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基于 MOPA 结构与高能量种子源的高功率皮秒掺铥光纤放大器

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摘　要:以单脉冲能量更高的孤子激光器为种子源,通过主振荡放大技术,获得了 2 μm 波段的高功率、皮秒脉冲激光器.该种子源是一个被动锁模的光纤激光器,通过优化、管理激光器谐振腔内的色散,获得了脉冲宽度为50 ps、重复频率为55.6 MHz、谱宽约为21 nm的高能量孤子脉冲输出.利用单模光纤在 2 μm波段的负啁啾色散特性,在进行功率放大之前将作为种子源的激光脉冲宽度展宽至 600 ps.最后,经过两级放大之后,获得平均功率约 23 W、脉宽为 660 ps 的激光输出.利用光栅对,对放大后的激光脉冲进行压缩,经测试压缩后的脉冲宽度约为 0.9 ps.

关键词:色散补偿;高能量;孤子种子源;主振荡放大;高功率;皮秒;掺铥;光纤激光器
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High Power Picosecond Thulium-doped Fiber MOPA with a High Energy Soliton Seed

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Abstract: Thulium-doped fiber Master Oscillator Power Amplifier (MOPA) was demonstrated for high power picosecond laser within the 2 μm wavelength range with a high energy soliton seed. The master oscillator was a passively mode-locked fiber laser, which can generate high energy soliton pulses with 50 ps pulse width, a repetition frequency of 55.6 MHz and a spectral width of ~21 nm by managing and optimizing its dispersion. The seed pulse was stretched to ~600 ps by a spool of passive fiber with anomalous dispersion before sent to two amplified stages. Finally, average power of about 23 W and pulse duration of 660 ps were achieved before the pulse compressor. With a grating-pair compressor, the chirped pulse can be compressed to about 0.9 ps.

Key words: Dispersion compensation; High energy; Soliton seed; MOPA; High power; Picosecond; Thulium-doped; Fiber laser
OCIS Codes: 230.2285; 060.2320; 140.7090; 140.3480; 140.3510; 190.4970

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0 Introduction

Tm-doped fiber lasers, as the widely accepted sources of 2 μm wavelength lasers, have drawn great attention due to a large number of interesting applications in various fields, such as super-continuum generation[1-2], mid-infrared spectroscopy generation[3-4], pump sources for longer mid-infrared optical parameter oscillators[4-5], material processing[4,6], medical surgery[4], optical communication[7] and so on. Mode-locked Tm-doped fiber lasers can provide high peak power and high time resolution in addition to the fiber laser's advantages of compactness, light-weightiness and robustness. Ultra-short pulse lasers at around 2 μm wavelength will open a new scenario of applications, such as precise material processing and ultrafast molecular imaging, etc.

In order to increase the output pulse energy and peak power beyond the mode-locked laser oscillators, fiber Master Oscillator Power Amplifier (MOPA) and Chirped Pulse Amplification (CPA) are the widely used routines[2,8-9]. After two stage pre-amplifiers and the final stage amplifier, average power of 78 W at the central wavelength of 2 011 nm was demonstrated before pulse compression from Thulium-doped fiber laser system[8]. After pulse compression, an average power of 36 W and a compressed pulse width of 790 fs were obtained. Instead of using complex chirped pulse amplifier technique, stable high average power picosecond pulse was generated from a simple thulium-doped all-fiber MOPA system[9]. The seed is a Semiconductor Saturable Absorber Mirror (SESAM) passively mode-locked picosecond thulium-doped fiber laser designed by utilizing a uniform narrow-band fiber Bragg grating on purpose to generate tens of picosecond pulse with a high repetition rate of 103 MHz, which was amplified to 20.7 W finally. A much higher average power, picosecond, thulium-doped, all-fiber MOPA with good thermal management was directly boost to average power of 120.4 W[2]. The laser oscillator was designed with high repetition rate of 333.75 MHz for the purpose of achieving high power in the power amplifier without the occurrence of high nonlinear effect and fiber facet damage.

