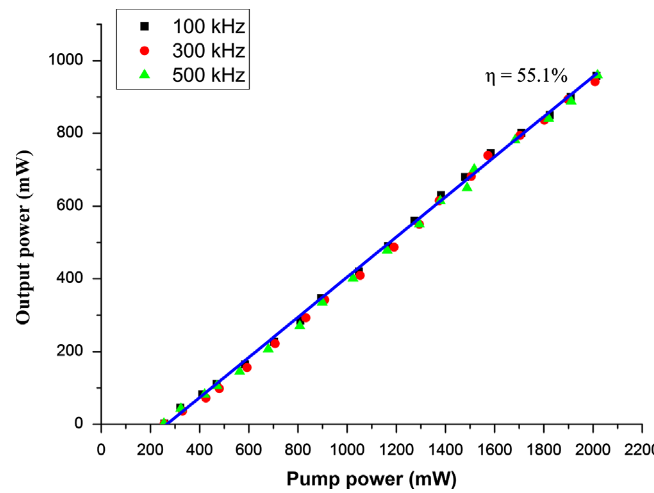

Fig. 2. The average output power at repetition rates of 100, 300 and 500 kHz versus 1.55 μm pump power.

In order to describe the output pulses of the gain-switched TDFL in detail, an InGaAs biased detector with sensing wavelength ranging from 1.2 μm to 2.6 μm (THORLABS, DET10D/M) and a two channel color digital phosphor oscilloscope (Tektronix, TDS3032) were utilized in the measurements of 2 μm output pulses. The pulse energy and the pulse duration at repetition rate of 100 kHz, 300 kHz and 500 kHz are shown in Fig. 3; however, the pulse shapes of output pulses at high repetition rates (especially at repetition rate of 500 kHz) could not be stabilized when the pump power was low, and therefore the pulse durations of those pulses are not recorded in the figure. As observed from Fig. 3, for any repetition measured, the pulse duration decreased as the pump power increased; by contrast, the pulse energy increased as the pump power increased, in accordance with the theory of gain switching [16]. Pulse duration of 135 ns at repetition rate of 500 kHz was achieved with the output average power of 960 mW, corresponding to the pulse energy of 1.93 μJ.

An output pulse train of the 2 μm output at the repetition rate of 500 kHz is presented in Fig. 4. Although the signal-to-noise ratio was low due to the strong background noise, the relaxation oscillation spiking behavior of the gain switching [15,16] did not occur and the output power remained to be stable with negligible fluctuation less than 5%. The stability of the pulse shape with low pulse energy could attribute to the use of the output FBG with $R=30\%$ for increasing the intracavity power.

The extinction ratio (*ER*) of the TDFL output was also tested. A fiber attenuator based on PM passive fiber and a cylinder polarization analyzer were utilized in the *ER* measurement. All operating conditions with $ER>17$ dB were recorded, corresponding to the laser output with more than 98% linearly

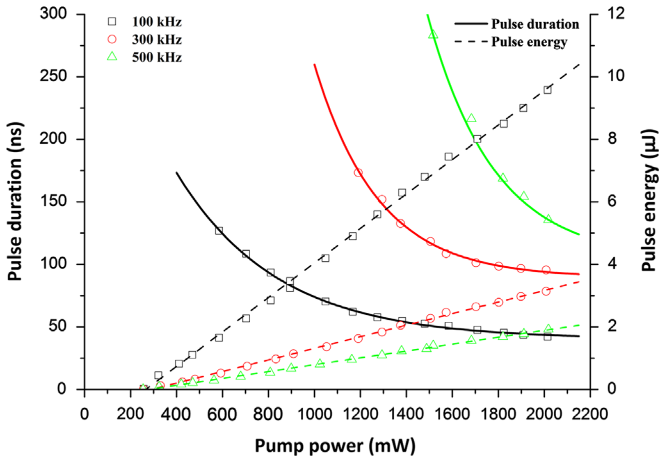

Fig. 3. The output pulse duration and pulse energy at repetition rates of 100, 300 and 500 kHz versus 1.55 μm pump power.

