High average power picosecond pulse generation from a thulium-doped all-fiber MOPA system

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Abstract: We report a stable highly-integrated high power picosecond thulium-doped all-fiber MOPA system without using conventional chirped pulse amplification technique. The master oscillator was passively mode-locked by a SESAM to generate average power of 15 mW at a fundamental repetition rate of 103 MHz in a short linear cavity, and a uniform narrow bandwidth FBG is employed to stabilize the passively mode-locked laser operation. Two-stage double-clad thulium-doped all-fiber amplifiers were used directly to boost average power to 20.7 W. The laser center wavelength was 1962.8 nm and the pulse width was 18 ps. The single pulse energy and peak-power after the amplication were 200 nJ and 11.2 kW respectively. To the best of our knowledge, this is the highest average power ever reported for a picosecond thulium-doped all-fiber MOPA system.

OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3070) Infrared and far-infrared lasers.

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1. Introduction

The interest for the development of stable highly integrated high power mid-infrared all-fiber laser systems for applications of atmospheric probing, laser medicine, and radar systems has been increased greatly over the past decade. Thulium-doped fiber lasers, which extend the wavelength range of fiber lasers to 1.7~2.1 μm, could be considered as one of the most important sources of mid-infrared laser radiation that has been developed and were intensively investigated for the last several years. So far, the output power of the continuous wave (CW) 2 μm thulium-doped fiber laser has reached kilowatt level [1], the power of single-frequency thulium-doped fiber master oscillator power amplifier (MOPA) has achieved 608 W [2] and high pulse energy of 220 μJ with 80 ns pulse width was also demonstrated in an all-fiber MOPA configuration at 1920 nm by using highly thulium-doped germanate fibers [3]. At the same time, ultrashort pulse generation of thulium-doped fiber lasers and power scaling of such short pulses in thulium-doped fiber amplifiers have been studied worldwidely [4–16], due to their uses for a variety of attractive applications in materials processing, gas sensing, eye-safe radar as well as mid-infrard broadband supercontinuum generation. However, the average output power is still limited within several watts level because of the nonlinearity and complexity of mid-infrared ultrashort pulse fiber amplification. Recently, F. Haxsen *et al*. achieved high energy and peak power pulses using chirped pulse amplification in a thulium-doped large-mode-area (LMA) fiber laser. The seed laser pulses were stretched in anomalous dispersion fiber and amplified to 151 nJ, which corresponds to an average power of 5.7 W at a repetition rate of 37.6 MHz [15]. L. M. Yang *et al*. demonstrated high energy MOPA based on a femtosecond seed source and a two-stage fiber amplifier at 2 μm with chirped pulse amplification technique as well. The seed laser generated pulse train at a repetition rate of 2.5 MHz and the two-stage fiber amplifiers boost the average power to 1.6 W, corresponding to single pulse energy of 0.65 μJ with a compressed pulse width of 820 fs [16].

In this contribution, we report on stable high average power picosecond pulse generation from a simple thulium-doped all-fiber MOPA system without using conventional chirped pulse amplification technique. The SESAM passively mode-locked picosecond thulium-doped all-fiber oscillator was designed by utilizing a uniform narrow-band fiber Bragg grating (FBG) on purpose to generate tens of picosecond pulses with high repetition rate of 103 MHz, which allowed the laser power to be boosted to 20.7 W with two-stage all-fiber amplifiers without the occurrence of nonlinear effect and fiber facet damage. The single pulse energy and peak-power after the amplication were 200 nJ and 11.2 kW respectively. The slope efficiency of the thulium-doped fiber power amplifier was 42%, and the maximum output power was currently limited by available pump power.

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2. Experimental setup and results