Because the dispersion and loss of silica fiber to the pulse with 2 μm wavelength are relatively high, the choice of seed is very important to an all-fiber pulse MOPA system. A general mode-locked fiber laser produces a serial of pulses with single pulse energy of several tens pico-joule and several nanometer bandwidth, making them difficult to be stretched and amplified. Sometimes, three or four amplification stages are needed to increase the average power larger than ten watts. In this paper, we demonstrate a two-stage MOPA system seeded with a high energy soliton mode-locked fiber laser. The high energy soliton seed source was mainly obtained by inserting a piece of passive fiber with positive dispersion in the oscillator on purpose to compensate the dispersion. After only two amplifier-stages, we increase the final output power to about 23 W, which is only limited by our available pump power. Finally, a pulse duration of 0.9 ps was obtained with a grating pair compressor.

1 Theory analysis

Compare with the traditional Ytterbium-doped and Erbium-doped fiber laser, the thulium-doped fiber laser operating at 2 μm wavelength has relatively high thresholds to produce the Stimulated Brillouin Scattering (SBS) and the Stimulated Raman Scattering (SRS), so it has a greater advantage to produce the laser pulse with narrower linewidth or higher pulse energy. The thulium-doped fiber laser could obtain pulse with high single-pulse energy and ultra-short pulse width by mode-locked technology. The most important physical processes were Group Velocity Dispersion (GVD), nonlinear phase change induced by nonlinear effects and self-amplitude modulation effect of the absorber and so on in passively mode-locked fiber laser[10]. Due to the small mode size and large propagation length of the fiber, nonlinear effects would be happened under lower power. In order to obtain high power pulsed fiber laser, it is vital to manage and control the dispersion and nonlinear effect of the oscillator. The group velocity dispersion of conventional fiber is negative at 2 μm wavelength range. In order to achieve high energy laser output, a piece of passive fiber with positive dispersion was inserted in the oscillator.

Consideration of the dispersion, the nonlinear effects and the loss, the pulse propagation equation in fiber based on the so-called Generalized Nonlinear Schrödinger Equation (NLSE) can be described as follows[11-12]

$$\frac{\partial A}{\partial z}=-\frac{\mathrm{i}}{2}\beta_2\frac{\partial^2 A}{\partial T^2}+\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3}+\mathrm{i}\gamma|A|^2A-\frac{1}{2}\alpha A \quad (1)$$

with $T=t-z/v_g=t-\beta_1 z$

Eq. (1) describes accurately the pulse propagation in the passive fiber for pulses width $T_0>5$ ps. Among, A is the slowly varying amplitude of optical pulse envelope, z is the transmission distance along the fiber direction, t is the time coordinate, v_g is the group dispersion, the β_1, β_2 and β_3 parameters are the first-, second- and three-order dispersion coefficient, γ is the nonlinear coefficient of the fiber; α is the attenuation coefficient.

The signal will be amplified in the active fiber. Without consideration of the frequency mismatch, the pulse propagation equation can be simplified

$$\frac{\partial A}{\partial Z}=-\frac{\mathrm{i}}{2}\beta_2\frac{\partial^2 A}{\partial T^2}+\frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3}+\mathrm{i}\gamma\mid A\mid^2+\frac{1}{2}(g-\alpha)A+g\frac{T_2^2}{2}\frac{\partial^2 A}{\partial T^2}\qquad(2)$$

where $g=g_0(1+P_{av}/P_{sat})$ is the gain coefficient of the doped fiber, P_{av} is the average power of the pulse, P_{sat} is the saturation power of the gain medium. $T_2=1/\Delta\omega$ is the transverse relaxation time, $\Delta\omega$ is the gain bandwidth. The final output pulses of the fiber laser and amplifiers result from the combined effects of dispersion, nonlinear effects, gain, and loss and so on.

