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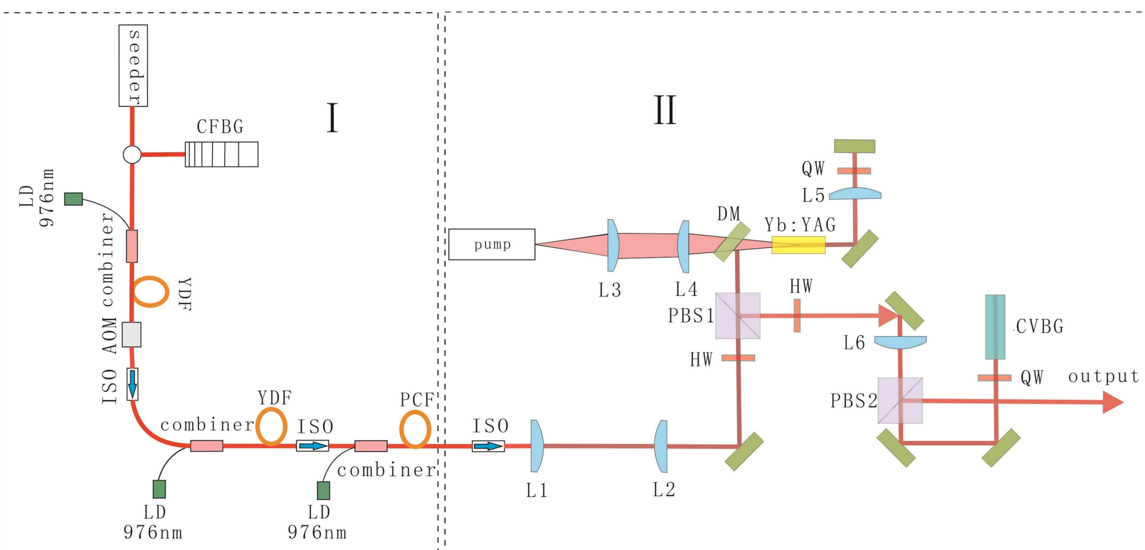

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23.9 W, 985 fs Chirped Pulse Amplification System Based on Yb:YAG Rod Amplifier

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Abstract: A stable and simple Yb:YAG rod amplifier based on chirped pulse amplification in a water cooling system has been demonstrated. The output power of 38 W at a 250 kHz repetition rate with a spectrum width of 4 nm centered at 1030 nm, which support Fourier-transform limited pulse duration of 389 fs has been generated. The compressed power of 23.9 W with pulse duration of 985 fs has been obtained with a chirped volume Bragg grating compressor. The power stability is measured to be 1.414% when the output power is 35 W. The system is worthwhile to popularize for its good performance and inexpensive cost.

Index Terms: Yb:YAG rod, chirped pluse amplification, ultrafast pulse.

1. Introduction

High average power, high repetition rate ultrafast lasers have a promising prospect in science and industrial applications, such as attosecond pulse generation, materials processing and coherent control [1]–[3]. Scientists have always been struggling to find ways to increase the average power and pulse energy of ultrafast lasers. Yb dopped fiber laser is stable and reliable and is proper for the generation of high average power for its long interaction length. For instance, 830 W, 640 fs at 78 MHz has been obtained from a fiber chirped-pulse amplification system [4]. However, it corresponds to pulse energy of only 106 nJ. Although the large surface-volume ratio makes fiber laser a good choice for high average power generation, the small cross section of the fiber limits the energy of pulse due to the nonlinear effect, such as self-phase modulation and stimulated Raman scattering during the amplification. Yb doped YAG crystal exhibits great advantages on the generation of high repetition rate, high pulse energy ultra-short pulse for its good thermo-optical properties and its wide emission spectrum. However, the high saturation fluence of Yb:YAG at room temperature(∼9 J/cm^2) [5] raise the requirement for heat dissipation. Cryogenic cooling technology is an effective way to produce high power, high repetition rate laser because Yb: YAG crystal's quasi-three-level system in room temperature will be converted to four level system in cryogenic temperature [6], which is more efficient in laser amplification. Furthermore, the improved thermal-optical properties reduce the thermo-optical effect of material in cryogenic temperature. Many breakthroughs have been achieved under the cryogenic cooling system in recent years. Based on cryogenic cooled Yb:YAG amplifier, 287 W, 5.5 ps at 78 MHz has been acquired, in which the optical-optical efficiency reaches 41% when the pump power is 700 W [7]. 40 mJ at 2 kHz repetition rate has also been obtained based on two-stage cryogenic chirped-pulse Yb:YAG amplifier [5], in which the beam quality is below 1.1. In addition, 250 W output power at 100 kHz repetition rate with a super–Gaussian spatial [8] has been demonstrated based on four pass Yb:YAG amplification, the extraction efficiency reaches 50% with cryogenically temperature when the pump power is 515 W. All these systems are efficient at cryogenic temperature. However, the emission spectrum of Yb:YAG in cryogenic temperature is 1.5 nm, which is not suitable for the generation of sub-ps pulses. In addition, the complex cooling system is not appropriate for generalization.

