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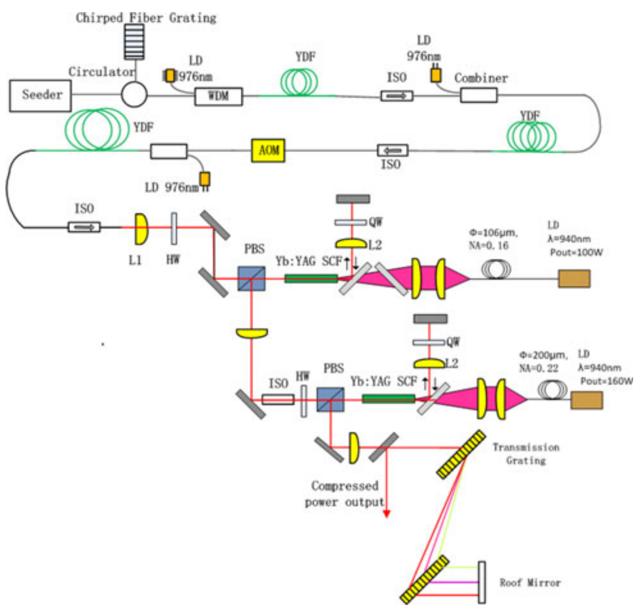

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Hundred Micro-Joules Level High Power Chirped Pulse Amplification of Femtosecond Laser Based on Single Crystal Fiber

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Abstract: We demonstrate a hundred micro-Joules level femtosecond laser system based on a compact and simple two-stage Yb:YAG single crystal fiber chirped pulse amplification system which delivers compressed power of 15.57 W, pulse width of 715 fs. The different amplification performance with different input seed power is experimentally studied. A maximum direct amplified power output of 44 W at 100 kHz is obtained for an input seed power of 12 W. To the best of our knowledge, this is the highest average power of femtosecond laser based on single crystal fiber at hundred micro-Joules energy level.

Index Terms: Fiber amplifier, single crystal fiber, femtosecond laser, chirped pulse amplification.

1. Introduction

Ultrafast lasers have already established a versatile application in science and industrial application, such as ultra-stable frequency combs [1], high-harmonic generation [2] and micromachining [3]–[5]. All kinds of laser systems are used to generate the femtosecond lasers. Solid-state laser amplifiers suffer from the thermal distortions and relatively low laser amplification gains. In solid-state lasers, Innoslab laser and thin disk laser have made some breakthroughs. Amplifiers based on Innoslab laser [6] have shown an impressive performance in terms of average power at high repetition. 1.1 kW, 615 fs laser is obtained at the repetition rate of 20 MHz. However, their inherent complexity and multiple passes of the signal with no optical waveguide pose a challenge for its stability and wider industrial applications. The thin disk laser has achieved 200 W, 210 fs pulses at 100 kHz [7], however, considering the low amplification gain of the single pass, it needs to employ the regenerative amplification, which adds the system's complexity. Fiber laser is another effective way to generate high power femtosecond laser, because it possess an average power scaling potential owing to their good thermal management due to high surface-to-volume ratio [8]. However, the signal confined in small-cross-section cores induces nonlinear effects, such as self-phase modulation, self-focusing and stimulated Raman scattering, which in turn limit the peak power and the pulse energy. In order to obtain high energy output, the large-mode-area fibers combined with chirped pulse amplification (CPA) technology are frequently employed to realize this goal [9]–[11].

Single crystal fiber (SCF) exhibits an aspect ratio of a short rod fiber or a thin and long crystal, which allows higher average powers than with conventional crystals and higher energy than with fibers in pulsed regime. Typically the diameter is less than 1 mm while the length is several tens of millimeters. Owing to the high surface-to-volume ratio, SCF amplifier can provide a good thermal management. Relatively short interaction length and large signal beam diameter minimize the nonlinear effects in ultrafast laser amplification which is very useful in scaling the femtosecond laser pulse energy. During the SCF amplification, the pump beam delivered by a fiber-coupled laser diode is confined by the guiding capacity of the SCF whereas the signal beam propagates in a manner similar to the one in free space, this characteristic improved the amplification gains due to the better overlap between the pump beam and signal beam. So it is a promising technology in ultrafast laser amplification with a compact size and simplicity, by employing this kind of amplifier, the system is more robust and less expensive.