2 Experimental setup

The whole configuration of Tm-doped fiber MOPA is shown in Fig. 1, where DCF is dispersion compensation fiber; WDM is wavelength division multiplexer; SMF is single mode fiber; TDF is Tm-doped fiber; ISO is isolator; CPS is cladding power stripper; 1 550/793 is laser diode at 1 550 nm or 793 nm. The seed is a passively mode-locked Tm-doped fiber laser, one end of the seed oscillator is a semiconductor saturable mirror (BATOP GmbH Co.) with 10ps relaxation time and 25% modulation depth. The advantages of the mode-locked fiber laser are its high single pulse energy and broad spectral bandwidth. In order to obtain high energy soliton pulses, a short length of active fiber and a dispersive compensated passive fiber were inserted into the cavity as we have described[13]. As the seed source of MOPA system, it has advantages to avoid nonlinear effects and make the pulse stretching easier. Laser pulses from the oscillator travelled through a 400-meter-long single mode fiber (SMF-28 e^+), which have the anomalous dispersion ($V_g=\sim 42$ ps • nm^{-1} • km^{-1}) in the 2 μm wavelength region. An Isolator was spliced before pulse stretching to protect the seed source.

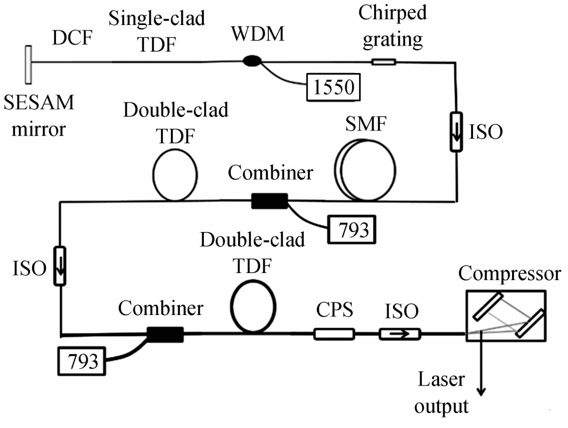

Fig. 1 Configuration of Tm-doped ultra-short pulsed fiber MOPA system

The whole amplification structure was comprised of two amplification stages. In the first-stage amplifier, the Tm-doped fiber (Nufern) was 2.1 m in length with 10/130 μm core/inner cladding diameter and 0.15/0.46NA (Numerical Aperture). The cladding absorption coefficient was about 3 dB/m at 793 nm. The Tm-doped fiber was directly fixed on a water-cooled plate by indium sheet and aluminum tape. The pump source were the fiber-pigtailed laser diodes (BWT Beijing Ltd.) at 793 nm with 105 μm fiber core diameter and 0.22NA. The residual pump light is filtered by splicing a piece of single mode fiber (SMF-28, 14 cm long) to the outlet of the Tm-doped fiber. In order to keep the one-way direction of the laser and suppress the Amplifier Spontaneous Emission (ASE), two isolators (AFR Hong Kong Ltd.) were inserted before the second stage amplifier, providing more than 45 dB isolation.

In the second-stage amplifier, we used Large Mode Area (LMA) fibers as the gain fiber to raise the nonlinear effect threshold during the amplification process. The double-clad Tm-doped silica fiber has a core/inner cladding diameter of 25/400 μm and a core/inner cladding numerical aperture of 0.09/0.46 (Nufern). The gain medium has a length of ~5 m (cladding absorption of 1.8 dB/m at 793 nm). About 63 W pump power from two laser diodes (BWT) was injected into the gain fiber through a multimode (6+1)× 1 fiber combiner (ITF). The 5 m gain fiber was coiled onto a 250 mm-diameter aluminum spool, which was cooled with water at ~18℃. The output fiber end of the thulium-doped Large Mode Area (LMA) fiber was angle cleaved with 8° to suppress parasitic oscillation. Due to the mode field mismatch of the fiber between the two amplification stages, we spliced a Mode Field Adaptor (MFA) between the two stage amplifiers.

3 Experimental result and analysis

The high energy soliton pulse from the mode-locked fiber oscillator was 50 ps in pulse duration and 21 nm for FWHM bandwidth as shown in Fig. 2 and Fig. 4. We observed the Kelly sidebands in the output spectra of the seed laser, which is the distinct characteristics for the dispersive soliton. Stable mode locking was realized at a repetition rate of 55.6 MHz, producing pulses with an average output power of about 60 mW. After the stretcher, the pulse duration of the seed oscillator was elongated to around 600 ps, the average power was reduced to 42 mW, but still large enough for amplification without worrying about parasitic noise in a high-gain amplifier.