The high power picosecond thulium-doped all-fiber MOPA system consists of a passively mode-locked thulium-doped fiber master oscillator and two-stage double-clad thulium-doped all-fiber amplifiers. The schematic setup of the fiber MOPA system is shown in Fig. 1. A high repetition rate semiconductor saturable absorber mirror (SESAM) passively mode-locked thulium-doped fiber laser has been used as master oscillator. The total cavity length of the oscillator is about 97 cm with total group-velocity dispersion (GVD) of –0.064 ps^2, which included about 70 cm thulium-doped single-clad fiber with GVD of about –0.065 ps^2/m. The core of the thulium-doped fiber has a diameter of 9.0 μm and a numerical aperture (NA) of 0.16 and its cladding has a diameter of 125 μm (core-absorption about 20 dB/m at 1550 nm). All other fiber segments used in the linear laser cavity were a total length of 27 cm standard single-mode passive fiber (SMF-28) with GVD of about –0.07 ps^2/m. The pump laser in the experiment was a home-made CW single-mode erbium-doped fiber laser, which has a center wavelength of 1550 nm and the maximum average output power of 900 mW. A 1550/2000 nm wavelength division multiplexer coupler (WDM) was used to deliver pump light and the efficient pump coupling to the core of thulium-doped fiber was over 90%. The cavity output coupler is a uniform narrow bandwidth FBG with 80% high-reflectivity at a center wavelength of 1963 nm (full-width at half-maximum (FWHM) of 2 nm). One end of the thulium-doped gain fiber is fusion spliced to the FBG; the other end is perpendicularly cleaved and butted to a SESAM. The SESAM has a modulation depth of 20%, non-saturable loss of 16%, relaxation time of 500 fs, and saturation fluence of 35 μJ/cm^2.

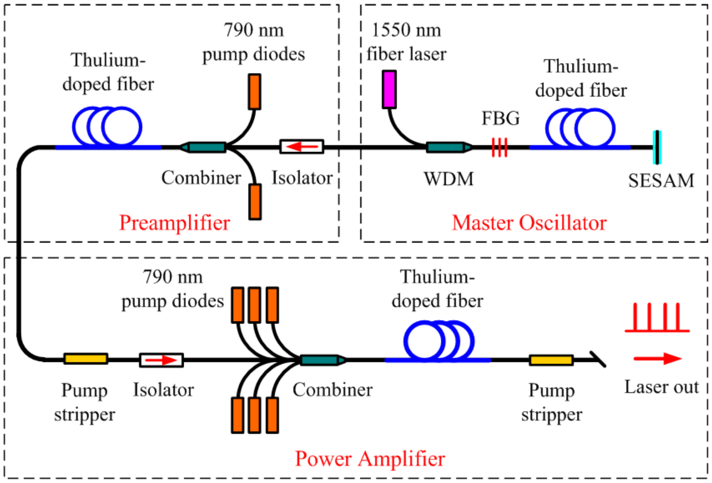

Fig. 1. Schematic setup of the high power picosecond thulium-doped all-fiber MOPA system. FBG, fiber Bragg grating; WDM, 1550/2000 nm wavelength division multiplexer coupler; SESAM, semiconductor saturable absorber mirror.

With proper adjustment of SESAM reflective coupling with the fiber end, stable self-started CW mode-locked pulses of the fiber oscillator occurred at about 210 mW incident pump power and the pulse repetition rate was 103 MHz. The laser pulses were monitored using a 25 GHz real-time oscilloscope (Agilent DSO-X92504A) and a 7.5 GHz InGaAs photodetector. With the incident pump power of 350 mW, the maximum average output power was 15 mW, which corresponds to single pulse energy of 0.15 nJ. Figure 2 shows the optical spectrum of the fiber oscillator, which was measured by an optical spectral analyzer (YOKOGAWA AQ 6375) with resolution of 0.05 nm. The central lasing wavelength was around 1962.7 nm, which is same to the resonant peak of the FBG; the spectral FWHM bandwidth was about 0.37 nm. The insert of Fig. 2 shows the measured oscilloscope trace over a 90 ns time scale. The laser always emitted single pulses with no pulse breaking or

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multiple pulse operation. We also measured radio frequency (RF) spectrum of the oscillator using a 7.5 GHz signal analyzer (Agilent N9000A-507). The fundamental peak located at the cavity repetition rate of 103 MHz has a signal-to-background ratio of 70 dB, indicating that the passively mode-locked state was stable. The narrow-band FBG (FWHM of 2 nm) also has the function of a spectral filter to balance the nonlinearity induced spectrum broadening effect [17]. Therefore, we can obtain easily stable passively mode-locked laser pulses with a high repetition rate of 103 MHz. Owing to the thermal influence of the SESAM under higher pump power, further increase of the incident pump power, the pulse train of the passively mode-locked fiber laser became unstable. The pulse width can’t characterized by our autocorrelator (FR-103XL) because of low average and peak power of the fiber oscillator, however, the relative low peak power of the oscillators makes it a good seed source for the high average power output by use of cascaded fiber amplification [18, 19].