High power laser amplification with SCF at high repetition rate were demonstrated in [12], [13]. By using three successive Yb:YAG SCF amplifier, laser power of 100 W and pulse duration of 750 fs were obtained at a repetition rate of 20 MHz [12], corresponding to a pulse energy of 5 μJ. Another femtosecond laser system employed two stages of Yb:YAG SCF amplifier, laser power of 160 W and pulse duration of 800 fs were obtained at 83.4 MHz [13], which corresponds to a pulse energy of only 1.918 μJ. These two high power laser systems were CPA free due to its low pulse energy, which proves the power scaling potential of SCF. Through direct amplification of femtosecond laser by using one stage SCF amplifier, a 12 W, 330 fs pulses was obtained at 30 MHz [14]. A high energy femtosecond CPA laser system based on Yb:YAG SCF obtained 1 mJ pulse energy at 10 kHz proves the possibility in high energy ultrafast laser amplification, but the SCF amplifier without describing the high energy pre-amplifier which can output 150 μJ at 10 kHz [15].

In this work, we report a fiber chirped pulse amplification system by employing two stages of Yb:YAG SCF amplifier. An average power of 15.57 W and compressed pulse duration of 715 fs are obtained at a repetition rate of 100 kHz. This corresponds to a single pulse energy of hundred micro-Joules. The different amplification performance with different input seed power is experimentally studied. A maximum amplified power of 44 W at 100 kHz is obtained when the input seed power is 12 W. To the best of our knowledge, this is the highest average power of femtosecond laser based on single crystal fiber at hundred micro-Joules energy level.

2. Experimental Setup

Fig. 1 shows the schematic diagram of the setup for the 100 kHz CPA laser system. It consists of an oscillator, a pulse stretcher, a pulse picker, multiple stages of amplifiers, and a pulse compressor. The oscillator was a typical mode-locked ytterbium (Yb)-doped fiber oscillator based on semiconductor saturable absorber mirror, which was designed to deliver 40.7 MHz mode-locked pulses with an average output power of 20 mW and a spectral bandwidth of 8 nm. The pulse duration of the seed laser was stretched to nearly 600 ps by a chiped fiber bragg grating so as to lower the nonlinearity in the amplification process. A polarization maintaining single mode Yb-doped fiber with a core of 6 μm, and a polarization maintaining double cladding fiber with a core diameter of 10 μm was used to boost the average power to 2 W. To get higher pulse energy in later amplification a fiber coupled acoustic modulator with average power handling capability of 5 W is then used as a pulse picker to reduce the pulse repetition rate. When the pulse repetition is reduced to a few hundred kilohertz, the average power drops to only a few milliwatts. A 25-μm core polarization maintaining double cladding fiber amplifier is built to boost the average power to about 1.4 W at 100 kHz.

