High average power picosecond pulse and supercontinuum generation from a thulium-doped, all-fiber amplifier

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We demonstrate a high-power, picosecond, thulium-doped, all-fiber master oscillator power amplifier with average power of 120.4 W. The compact fiber oscillator is carefully designed with high repetition rate for the purpose of overcoming the detrimental effects of fiber nonlinearity in the later fiber amplifiers. The pulse duration of 16 ps at 333.75 MHz repetition rate results in a peak power of 22.5 kW in the final fiber power amplifier. To the best of our knowledge, this is the first demonstration of average power exceeding 100 W from an ultrashort pulse laser at 2 μm wavelength. On the other hand, by decreasing the fiber oscillator repetition rate and pulse duration for enhancing the fiber nonlinearity effects, we also demonstrate a high-power supercontinuum source with average power of 36 W from 1.95 μm to beyond 2.4 μm in the final fiber power amplifier.

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The research on ultrashort pulse generation in thulium-doped fiber lasers [1–8] and power scaling of such short pulses in thulium-doped fiber amplifiers [9–11] has attracted worldwide attention in the last several years because of their potential applications in polymeric material processing [12], pump source for mid-infrared (Mid-IR) optical parametric oscillators [13,14], and Mid-IR supercontinuum generation [15–19]. In most cases, the well-known chirped pulse amplification (CPA) technique in combination with highly thulium-doped large-mode-area (LMA) active fibers was also adopted to reduce the detrimental nonlinearity effects during the high average power or high pulse energy fiber amplification. The pulse is first chirped before amplification in order to decrease the peak power intensities, and then it is compressed by using pulse compression gating after high power fiber amplification. For example, Haxsen *et al.* achieved high-power and high-energy ultrashort pulses using CPA technique in a thulium-doped LMA fiber amplifier [20] in 2010. The amplifier produces 5.4 W average power and 151 nJ pulse energy. More recently, Sims *et al.* used multistage thulium-doped fiber amplifiers to boost Raman-shifted pulses to the pulse energy of 1 μJ and peak power of 1 MW [21]. Wan *et al.* demonstrated a higher pulse energy CPA system based on a picosecond fiber oscillator and multistage fiber amplifiers [22]. The final fiber power amplifier boosts the average power to 5.4 W, corresponding to pulse energy of 36.7 μJ with a compressed pulse duration of 910 fs. All of these earlier experiments involved a lot of free space optics, such as large bulk grating pairs, and inevitably resulted in the loss of an all-fiber scheme, which is considered the most distinguished property of fiber lasers. The high-power chirped pulse compression gratings for the 2 μm wavelength region have also been expensive and complex components for fabrication up to now, and suppliers are limited to one or two companies.

In this Letter, we report on a much higher average power picosecond, thulium-doped, all-fiber master oscillator power amplifier (MOPA) without using conventional CPA technique. The simple picosecond, all-fiber oscillator was carefully designed with high repetition rate for the purpose of achieving high average power and high peak power pulses in the later fiber amplification stages without the occurrence of high fiber nonlinear effect and fiber damage. The picosecond, all-fiber oscillator was mode locked by a semiconductor saturable absorber mirror (SESAM) at a fundamental repetition rate of 333.7 MHz in a short linear cavity. Compact, three-stage, thulium-doped, all-fiber amplifiers with good thermal management were used directly to boost average output power to 120.4 W, corresponding to a slope efficiency of 59%. The pulse duration and peak power after the amplification were 16 ps and 22.5 kW, respectively. On the other hand, by decreasing the fiber oscillator repetition rate and pulse duration for the purpose of enhancing the fiber nonlinearity effects in the later fiber amplifiers, we also generated a high power supercontinuum with average output power of 36 W from 1.95 μm to beyond 2.4 μm in the fiber power amplifier. The spectral flatness of the supercontinuum was better than 10 dB and the slope efficiency was ~30%.

The schematic setup of the high-power picosecond, thulium-doped, all-fiber amplifiers is shown in Fig. 1.

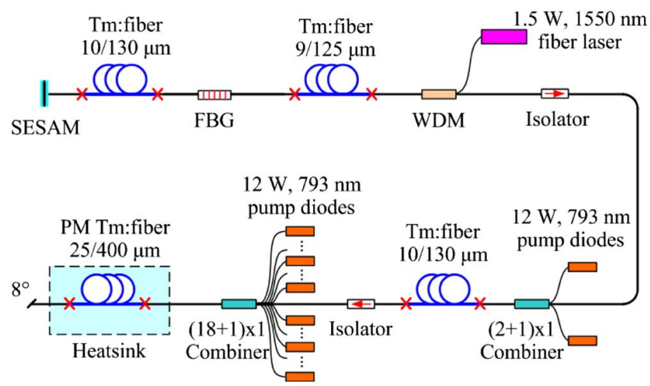

Fig. 1. Schematic setup of the high average power picosecond, thulium-doped, all-fiber MOPA system.

