Research Article | Vol. 31, No. 8 / 10 Apr 2023 / Optics Express 12212

Optics EXPRESS

High average power amplification of femtosecond pulses based on the Yb:CaYAlO$_4$ crystal

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Abstract: In this paper, we demonstrated the direct amplification of femtosecond pulses with the Yb:CaYAlO$_4$ crystal for the first time. A compact and simple two-stage amplifier delivered amplified pulses with the average powers of 55.4 W for σ-polarization and 39.4 W for π-polarization at the center wavelengthes of 1032 nm and 1030 nm, corresponding to 28.3% and 16.3% optical-to-optical efficiencies, respectively. These are to the best of our knowledge the highest value achieved with a Yb:CaYAlO$_4$ amplifier. Upon using a compressor consisting of prisms and GTI mirrors, a pulse duration of 166-fs was measured. Thanks to the good thermal management, the beam quality (M^2) parameters <1.3 along each axis were maintained in each stage.

1. Introduction

Ytterbium (Yb)-doped all-solid-state ultrashort pulse amplification systems with high repetition rate and high average power are widely used in some promising applications, such as high harmonic generation [1], mechanical or chemical material processing [2] and Terahertz generation [3,4]. Proceeded after oscillators or regenerative amplifiers with several watts output power and above, multi-pass traveling-wave amplifier is an efficient and compact method to further boost the average power. As one of the most mature gain materials, Yb:YAG crystal is an ideal material for high average power traveling-wave amplification on account of its high thermal conductivity and a large emission cross-section. As a result, it has been widely used for femtosecond pulse amplification but, unfortunately, always accompanying with sub-ps pulse duration due to its limited gain bandwidth [5,6]. Using Yb:YAG crystals, thin disk and slab technologies have been proven to be very efficient and to enable high output powers with up to several kW of output power because of their advantages of thermal management. 7.3 ps pulses with an average output power of 1.103 kW at a repetition rate of 800 kHz (1.38 mJ of pulse energy) were demonstrated using thin disk amplifier [7], and 1.1 kW of average power at 20 MHz repetition rate with 615-fs pulses using the Innoslab Yb:YAG concept [8]. In addition, high average powers up to the hundreds watt or more have been demonstrated with direct amplification of high repetition-rate oscillators, achieving 160-W 800-fs pulses at 83.4 MHz by a single crystal fiber Yb:YAG amplifier [9]. Furthermore, combining with cryogenic cooling technology to increase heat dissipation in a Yb:YAG crystal amplifier allow one to generate 1.1-ps, 250-W pulses at a repetition rate of 100 kHz [10]. However, there are very few results pertaining to traveling-wave amplifiers based on

#488013 https://doi.org/10.1364/OE.488013
Journal © 2023 Received 16 Feb 2023; revised 10 Mar 2023; accepted 10 Mar 2023; published 27 Mar 2023

other Yb-doped materials. In a single-stage and direct four-pass amplification scheme based on $Yb{:}Y_2O_3$ ceramic, the amplifier delivers maximum output power of 8.1 W at 80 MHz with 239 fs pulses [11]. Nonetheless, even with the shorter pulse width obtained, the average output power was only 10 watts level.

In contrast, Yb doped $CaYAlO_4$ (Yb: CALYO) has attractive spectroscopic properties(77 nm emission bandwidth for σ polarization) which makes it a promising material for sub-100 fs pulse generation [12]. Upon to know, the shortest pulse duration of 17 fs based on Yb: CALYO crystal was demonstrated from a Kerr-lens mode-locked oscillator [13]. In addition, it also has a moderate stimulated emission cross-section ($\sim 0.8 \times 10^{-20}$ cm^2 for σ-polarization and $\sim 0.5 \times 10^{-20}$ cm^2 for π-polarization), a good thermal conductivity (3.6 W/m/K for σ-polarization and 3.2 W/m/K for π-polarization) and a long upper-level lifetime (~426 µs) [14]. As a result, the potential of energy boosting in a regenerative amplifier has also been investigated in recent years. In 2016, Alexander Rudenkov of Russia reported the regenerative amplification based on Yb: CALYO crystal, which obtained the output power of 4.2 W with 310 fs pulse duration for σ-polarization and 190 fs with 2.3 W output power for π-polarization [15]. The output energy of millijoule magnitude also has been demonstrated by LS Petrov of Bulgaria in 2022, achieving a single pulse energy of 1 mJ and a pulse duration of 135 fs at 1 kHz repetition frequency [16]. Most recently, We have also reported on a Yb: CALYO regenerative amplifier that delivering over 28.7 W average power for σ-polarization and 16.1 W average power for π-polarization at 10 kHz repetition rate [17]. However, the multi-pass traveling-wave amplification with the Yb: CALYO crystal has not been investigated yet.