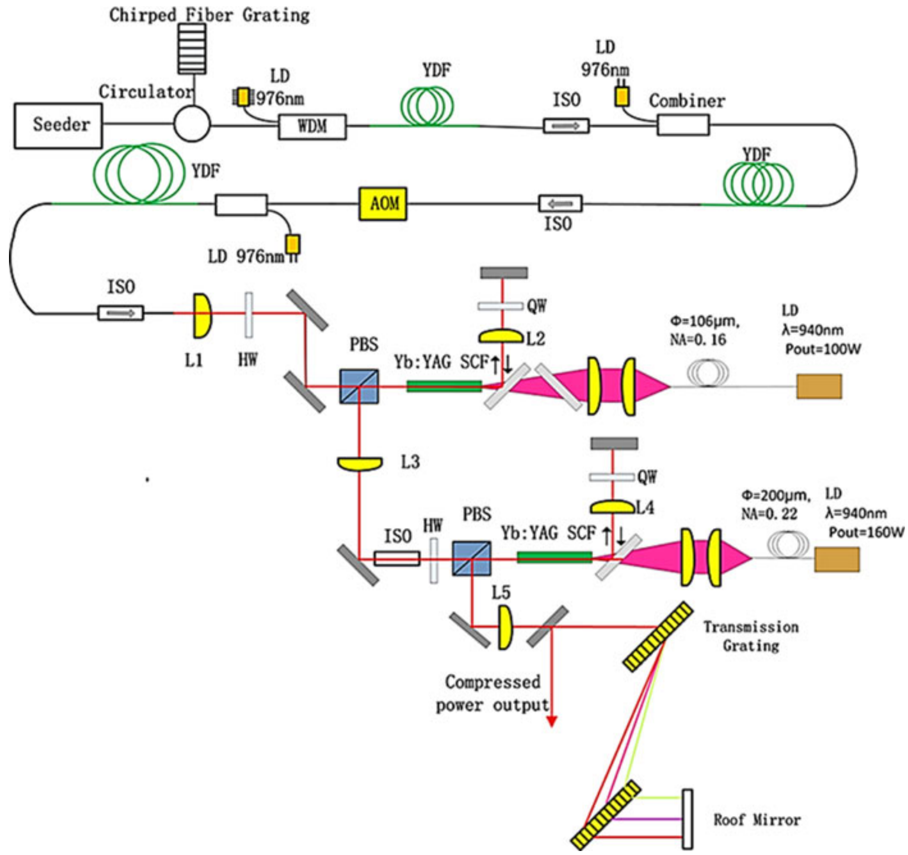

Fig. 1. Schematic diagram of the high energy chirped-pulse amplification system WDM: wavelength-division multiplexer; YDF: Yb-doped fiber; ISO: isolator; AOM: acoustic-optic modulator; LD: laser diode; HW: half-wave plate; PBS:polarization beam splitter; L1: Lens 1; Yb:YAG SCF:Yb:YAG single crystal fiber; QW: quarter-wave plate; L2: Lens 2.

The Yb:YAG single crystal fibers of two-stage amplifiers have the same parameters, e.g., 30 mm long, 1 mm diameter with a 1 at. % doping rate, whose facets are anti-reflection coated for both the signal and the pump wavelength to prevent parasitic lasing and excess losses at the interfaces. The SCF mount is water-cooled at a temperature of 17 °C. In the first amplification stage, the laser output from the polarization maintaining double cladding fiber is collimated into the SCF with a beam spot diameter of 400 μm. A 100 W, 940 nm fiber coupled laser diode with core diameter of 106 μm and NA of 0.22 is employed to end pump the SCF. The pump is imaged inside the SCF with a magnification factor of 3.75 using two plano convex lens. A pair of dichroic mirrors is used to separate the incoming pump beam from the first-pass output of the signal beam. To perform a second pass of amplification into the gain module, the signal waist after the first pass is imaged on a highly reflective plane mirror using a lens (L2) operating in f–f configuration. To avoid damaging the single crystal facet, the lens position should be carefully adjusted to guarantee that the beam waist is not imaged in the facet. The output laser of the single pass is reflected by a highly reflective mirror coating at 0 degree. A quarter wave plate is inserted before the reflective mirror to rotate the polarization direction by 90° when the laser passed the quarter waveplate twice, which allows extraction by the polarizing cubic beam splitter. The laser output from the first-stage SCF amplifier is collimated by a lens (L3). The double pass configuration is nearly the same except for the pump structure. The pump source is a 160 W, 940 nm fiber coupled laser diode with a core diameter of 200 μm and NA of 0.22. We choose another two plano convex lens with a magnification factor of 2 to inject the pump beam into the crystal.

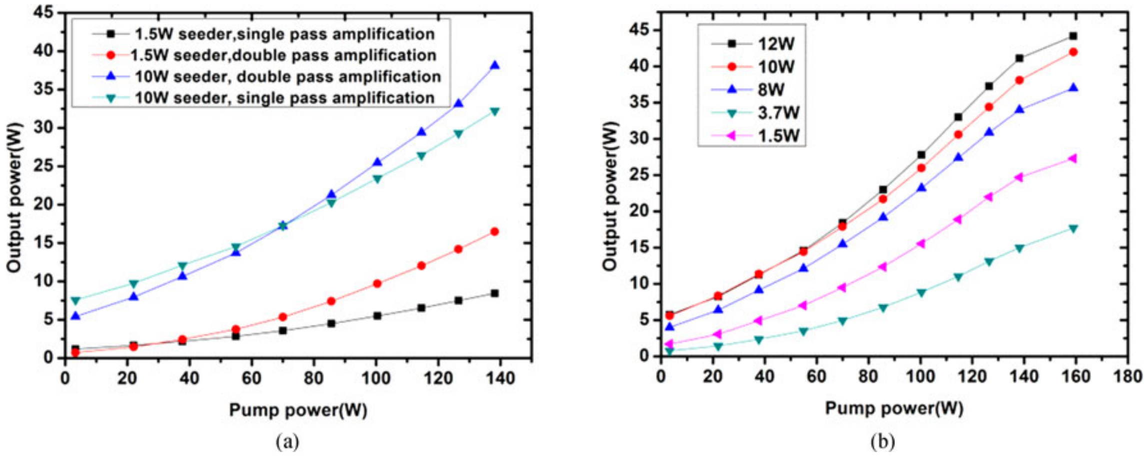

Fig. 2. Amplification performance (a) Single-pass and double-pass amplification performance versus incident pump power (b) Amplification performance of double-pass configuration with different seeding power.