The seed source was a SESAM mode-locked fiber oscillator working at 1963 nm, similar to the one described in our previous work [10]. The SESAM had a modulation depth of 8% and a relaxation time of 500 fs. The active fiber of the oscillator was ~0.23 m thulium-doped, double-clad, single-mode fiber (Nufern, Inc.; core absorption of ~150 dB/m at 1550 nm) with 10 μm core pumped with a homemade continuous-wave 1550 nm fiber laser. A narrow bandwidth fiber Bragg grating (FBG) (80% reflectivity at a 1963 nm wavelength region, 2 nm spectral bandwidth) was used for pulse spectrum formation in order to achieve tens of picosecond pulse duration. The pulses were monitored using a 25 GHz real-time oscilloscope (Agilent, Inc.; DSO-X92504A) and a 12.5 GHz InGaAs photodetector (EOT, Inc.; ET-5000F). The fiber oscillator generated stable, nearly transform-limited picosecond pulses with fundamental repetition rate of 333.75 MHz, as presented in Fig. 2. The fundamental peak located at the cavity repetition rate of 333.75 MHz has a signal-to-background ratio of 65 dB, indicating that the mode-locked state was stable. In order to provide enough power for the second thulium-doped fiber preamplifier, a simple first preamplifier composed of a 0.75 m thulium-doped, single-clad fiber was spliced directly to the other end of the narrow bandwidth FBG. The active fiber has a diameter of 9.0 μm and its cladding has a diameter of 125 μm (core absorption of ~20 dB/m at 1550 nm). The residual 1550 nm laser transmitted through thulium-doped single-clad fiber is used to pump the fiber oscillator. With the pump power of 900 mW, the fiber oscillator and first preamplifier together yielded an average power of 120 mW with center wavelength of 1963 nm. The 3 dB spectral bandwidth was measured to be 0.32 nm by the optical spectral analyzer (YOKOGAWA, AQ 6375), as shown in Fig. 3. The pulse duration after the first fiber preamplifier was measured by our autocorrelator (Femtochrome, FR-103XL), and the full width at half-maximum width of the autocorrelation trace was 30 ps, as shown in Fig. 3. If a sech^2 pulse profile is assumed, the pulse duration is 19.5 ps.

In the second fiber preamplifier, the active fiber was a 4 m, thulium-doped, double-clad fiber, characterized by the same parameters as the oscillator mentioned above (cladding absorption of 3 dB/m at 793 nm). Two fiber-pigtailed diodes (BWT Beijing Ltd., China; fiber core diameter of 105 μm, NA = 0.22) at 793 nm are employed as the pump source, and the total output power was 24 W. The second preamplifier produced 5 W average power at 17 W pump power. In this stage, the pulse duration and 3 dB spectral bandwidth are the same as that in the first preamplifier. The pulse peak power is usually limited by nonlinear interactions in fiber caused by high irradiances in the core and large interaction length [23]. In order to decrease the effects of high fiber nonlinearity, a segment of about 4 m polarization-maintaining (PM), thulium-doped LMA fiber was used as the gain medium in the final fiber power amplifier. The active fiber has a core diameter of 25 μm, NA of 0.09, inner cladding diameter of 400 μm, and a NA of 0.46 (Nufern, Inc.; cladding-absorption of ~2.4 dB/m at 793 nm). The active fiber was cooled to ~10°C to promote efficient two-for-one cross relaxation. The pump sources were 18 diodes at 793 nm with 105 μm (NA = 0.22) pigtail fibers, which match to the pump fiber of the combiner. The total output power of these pump diodes was ~216 W. A $(18 + 1) \times 1$ high power pump combiner was used to deliver pump light to the thulium-doped LMA fiber with a coupling efficiency of ~95%. The output end of the thulium-doped LMA fiber was spliced to 0.5 m passive fiber with matched core, and the output facet was cleaved at 8° to frustrate parasitic lasing.