Innoslab amplifier and thin disk amplifier are also popular for their good thermal management. 1.1 kW, 615 fs at 20 MHz has been obtained based on cascading Innoslab amplifier in room temperature [9]. Then, 250 W sub-ps pulse duration at tens of kHz centered at 1030 nm has been achieved based on Innoslab amplifier [10], which corresponds to maximum pulse energy of 20 mJ. Based on two stage cascaded thin disk multipass amplifier, 14 kW at 100 kHz repetition rate laser has been produced [11], which corresponds to pulse energy of 140 mJ. The above two kind of amplifiers are appropriate for the generation of high power, high energy ultrafast laser for their good cooling performance. However, as for Innoslab amplifer, the signal has to pass many times in the gain medium without waveguide, which poses a challenge to obtain high beam quality pulses. In the meanwhile, thin disk amplifier suffers from phase front aberrations [12] and is not commonplace for its difficult cooling technology and expensive cost.

Yb doped single crystal fiber (SCF) is another emerging technology to scale the power and energy of laser. SCF are long thin rods in which the pump propagates in waveguide manner and the seeder travel freely without reflection. The length is several tens of millimeters whereas the diameter is approximately 1 mm, which permit larger beam diameter than conventional fiber to reduce nonlinear effect. 160 W, 800 fs pulse duration has been obtained at repetition rate of 83.4 MHz by two stages of Yb:YAG SCF amplifier without CPA [13], which employed end pump in the first stage and bidirection pump in the second stage. 28 W average power, 2.5 mJ pulse energy has also been acquired based on two stage double pass amplifier [14]. However, the area of end face is still too small which limit the output parameter for the optical breakdown of AR coating.

In this work, we report a compact and stable high beam quality CPA system based on water cooled Yb:YAG rod amplifier. A maximum power of 38 W is obtained at repetition rate of 250 kHz. The amplified power shows pulse duration of 350 ps and spectrum width of 4 nm centered at 1030 nm, which corresponds to Fourier transform-limited pulse duration of 389 fs. The M_x^2 and M_y^2 is 1.176 and 1.062 when the output power is 35 W, which result from the accurate collimate of the pump and the seeder. 35 W is seeded into the CVBG whose compression parameter is 106 ps/nm to compensate the chirp and 23.9 W, 985 fs has been obtained. The pulse duration will be even shorter by using a CVBG whose compression parameter is 100 ps/nm to match the CFBG in the front end whose broaden parameter is also 100 ps/nm. The amplification module shows good amplification performance, which is a promising substitute of single crystal fiber (SCF).