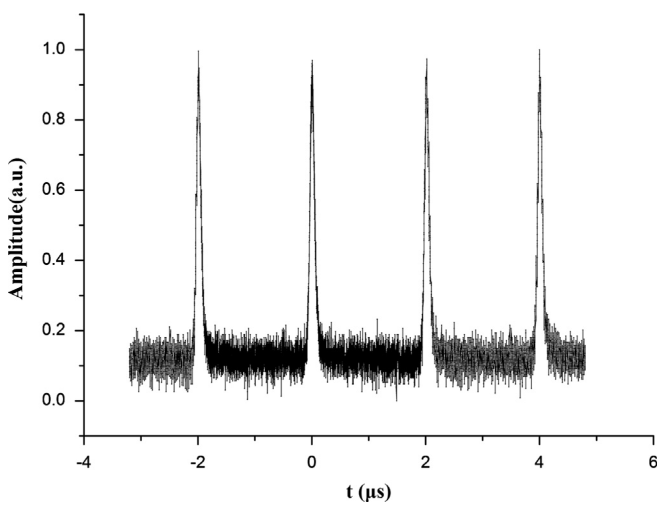

Fig. 4. A stable output pulse train of the gain-switch TDFL at the repetition rates of 500 kHz.

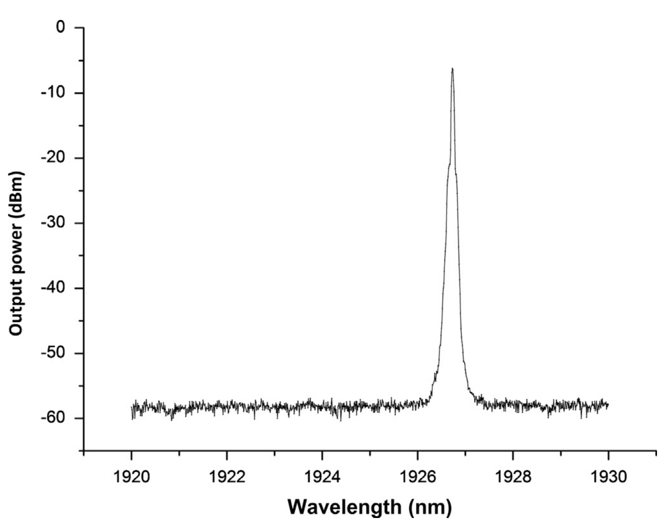

Fig. 5. The spectrum of the gain-switch TDFL at the repetition rates of 500 kHz with the center wavelength of 1926.7 nm and a 3 dB bandwidth of 0.0476 nm (resolution limit).

polarized. In order to improve the *ER*, a more accurate angular alignment of the stress rods is needed when fusion splicing PM Thulium-doped fiber and PM FBGs.

The spectrum of 2 μm output was measured by propagating it into an optical spectrum analyzer (OSA) (YOKOGAWA, AQ6375). As presented in Fig. 5, a narrow output spectrum was achieved with the center wavelength of 1926.7 nm and a 3 dB bandwidth of 0.0476 nm restricted by the resolution limit of OSA. The small spectral overlap of the input and output FBGs are believed to contribute to the narrow-linewidth output. The TDFL operated on a single spectral line without the obvious occurrence of any nonlinear optical effects and amplified spontaneous emission at other wavelengths.

4. Conclusion

In conclusion, we have demonstrated a polarized all-fiber gain-switched TDFL. The laser generated stable pulses with average power of 960 mW and pulse duration of 135 ns at repetition rate of 500 kHz. The slope efficiency of 55.1% and the center wavelength of 1926.7 nm with a narrow spectral width of <50 pm were achieved. The TDFL system would be able to meet the requirements for applications with further power scaling through an efficient master oscillator power amplifier structure.

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