In this work, we report on direct amplification of the femtosecond pulses in a two-stage traveling-wave amplifier of Yb: CALYO crystal. The first stage that with a four-pass amplification scheme delivers the maximum output power of 25.4 W with 5.5 W seed at 150 W pumping, corresponding to an optical-to-optical efficiency of 15.2%. The M^2 factors in the vertical and horizontal directions measured at the 25.4 W output power were 1.16 and 1.22, respectively. Furthermore, the second stage that with a two-pass amplification configuration delivers the maximum output power of 54.4 W at 125 W pumping. The optical-to-optical efficiency, measured with respect to the pump power, is 28.3%. By combing the Gires–Tournois interferometer (GTI) mirrors with a pair of prisms to compensate the dispersion, the output of the final stage was compressed to 166-fs pulses of a $sech^2$-shaping with 51.8 W output power.

2. Experimental setup

The optical layout of the multi-pass Yb: CALYO amplifier without chirp pulse amplification is shown in Fig. 1. It consisted of a femtosecond Yb:KGW oscillator (LIGHT CONVERSION, Flint), two stage traveling-wave amplifiers and a compressor. The maximum output power of the oscillator was 6 W at 75 MHz and the pulse duration was 105 fs, maintaining a beam quality factor of 1.15. The spectrum was centered at 1034 nm with a full width at half maximum (FWHM) bandwidth of 17.5 nm. The beam spot before $telescope_1$ was 2.7 mm in diameter, and it was re-collimated to 1.12 mm by using two concave lenses with the focal lengths of 300 mm and 125 mm, respectively.

The Yb: CALYO crystal used in the first stage was 18-mm long, 2at. % Yb^{3+}-doped, and anti-reflection coated around 970-1100 nm. It was cut along a-direction with a cross-section of 3 mm × 6 mm. For effective thermal load dissipation, the crystal was wrapped with an indium foil and mounted tightly on a water-cooled copper heat sink that remaining at a constant temperature of 14°C. A 150 W, fiber coupled 976 nm laser diode (LD, BWT Inc.) with the core diameter of 105 µm and NA of 0.22 was employed to end pump the crystal. The pump was imaged inside the Yb: CALYO crystal with a 210 µm diameter spot, while the seed beam was focused to a diameter of 205 µm by a plano-convex lens (L1) with a focal length of 150 mm. L1 was placed at 155 mm distance from the Yb: CALYO crystal to compensate pump induced thermal lens. The beam

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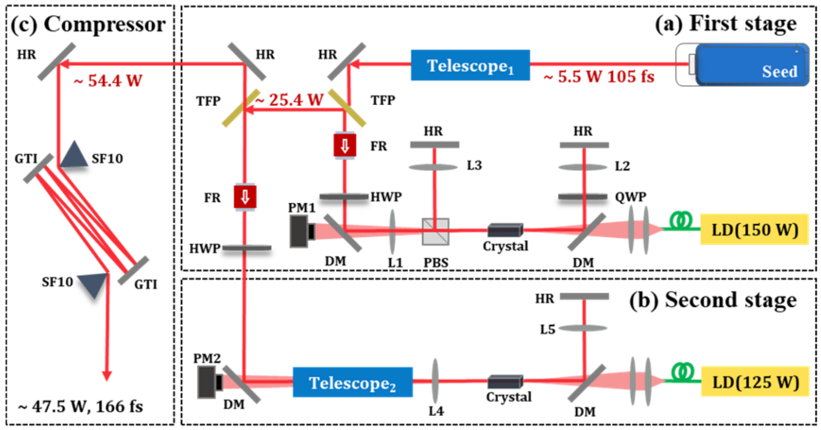

Fig. 1. The scheme of the high power two-stage Yb: CALYO amplifier. TFP: thin film polarizer; FR: Faraday rotator; HWP: half-wave plate; QWP: quarter-wave plate; L1-L5: lenses; PBS: polarization beam splitter; DM: dichroic mirror; LD: laser diode; GTI: Gires–Tournois interferometer. SF10: dense flint, HR: High reflective mirror; PM: power meter.

waist of the seed after the first pass was imaged back to the crystal using a highly reflective (HR) plane mirror and a second lens (L2) operating in the f-f configuration, while the double-passing of the quarter-wave plate (QWP) rotated the polarization by 90°. Therefore, the seed beam was reflected by a PBS after two-pass amplification and imaged to the crystal by a HR mirror and a third lens (L3) with the same function as L2. Then, the seed experienced two-pass amplification as well as 90° polarization rotating again. Finally, the amplified seed was returned along the original and injected into the secondary amplifier.