2. Experiment Setup

Fig. 1 shows the setup of the Yb:YAG rod amplifier system. The first part is a homemade all-fiber laser starting at a Yb doped mode-locked oscillator based on semiconductor saturable absorption mirror operating at 40.7 MHz. Then the output power is broaden to hundreds of ps by a Chirped Fiber Bragg Grating (CFBG) stretcher whose broaden parameter is 100 ps/nm to lower the nonlinear effect in the next fiber amplification stages. Then the broaden pulses is injected into the double-clad fiber whose inner diameter is 101.25 μm to be amplified. To obtain higher pulse energy, the pulse repetition rate is reduced from 40.7 MHz to 250 kHz by the acoustic-optic modulator (AOM). After being amplified by the polarization-maintaining single mode amplifier and the photonic crystal fiber (PCF) whose inner diameter is 40 μm, output power of 7.4 W at 250 kHz repetition rate has been obtained.

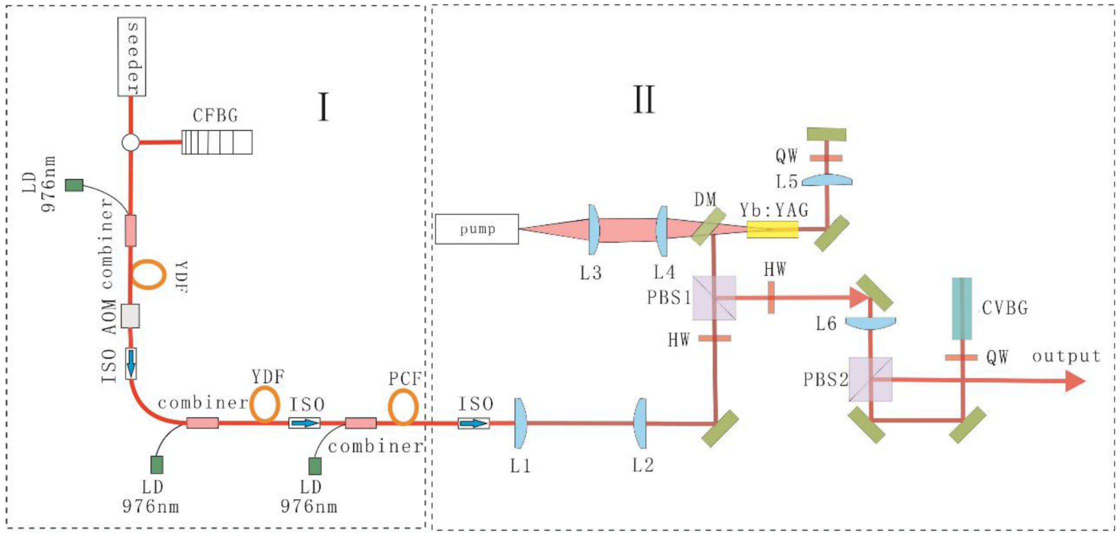

Fig. 1. Schematic diagram of the Yb:YAG amplifier. CFBG: Chirped Fiber Bragg Grating; LD: laser diode; YDF: Yb doped fiber; AOM: acoustic-optic modulator; L1: lens 1; L2: lens 2; HW: half-wave plate; PBS: polarization beam splitter; Yb:YAG: Yb:YAG rod; QW: quarter-wave plate; LD: laser diode; DM: dichroic mirror; CVBG: Compression Volume Bragg Grating.

The second part shows the Yb:YAG amplifier and the simple compression device. The gain material is a bonded Yb:YAG rod with length of 70 mm and diameter of 3 mm. The signal laser was focused through a 14 mm long non-doped YAG on the center of Yb doped YAG, which is 24 mm long with doping rate of 2 at%. The exit end is non-doped YAG with length of 32 mm. The facets of rod are anti-reflected for both the signal and the pump wavelength to avoid parasite lasing. The seeder is downsized from 3200 μm to 430 μm by a pair of plano-convex lens whose focal length are 500 mm and 100 mm respectively, then the seeder is reflected into the middle of the Yb:YAG rod with focused beam spot diameter of 430 μm by a dichroic mirror. A 135 W, 940 nm fiber coupled laser diode with core diameter of 200 μm and NA of 0.22 is employed to front pump the crystal. The end face of the pump is imaged into the middle of the rod with focused pump beam diameter $\sim$400 μm by a pair of plano convex lens. A dichroic mirror (HT@940 nm, HR@1030 nm) is used to separate the pump and the seed pulses. The signal is imaged on a high reflective mirror by a lens with focal length of 30 mm to insure the beam can propagate back along the incident optical path. A quarter-wave plate (QW) is used to rotate the polarization of the signal by 90 degree when the pulse passes twice to guarantee the amplified power can be output by the PBS. The amplified power is focused in the reflective type CVBG by a Lens (lens 6) to compensate the dispersion. Another quarter-wave plate is inserted after the second PBS to insure that the compressed pulse can be output by PBS. The crystal is cooled by flowing water directly with temperature of 279 K in this experiment.