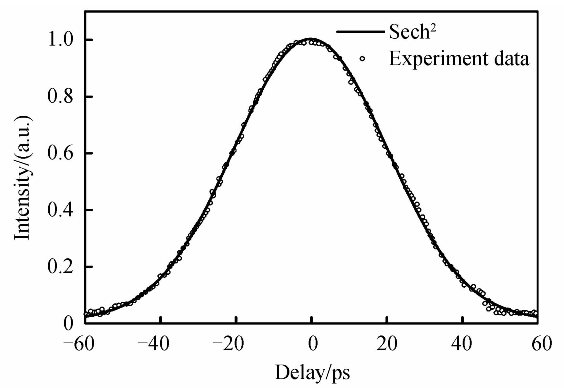

Fig. 2 Characteristic of high energy soliton pulse

In the first-stage amplifier, up to 24 W pump power from two pump laser diodes can be injected into the gain fiber directly through a (2+1)×1 multimode combiner(ITF). To avoid the nonlinear effects and ASE, we observed the output spectrum and pulse shape after two isolators with a mid-infrared analyzer (SIR 5000, SandHouse Co.), a 2.5 GHz Agilent Oscilloscope (DSO9254A) and a 3.5 GHz InGaAs detector. Finally, we limited the average output power of the first-stage amplifier to about 3.5 W at the pump power of 15.3 W.

To increase the nonlinear effect thresholds and achieve high output power, the second-stage amplifier was constructed with LMA fiber. Average output power of the final stage (measured by a power meter sensor S314C, Thorlabs) is shown in Fig. 3 as a function of incident pump power. Benefited from high signal power input to the second amplifier, high slope efficiency of 46.3% was achieved with the maximum output power of 23 W at the launched pump power of 63 W, corresponding to pulse energy of 0.4 μJ. The power increased linearly with the input pumping. The average power was limited only by our available pump source.

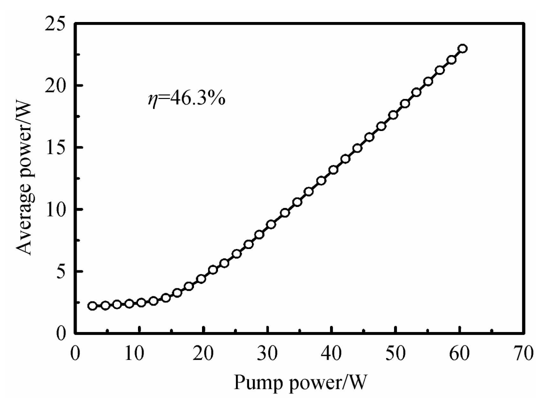

Fig. 3 Average output power versus incident pump power of the final amplifier

The laser spectra were compared for the oscillator, the first- and the second- stage amplifiers in Fig. 4. In the second-stage amplifier, the center wavelength was red-shifted to 1 954 nm from 1 940 nm for the oscillator. We think the red-shifted phenomenon of the amplified pulse was maybe due to the soliton self-frequency shift. The spectral width of the soliton pulse we used was wide enough, the high-frequency component would transfer energy to the lower-frequency component. Moreover, a small dip was observed in the center of spectral profile. The main distortion comes from the combined effects of gain narrow, gain saturation and re-absorption of Tm-doped fiber. Another reason may be the mode dispersion since the fiber used in the second stage amplification was not the single mode fiber and about 3 modes can be supported in it. Usually, the mode dispersion is more than 100 times larger than the material dispersion, leading to spectral distortion of amplified pulse.