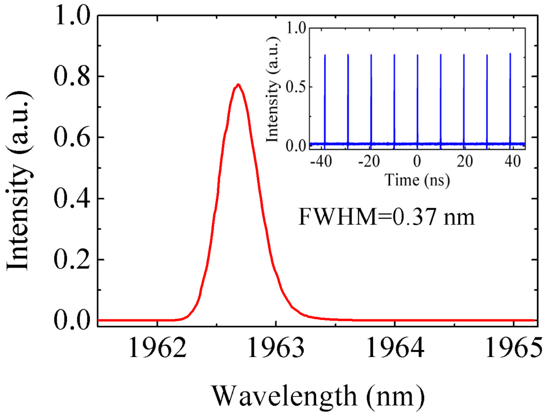

Fig. 2. Optical spectrum of the thulium-doped fiber master oscillator. Insert, stable passively mode-locked pulse train of the fiber oscillator at 103 MHz repetition rate.

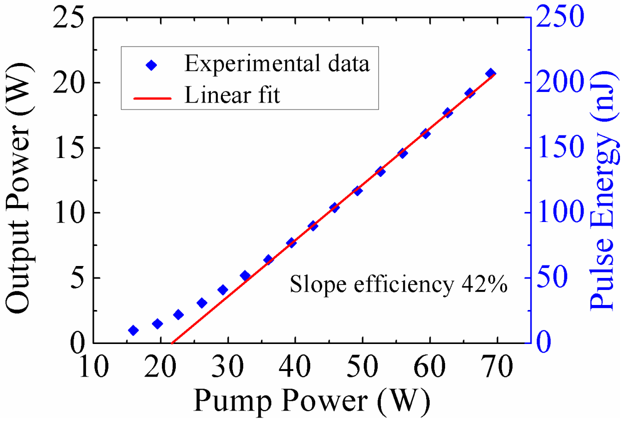

Fig. 3. Average output power and pulse energy of the fiber power amplifier with the increase of incident pump power.

The output pulses from the fiber master oscillator with 15 mW average power were amplified by one-stage thulium-doped fiber preamplifier in order to provide enough power for the second-stage fiber power amplifier. The amplification gain medium is a 6 m long thulium-doped double-clad single-mode fiber with a core diameter of 10 μm and a cladding diameter of 130 μm, the NA was 0.15 for the core and 0.46 for the inner cladding (cladding-absorption about 3 dB/m at 790 nm). Two fiber-pigtailed multimode diodes at 790 nm with fiber core of 105 µm are combined as the pump source, as shown in Fig. 1. An isolator is used for suppressing spurious intra-cavity reflections between the master oscillator and preamplifier, which can prevent self-starting and impair the mode-locking stability. In the experiment, the first-stage preamplifier produced 400 mW average output power for 4.5 W incident pump power, and the pulse width was measured to be about 20 ps by our autocorrelator (FR-103XL). The center wavelength and the spectral bandwidth of the fiber preamplifier were 1962.7 nm and 0.38 nm respectively.

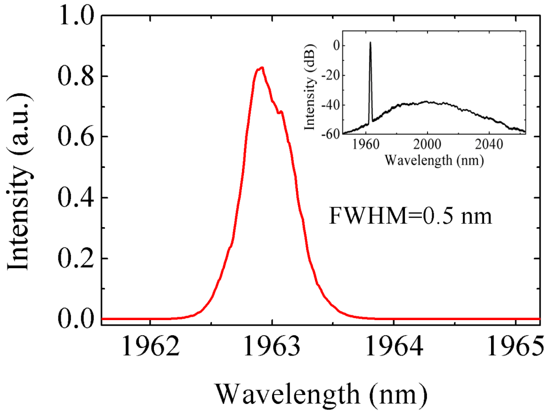

Fig. 4. Optical spectrum of the fiber power amplifier at maximum average output power. Insert, optical spectrum of the fiber power amplifier over a 120 nm bandwidth scale.

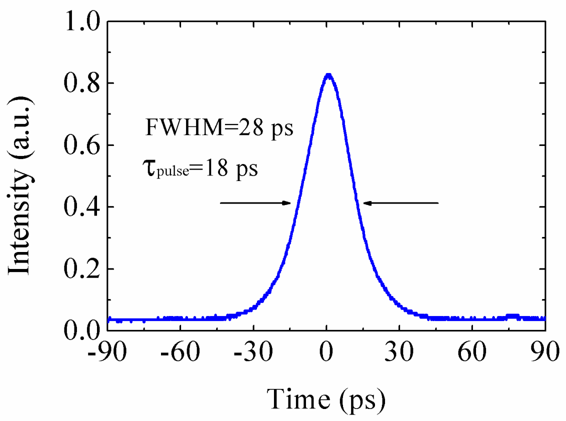

Fig. 5. Autocorrelation trace of the fiber power amplifier at maximum average output power.