3. Results

As shown in Fig. 2(a), the slope efficiency of the double pass amplification is obviously higher than the single pass amplification. In the double pass, a maximum output power of 38 W is obtained at pump power of 135 W by injecting seed power of 7.4 W while a maximum output power of 19.1 W is obtained when the seed power is 1.45 W. The gain is 13.1 when the seed power is 1.45 W, which is much higher than the single pass gain of 4.4. The extraction efficiency is 22.6% when the seed power is 7.4 W. The amplification performance of double pass for different seed power is shown in Fig. 2(b). With seed power increased from 0.2 W to 7.4 W, the conversion efficiency increased from 8% to 22.6%. The slope efficiency continue to grow at maximum pump power for single and double

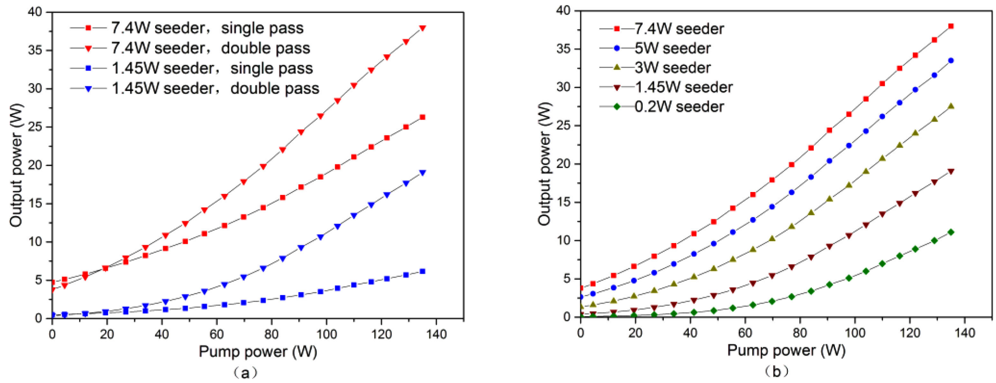

Fig. 2. Amplification performance of: (a) single and double pass output power versus pump power. (b) output power versus pump power for different seed powers in double pass configurations.

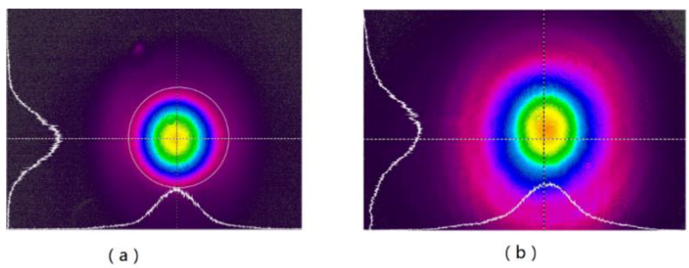

Fig. 3. Beam profile of the amplified power of double pass when the seed power is 7.4 W. (a) output power of 30 W; (b) output power of 35 W.

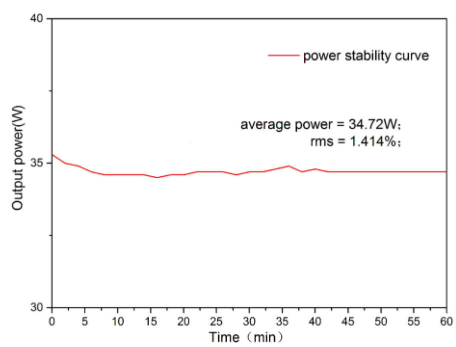

Fig. 4. Instability of the output power.

pass, which means the optical-optical efficiency can be improved by increasing the pump power. However, the beam quality deteriorate for the thermo-optical effect if we continue to increase the pump power, which is because the gain of the center of the rod begin to decrease and the gain of the surrounding of the rod begin to increase with higher pump power.