The beam spot after the first stage was reshaped with the second telescope system and then focused by a lens of 150 mm focal length (L4) to a 195 µm diameter on the second Yb: CALYO crystal. The crystal was also 2at. %-doped and anti-reflection coated around 970-1100 nm. It was cut along a-direction with a cross-section of 3 mm × 3 mm and a thickness of 16 mm. The pump source of the second amplification stage was a 125 W, fiber-coupled 981 nm LD with the core diameter of 105 µm and NA of 0.15 (BWT Inc.). Instead of using a four-pass configuration as in the first stage, we implemented a simple double-pass configuration in the second stage amplifier to investigate the polarization depended amplification properties. For this purpose, the polarization of the seed could be selected to along the σ axis or π axis of the crystal via a half-wave plate (HWP) behind the second Faraday rotator (FR).

Finally, the combination of a pair of prisms and two GTI mirrors were used to compensate both of the second order and third order dispersion introduced during the amplification. The distance between the two prisms was 1450 mm, which could provide a group-delay dispersion (GDD) of -13547.042 fs^2 and a third-order dispersion (TOD) of -26286.269 fs^3. In between the two prisms, two GTI mirrors with -3000 fs^2 in the range of 1020-1040 nm and -1000 fs^2 in the range of 1020-1040 nm of GDD per bounce was used, on each of which the amplified laser was bounced twice. In addition, the minutely tunable dispersion could be achieved by changing the insertion amount of the two prisms.

3. Result and discussion

3.1. First stage

First of all, the gain potential of the Yb: CALYO crystal in traveling-wave amplification was studied at the first stage.

Seed pulses with a single-pulse energy of 73 nJ at repetition rate of 75.4 MHz were injected into the amplification, corresponding to an average power of 5.5 W in the first stage. The output power of the four-pass setup was 2.73 W without pumping due to reabsorption of the crystal. High brightness pumping configuration beyond saturation pumping allowed us to achieve high signal gain value in low energy seed injection. As shown in Fig. 2(a), the maximum output power obtained was 25.4 W at a pump power of 150 W. According to measurements in the experiment, the pump absorption of the crystal decreases from 99% to 74% as the pump power increases because of the saturation, and the maximum absorbed pump power was only 111W. As a result, the highest optical-to-optical efficiency of 15.2% was obtained. It is worth noting that higher power will be further obtained by using longer crystals or that with higher doping to improve the pump absorption at high pump power. In addition, the system could operate at very low seed powers without disturbance by amplified spontaneous emission (ASE). When the seed beam is blocked, the ASE at the maximum pump power was zero.

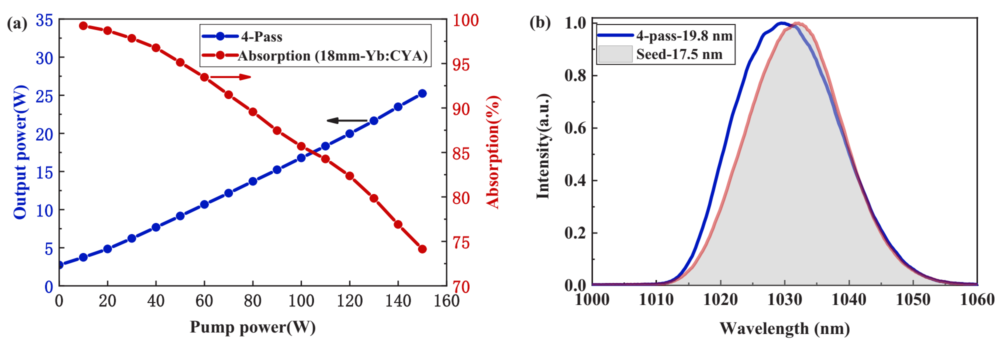

Fig. 2. (a) Amplified output power of four-pass (black) amplification as function of the input pump power. (b) injected seed spectrum (red) and four-pass amplified spectrum(blue).

The recorded spectra are shown in Fig. 2(b), the central wavelength was at 1030 nm with a FWHM of 19.8 nm. Compared with the spectrum of the seed, a slight spectral blue-shift phenomenon accompanied by a certain broadening is observed in the amplified spectrum due to the flat gain spectrum of the Yb: CALYO crystal.