Figure 4 shows the average output power of the thulium-doped fiber power amplifier versus incident pump power. The maximum average output power was 120.4 W at 205 W incident pump power limited by

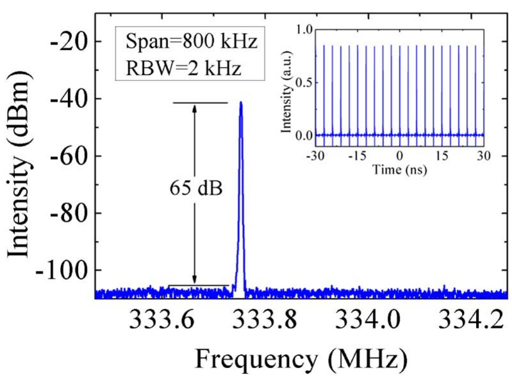

Fig. 2. RF spectrum of the thulium-doped fiber oscillator. Insert, pulse train of the fiber oscillator at 333.75 MHz.

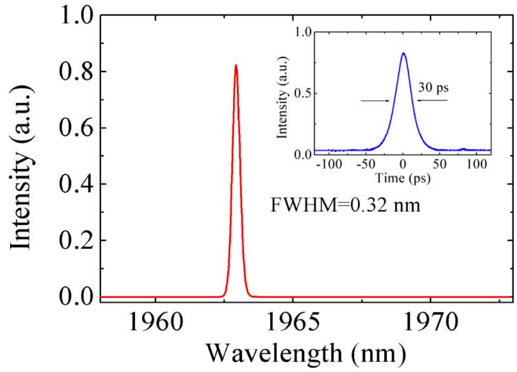

Fig. 3. Optical spectrum of the first thulium-doped fiber preamplifier. Insert, autocorrelation trace of the pulse of first thulium-doped fiber preamplifier at average power of 120 mW.

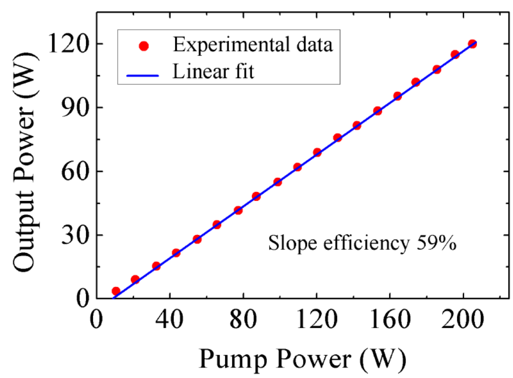

Fig. 4. Average output power of the thulium-doped LMA fiber power amplifier with the increase of incident pump power.

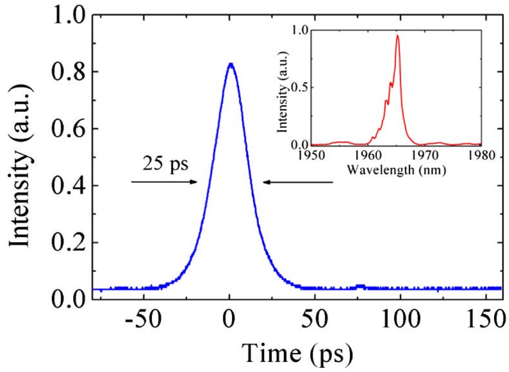

Fig. 5. Autocorrelation trace of the pulse of the thulium-doped fiber power amplifier. Insert, optical spectrum of the thulium-doped fiber power amplifier at maximum average output power.

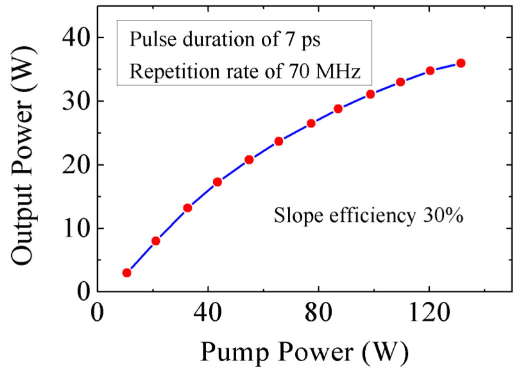

Fig. 6. Average output power of the supercontinuum source with the increase of incident pump power. The pulse duration and repetition rate of the fiber oscillator were 7 ps and 70 MHz, respectively.