In the second-stage power amplifier, a segment of 4.7 m long thulium-doped double-clad LMA fiber was used as the gain medium (cladding-absorption about 4.5 dB/m at 790 nm), which has a core diameter of 20 µm and an inner cladding diameter of 400 µm, the NA is 0.11 for the core and 0.45 for the inner cladding. A (6 + 1) x1 pump combiner was used to deliver pump light to the thulium-doped LMA fiber from six fiber-pigtailed high power multimode diodes, which give the total output power of 69 W at 790 nm in a 0.45 NA 20/400 µm double-clad passive fiber. Figure 3 shows the fiber power amplifier average output power and pulse energy versus incident pump power. The average output power increased almost linearly with the rise of incident pump power. The maximum average output power was 20.7 W for 69 W incident pump power, which corresponds to single pulse energy of 200 nJ. And the slope efficiency for the fiber power amplifier was about 42%. In addition, the slope efficiency can be improved further by optimizing the length and the efficient thermal management of the thulium-doped LMA fiber in the power amplifier [1]. The amplifier output spectrum is shown in Fig. 4; the center wavelength is 1962.8 nm, which is almost same as those of the fiber oscillator. The spectral bandwidth is about 0.5 nm. The self-phase modulation (SPM) effect in the fiber results in the broaden of the amplifier output spectrum. The amplified spontaneous emission (ASE) in the second-stage fiber power amplifier is about 40 dB down compared with the amplified signal, as shown in insert of Fig. 4. The autocorrelation trace of the laser pulse in the fiber power amplifier is shown in Fig. 5, and it has a FWHM width of 28 ps. If a sech^2 pulse profile is assumed, the pulse width is about 18 ps. Thus, the time-bandwidth product of the laser pulse is about 0.7, slightly higher than the transform limit. The maximum peak-power of the fiber power amplifier was 11.2 kW and the maximum output power is currently limited by available pump power. The MOPA system has been operated for a few hours per day over a one-week period without any adjustments. The average output power fluctuation of the high power thulium-doped all-fiber MOPA system is less than ± 2%. Because of the stable fiber master oscillator and all-fiber highly-integrated components for the two-stage thulium-doped fiber amplifiers, the high power MOPA system was stable and reliable, and would be very attractive for high power applications, such as pump source for mid-IR supercontinuum generation [20, 21]. The core diameter and the NA of thulium-doped double-clad LMA fiber were 20 μm and 0.11 respectively. The V-number of the core was 3.52, which means that in theory the core can support approximately 5 modes. In this case, M^2 should be less than 2, but the exact value can't be measured in our lab at present because of the lack of the measurement equipment.

Furthermore, we obtained stable SESAM passively mode-locked laser pulses with a fundamental repetition rate up to 430 MHz by shortening the cavity length of the fiber master oscillator to about 23 cm using a similar cavity configuration. The high repetition rate passively mode-locked fiber oscillators made it a good seed source for the cascaded fiber amplification. Fiber amplifier stages can be adopted to boost the average power to hundreds of Watts if higher output power is required for various applications including materials processing, laser ranging and broadband supercontinuum generation. A future work will focus on higher single pulse energy and peak-power generation by using thulium-doped LMA fibers and applications of such high power sources for mid-IR laser and supercontinuum generation.

3. Conclusion

In summary, we have demonstrated stable highly-integrated picosecond pulse generation from a SESAM passively mode-locked thulium-doped fiber laser by utilizing a short linear cavity and a narrow-band FBG. Using the high repetition rate of 103 MHz laser as a seed source, we have also demonstrated a 20.7 W high average power in a simple thulium-doped all-fiber MOPA system with pulse width of 18 ps at 1962.8 nm, which represent a significant average output power increase and a record power level compared to reported pulsed high power 2 μm thulium-doped MOPA systems [15, 16]. The maximum single pulse energy and peak-power were 200 nJ and 11.2 kW respectively, without using complex chirped pulse amplification technique. The slope efficiency of the fiber main amplifier was 42% with respect to pump power. The maximum output power was currently limited by available pump power. Based on the experimental results in this report, power scaling to the hectowatt level at 2 μm wavelength is feasible by applying for high repetition rate picosecond seeder sources and cascaded high power fiber amplification.

Acknowledgments

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