Beam profile of amplified laser in double pass is shown in Fig. 3. The beam profile is excellent when the output power is 30 W, as shown in Fig. 3(a). However there is a little distortion at 35 W for thermal-optical effective, as shown in Fig. 3(b). The power stability is measured for 60 minutes when the output power is 35 W, which is 1.414%, as shown in Fig. 4. The power drops from 35.3 W to 34.7 W in the first 10 minutes, which is for the wavelength drifting of the pump laser, and then is

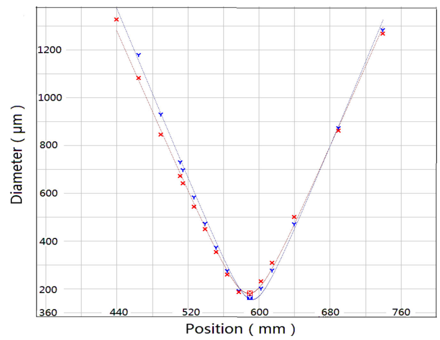

Fig. 5. Beam quality of 35 W when the seed power is 7.4 W.

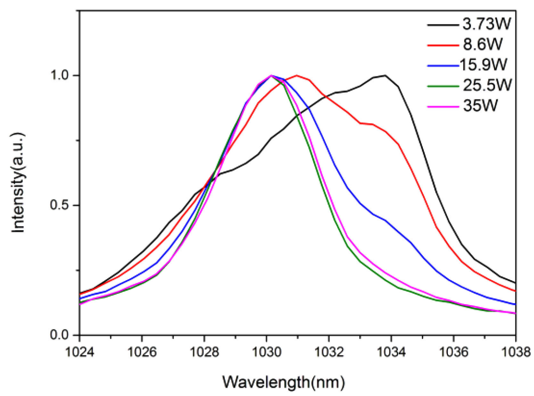

Fig. 6. The development of spectrum with the increase of output power when the seed power is 7.4 W in the double pass.

stabilized at 34.7 W. The beam quality is measured by the Spiricon M2-200s. The M_x^2 and M_y^2 of 35 W is 1.176 and 1.062 respectively, as shown in Fig. 5.

The development of output spectrum in double pass is shown in Fig. 6. When the output power increased from 3.73 W to 25.5 W, the central wavelength of spectrum shifts from 1033 nm to 1030 nm, which is because the emission spectrum of Yb:YAG is centered at 1030 nm. Gain narrowing is also observed. The seeder exhibits spectrum width of 10 nm whereas the output pulse shows spectrum width of 4 nm when the output power is 25.5 W. As the amplified power increases from 25.5 W to 35 W, the central wavelength of spectrum is stabilized at 1030 nm with no gain narrowing, which means the output spectrum coincidents with the emission spectrum of Yb:YAG. The 4 nm spectrum width centered at 1030 nm corresponds to Fourier transform limited pulse of 389 fs.

The pulse duration before compression is measured by the oscilloscope whose type is SDA11000 produced by LeCroy. The photodetector model is KG-PD-10G which supports 10 GHz bandwidth in 3 dB. As shown in Fig. 7(a), the pulse duration is 752 ps before amplification. However, the pulse shows pulse duration of 330 ps when the output power is 35 W, which is because gain narrowing of spectrum result in the narrowing of pulse duration. 35 W has been reflected into the CVBG whose compression parameter is 106 nm/ps to be compressed. The autocorrelation trace is shown in Fig. 7(b), which corresponds to pulse width of 985 fs. The pulse width will be even shorter if the CVBG is 100 nm/ps to realize the second-dispersion match of the output pulse and the CVBG. The compression efficiency of CVBG has also been explored.