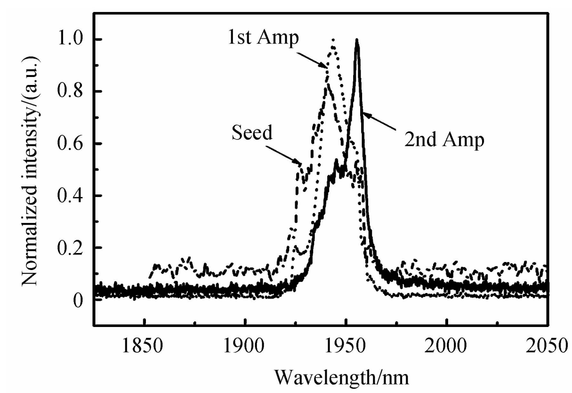

Fig. 4 Laser spectra from the oscillator, the first- and second- stage amplifier

We measured the pulse duration after the second-stage amplifier with a fast photo detector (Thorlabs) and a 2.5 GHz Digital storage oscilloscope (DSO9254A). The temporal pulse profiles from the two stage amplifiers were shown in Fig. 5, in comparison with that after the pulse stretcher. The pulse duration of the second-stage amplifier was given with 660 ps, which is slight bigger than that of the input pulse before amplification. The dispersion of silica fiber is negative for pulses around the 2 μm

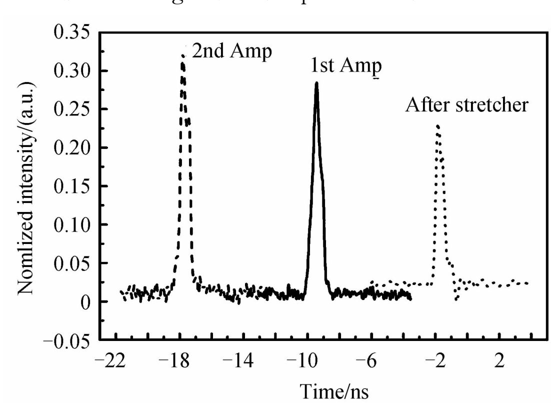

Fig. 5 Pulse profiles from the stretcher, the first- second- stage amplifier

wavelength, so that the short wavelength component is in the front part of the stretched pulse. In such a way, the gain saturation effect is balanced in some extent by the re-absorption of this short wavelength component. Significant distortion in the pulse profile does not exist.

The soliton pulse is not transform limited. As a stand-alone device, the pulse should be compressed for ultrafast applications[14-16], such as studying some ultrafast dynamics processes with Pump-Probe technology and pump sources for mid-IR light generation via nonlinear processes, etc. After the second amplifier, the pulse was compressed by a pair of gratings (OptiGrate), an autocorrelation trace was shown in Fig. 6, and giving 0.9 ps pulse duration (Pulse Check, APE). Up to 10.4 W output power was obtained after compressor with input power of about 23.0 W. We also observed the spectrum of the compressed pulse, it was almost same to the spectrum before compressed.

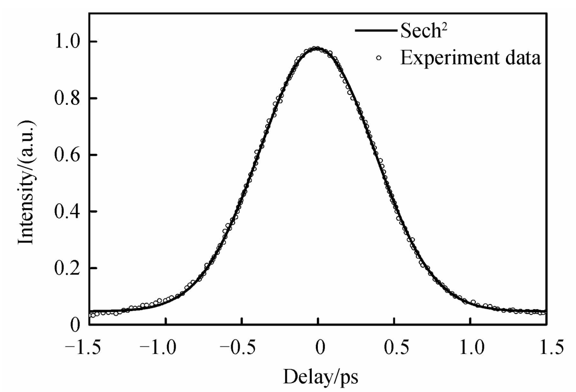

Fig. 6 Autocorrelation trace of single pulse after compressed

4 Conclusion

In conclusion, we have demonstrated a 2 μm wavelength ultra-short pulse MOPA system, in which a high energy soliton mode-locked Tm-doped fiber laser was used as the seed source. The soliton seed source with high power output was a big advantage to the Tm-doped fiber amplifier, because the saturation gain of Tm-doped silica fiber was much higher than that of Yb-doped silica fiber. Using only two stage amplifiers, we obtained 23 W average power with the repetition rate of 55.6 MHz and 660 ps pulse duration before compression. Due to the revised effect of re-absorption and gain saturation to the negative chirped pulse, the spectral and temporal distortions were not serious. With a pair of compressed gratings, the pulse can be compressed to 0.9 ps. The parasitic oscillation and nonlinear effects were not observed. Power scaling to high average can be expected with more pump power.

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