In addition, M^2 values of 1.16 for the x-axis and 1.22 for the y-axis were measured with a commercial M^2-meter (Ophir, BSQ-SP920) at 25.4 W operation as shown in Fig. 3. There is a difference in the beam quality of the two axes due to the uneven heat dissipation of the system caused by the 3×6 mm crystal section. However, the spot ellipticity of 0.94 was obtained at the output port.

3.2. Second stage

The amplification properties of Yb: CALYO crystal for different polarization pulses could be more clearly demonstrated by higher amplified efficiency, which can be achieved by increasing the seed pulse energy. Therefore, the output of the first stage was then seeded into the second stage amplifier and the polarization depended amplification was investigated.

The output powers of single- and double-pass configuration without pumping were all 21 W and 19 W for both polarizations due to the reabsorption of crystal. Fig. 4(a) shows the amplification properties of the π-polarization. The maximum output powers of one- and

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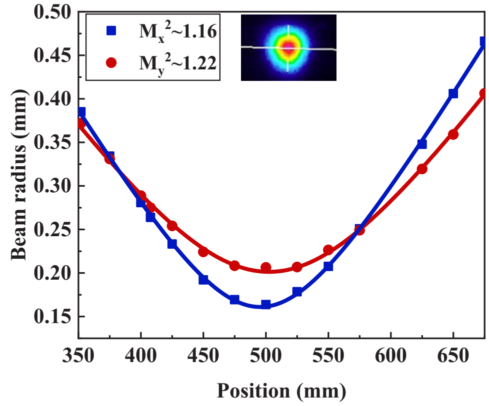

Fig. 3. Beam quality and the near-field beam profile(inset) measurement after four-pass amplification at 25.4 W output power

dual-pass amplification were 34.5 W and 39.4 W for 125 W pump power, corresponding to the optical-to-optical efficiencies of 10.8% and 16.3%, respectively. The maximum efficiency of double-pass is much lower than twice of that of single-pass at the maximum pump power which is due to the gain saturation. In this case, σ-polarization shown a much better power scaling potential due to its larger gain cross section, compared to π-polarization. Fig. 4(b) compares the output power versus the pump power in the single- and double-pass configurations of σ-polarization. The 40 W and 54.4 W of one- and dual-pass amplification were reached at an pump power of 125 W, corresponding to the optical-to-optical efficiencies of 15.2% and 28.3%, respectively. The maximum efficiency of double-pass amplified was about 1.6 times of the single-pass according to the measurement. Although also with minor signs of gain saturation, it exhibits better performance compared to π-polarization. In addition, the amplification slope efficiency for the double-pass amplification was almost constant with a slope efficiency of 28.5%, proving its potential for further power expansion.

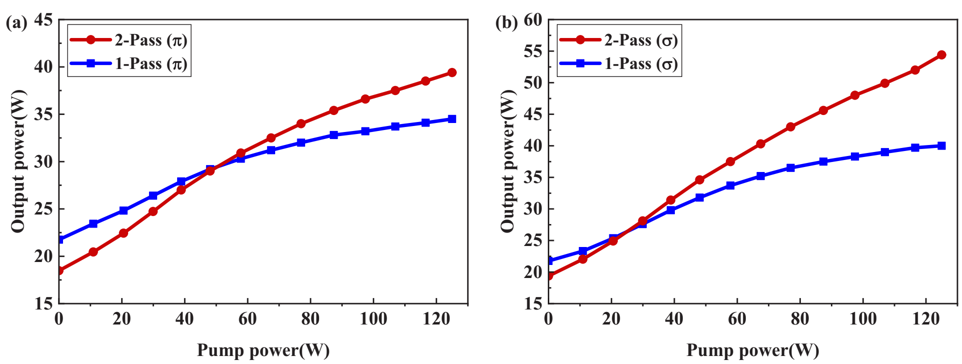

Fig. 4. (a)Amplified output power of single- and dual-pass as a function of the pump power(π); (b) Amplified output power of single- and dual-pass as a function of the pump power(σ).

The optical spectrum of the π-polarization amplification was centered at 1030 nm with a FWHM bandwidth of 16.8 nm (red curve), exhibiting a slightly gain narrowing as shown in Fig. 5(a). The output spectrum of the σ-polarization amplification featured with gain narrowing and red-shifting with a central wavelength of 1032 nm and a FWHM of 17.1 nm (blue curve), corresponding to a Fourier-Transform limited pulse duration of 91 fs.