Considering the destroy threshold of the CVBG, the output laser is concentrated to be 1.5 mm. 1.82 W has been transmitted and 1.04 W has been absorbed when the input power is 3.73 W

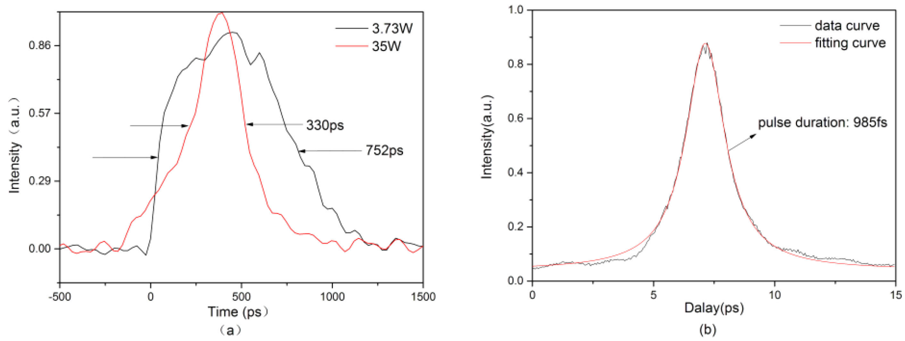

Fig. 7. (a) Pulse duration of seed power of 7.4 W (b) Autocorrelation trace of the compressed pulse and amplified power of 35 W.

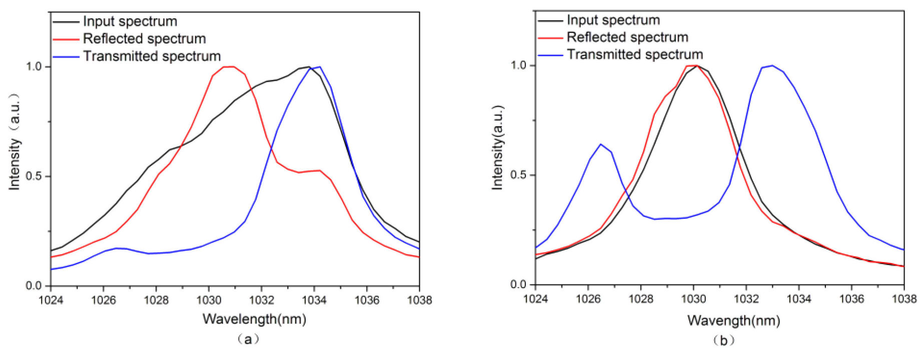

Fig. 8. Spectrum of the compressed pulse,transmitted pulse and the reflected pulse when the pump power is (a) 0 W; (b) 135 W.

without pump power, which corresponds to compression efficiency of 27.9%. The low compression efficiency of the seed power is because the spectrum of the seed pulse is 10 nm, which is much wider than the reflection spectrum of CVBG (5 nm), as shown in Fig. 8(a). Fig. 8(b) shows the the spectrum of input pulse, transmitted pulse and the reflected pulse of CBVG when the input power is 35 W. 5 W has been absorbed and 6.1 W has been transmitted by the CVBG during the compression. 23.9 W compressed power has been obtained at last, which corresponds to compress efficiency of 68.2%. The compression efficiency will be improved further if the spectrum of the seed power is filtered before amplification.

4. Conclusion

In conclusion, we have shown that the 70 mm long, 3 mm diameter water cooled bonded Yb:YAG module is a promising pulse amplifier. With homemade all fiber laser which can output power of 7.4 W as the seeder, a maximum amplified output power of 38 W has been achieved at 250 KHz, which corresponds to optical-optical efficiency of 22.6%. The beam profile is good when the output power is 35 W. The spectrum of output power of 35 W is 4 nm, which corresponds to Fourier-transform limited pulse duration of 389 fs. With 35 W reflected into the CVBG, 23.9 W compressed power is obtained corresponding to pulse duration of 985 fs, which will be even shorter with accurate chirp compensation. The compact and stable ultrafast laser system is worthwhile to popularize for its good amplification characteristic and inexpensive cost.

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