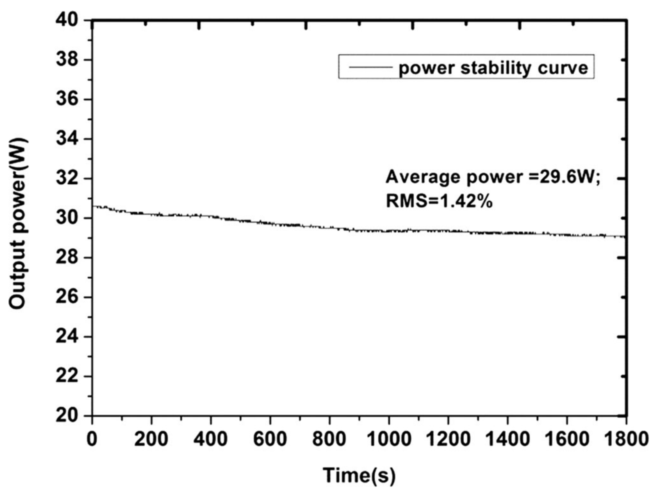

Fig. 3. Power stability measurement result.

The amplified power is then collimated by a plano convex lens L5 with a focal length of 500 mm, the amplified pulses are compressed by a conventional transmitted grating pair in a double-pass configuration. A pair of 1450 groove mm^{-1} transmitted gratings located at a distance of around 3.40 m is used to compress the pulse.

3. Experimental Results and Discussion

In the first stage of SCF amplification, by injecting about 100 W pump power and 1.4 W seed power at a repetition of 100 kHz, the maximum laser output of 14.6 W is obtained by the double-pass amplifier configuration. By controlling the pump power of the first stage of SCF, we explored the single-pass and double-pass amplification performance of the second stage with input seed powers of 1.5 W and 10 W, respectively. As shown in Fig. 2(a), we can see that double pass configuration have much better performance for small signal amplification. For an input seed power of 10 W, the output power difference is not so obvious, this is because the absorption of SCF crystal of signal power. But we can find that the slope efficiency of double-pass configuration is higher than that of

Fig. 4. Beam profiles of the amplified laser (a) double-pass amplification case with an output power of 38 W; (b) single-pass amplification case with an output power of 34 W.

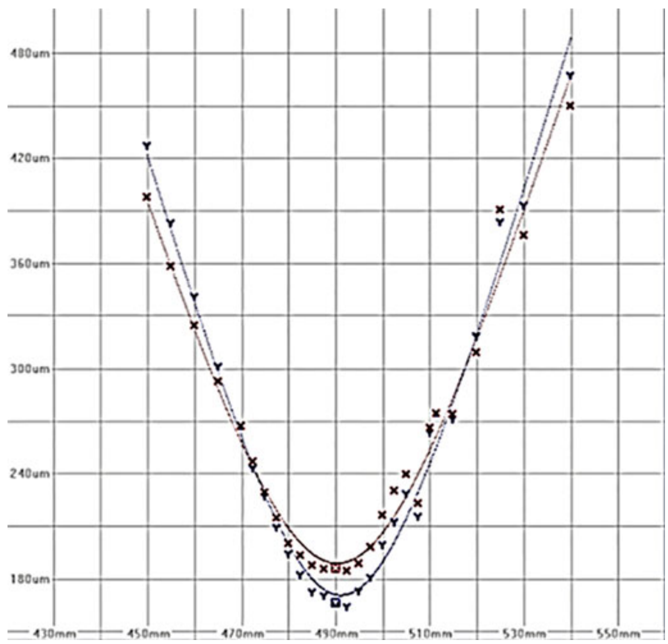

Fig. 5. The beam quality measurement.

single-pass one. Therefore, the performance of double-pass amplification can be improved with the use of a high power 940 nm laser diode. Furthermore, the amplification performance of double-pass configuration with different seeding power is also studied. A maximum amplified output power of 44 W is obtained for an input seed power of 12 W which corresponds to a pulse energy of as high as 440 μJ. When the amplified output power reaches around 30 W, we also test the power stability for a total lasting time of 30 min. The RMS value of the power stability is about 1.42%. The power drops slightly at the beginning of measurement resulting from the spectrum shift of the pump laser diode, the spectrum center is slightly deviated from the optimal pump wavelength of 940 nm, which is observed by the spectrometer. The laser output power becomes stable when the pump laser diode is thermally stable.