available pump power, which corresponds to a slope efficiency of ~59%, and the average power increased almost linearly with the increase of incident pump power. The core diameter and the NA of the thulium-doped LMA fiber were 25 μm and 0.09, respectively. The V-number of the core was 3.6, 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 cannot be measured in our lab at present because of the lack of measurement equipment. Due to the quasi-three-level nature of the laser, cooling the thulium-doped fiber to the lower temperature was very critical for achieving high slope efficiency in the power amplifier [24–27]. The slope efficiency is slightly lower than that achieved in [28,29], which is mainly caused by the nonlinear effects (self-phase modulation, SPM) in our fiber power amplifier. The pulse duration and output spectrum of the fiber power amplifier are shown in Fig. 5. If a sech^2 pulse profile is assumed, the pulse duration is 16 ps, corresponding to the peak power of 22.5 kW. The central wavelength is 1965 nm and the 3 dB spectral bandwidth is ~1.9 nm. In addition, we didn't find that the fiber facet was damaged at highest average output power, which can be attributed to the fact that the fiber amplifier operated at high repetition rate and the thulium-doped LMA fiber has a core diameter of 25 μm.

In addition, we obtained a 36 W average output power supercontinuum source around 2 μm in the thulium-doped fiber MOPA system by lengthening the passive fiber (SMF-28) of fiber oscillator to decrease the oscillator repetition rate from 333.75 to 70 MHz and the pulse duration from 19.5 to 7 ps. Furthermore, in order to enhance the high fiber nonlinearity effects in the fiber power amplifier, the length of the PM thulium-doped LMA fiber and the matched passive fiber changed from 4 m, 0.5 m to 5 m, 2.5 m, respectively. This will be more useful for broadband supercontinuum generation [18,30]. Figure 6 shows the average output power scaling of the supercontinuum in the final thulium-doped fiber power amplifier from 3 to 36 W with the increase of incident pump power. Due to the strong fiber nonlinear effects such as SPM, modulation instability, and stimulated Raman scattering under high incident pump power, the final thulium-doped fiber power amplifier generated high-spectral-flatness supercontinuum. Figure 7 shows the optical spectrum of the supercontinuum source. The supercontinuum source covers from 1950 to beyond 2400 nm (limited by our optical spectral analyzer, AQ 6375) with spectral flatness better than 10 dB and 30% slope efficiency. In order to avoid the thermally induced damage to the thulium-doped fiber caused by the lower optical to optical conversion, we do not further increase the incident pump power. The dropping of slope efficiency in the final fiber power amplifier is caused by the strong fiber nonlinear effects.

In conclusion, we have demonstrated a high-power picosecond pulse generation from a compact, thulium-doped, all-fiber MOPA without using conventional CPA technique. The fiber oscillator was carefully designed with high repetition rate for the purpose of achieving high average power and relative high peak power in the fiber power amplifier without the occurrence of high nonlinear effect and fiber facet damage. The thulium-doped, all-fiber amplifiers produced maximum average output power of 120.4 W and pulse duration of 16 ps, corresponding to the peak power of 22.5 kW. This is the first demonstration, to our knowledge, of average power exceeding 100 W from an ultrashort pulse laser at the 2.0 μm wavelength region. This kind of high average power, high repetition rate picosecond source represents an attractive technology for the generation of high output power

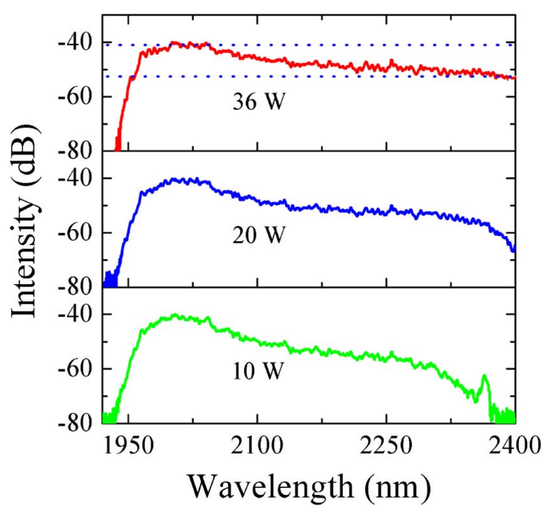

Fig. 7. Optical spectrum of the supercontinuum source at different average output power.

Mid-IR laser via nonlinear frequency conversion. In addition, we obtained high power supercontinuum with average power of 36 W from 1.95 to 2.4 μm by enhancing the effects of fiber nonlinearity in the later amplification stages. The spectral flatness of the supercontinuum source was better than 10 dB and the slope efficiency was ~30%. To the best of our knowledge, this is the highest average output power supercontinuum ever reported in this spectral range.

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