During the amplification, the beam profile is also carefully detected in the double-pass configuration. As shown in Fig. 4, when the laser is amplified to about 38 W, the beam profile has a little distortion. But in the single-pass amplification, the laser exhibits an excellent beam profile for an amplified output power of 34 W. It needs to make a better alignment in the double-pass amplification to improve the beam profile, because when the second-pass laser beam from the SCF is slightly misaligned, the total amplification gains as well as the output power experience no obvious change. However, the gain extracted from SCF in space will be different, which will in turn affect the output laser beam profile. The beam quality of the single pass amplified power of 34 W is also measured

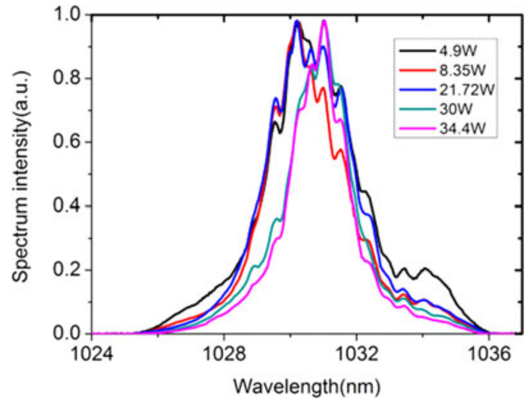

Fig. 6. The spectra at different output power.

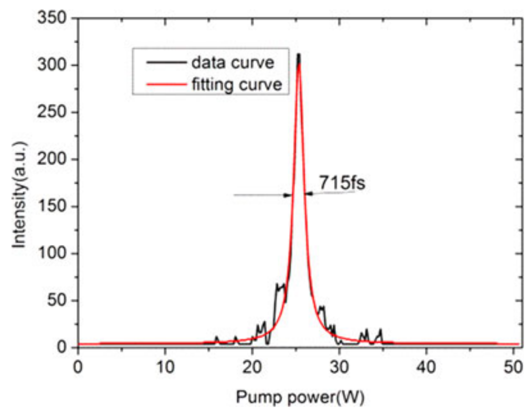

Fig. 7. Autocorrelation curves of the pulse.

by the Spiricon M2-200 s, as shown in Fig. 5. The measured M^2 values are 1.241 in the horizontal direction and 1.220 in the vertical direction, respectively.

The spectrum evolution during the single pass amplification with 12 W seeding power is measured with an optical spectrum analyzer (YOKOGAWA AQ6370C) and the result is shown in Fig. 6. The gain narrowing effect is observed and when the laser is amplified to 34.4 W, the spectrum width is decreased to about 2 nm. The reason that gain narrowing effect occurs is because the emission spectrum width of Yb:YAG is relatively narrow. Explicitly, the emission spectrum width is less than 8 nm at the cooling temperature of 17 °C. Moreover, the emission spectrum of Yb:YAG is not flat. Specifically speaking, the central wavelength component has a higher gain than the off-center wavelengths. As a result, the spectrum width is narrowed during the amplification. The output laser is then collimated and compressed by a 1450 groove mm^{-1} transmitted gratings. The power injected into the compressor is 34 W. A pulse width of 715 fs together with an average power of 15.57 W are obtained after the compressor. Fig. 7 shows the measured autocorrelation curve by APE pulse check autocorrelator. The FWHM width of the autocorrelation curve is 1.431 ps which corresponds to a retrieved pulse width of 715 fs under a Lorentzian fitting. The whole compression efficiency of 45.79% is relatively low, because the single-pass diffraction efficiency of the available grating is less than 90%. The gratings from Lightsmith which has the single-pass diffraction efficiency of more than 93% or the chirped volume Bragg grating with whole efficiency of more than 85% from Optigrate can further greatly scale the pulse energy. Considering an injected power of 34 W and a diffraction efficiency of 85%, we can obtain an output power of 28.9 W corresponding to a pulse energy of 289 μJ. Another way to scale the pulse energy is to use a high power laser diode with a central wavelength of 940 nm. In our experiment, the parameters of the laser diode are not so ideal. The spectrum width is 5 nm and more importantly, the central wavelength shifts at different pump current. 940 nm pump laser diode is ideal because the absorption peak of Yb:YAG SCF is around 940 nm. Unfortunately, at the 160 W power output, the central wavelength of the laser diode has shifted to 943 nm. So in the Fig. 2(b), a little saturation can be observed.

4. Conclusion

In conclusion, a hundred micro-Joules level femtosecond chirped-pulse amplification system based on a compact and simple two-stages Yb:YAG SCF amplifiers is demonstrated. Pulses with an average power of 15.57 W and pulse width of 715 fs are obtained at 100 kHz. The different amplification performance with different input seed power is experimentally studied. A maximum amplified output power of 44 W at 100 kHz is obtained for the seeding power of 12 W. To the best of our knowledge, this is the highest average power ever obtained in SCF based laser amplification system which delivers hundred micro-Joules pulse energy. The reported laser amplification method is helpful in finding the balance between high average power and high pulse energy in femtosecond laser systems.

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