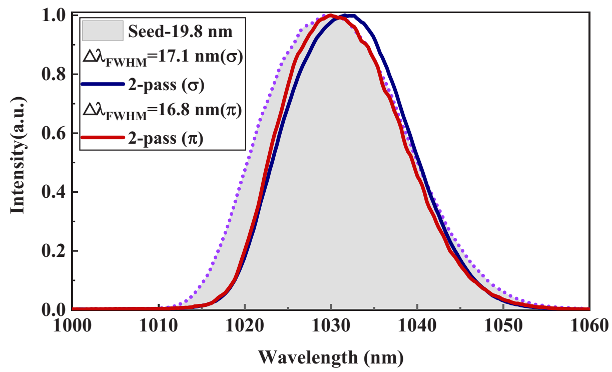

Fig. 5. (a)injected seed spectrum after first-stage (dot), two-pass amplified spectra of σ(bule) and π(red).

Figure 6(a) shows the temporal properties of the amplified laser before (gray) and after (pink) the compressor. We first measured the amplified auto-correlation trace directly by an intensity auto-correlator (APE, PulseCheck), and recorded a pulse duration of 726 fs assuming a Gauss pulse shape, which is around 8 times of the Fourier limit. The stretching of the pulse was attributed to the dispersion of material added to the pulse throughout the two-stage experiment, mainly introduced by Faraday isolators, lenses, polarized beam splitters and the crystals with approximately a GDD of +27134.9 fs^2 and a third-order dispersion of +26566.2 fs^3. After pulse compression, a pulse duration of 166 fs assuming a sech^2 pulse shape was achieved, corresponding to a time-bandwidth product of 0.799. The reason for the inability to compress to the Fourier limit pulse duration is that the combination of the prism pair and GTI mirrors can't fully compensate for the chirp in the amplification process. Shorter pulse widths of 130 fs assuming a sech^2 pulse shape can also be obtained by just adding two GTI mirrors of totally -6000fs^2 GDD in the range of 1020-1040 nm as shown in Fig. 6(b), however a pedestal was appeared in the intensity autocorrelation trace due to the limited bandwidth of our GTI mirrors. Finally, the maximum average power of 51.8W after compression was obtained, with a compression efficiency of 95.2%.

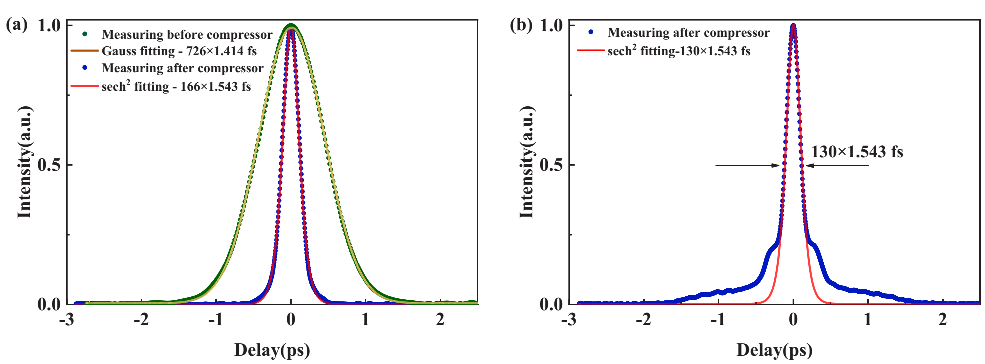

Fig. 6. (a) Intensity autocorrelation trace of the output pulses and corresponding gauss fit (before compressor) and sech^2 fit(after compressor); (b) Intensity autocorrelation trace of the output pulses and corresponding sech^2 fit after compressor.

The output beam quality and the beam profile of the compressed laser are displayed in Fig. 7. The beam was nearly TEM_{00} with the spot ellipticity of 0.92 with M^2 parameters of 1.30 and 1.28 along each axis, respectively. Benefit from the uniformity of heat dissipation by the choice of the 3×3 mm crystal section, the beam focus of the x and y axes tend to coincident.

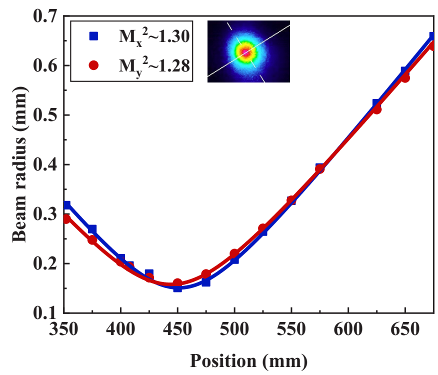

Fig. 7. Beam quality and beam profile(inset) measurement after compression

4. Conclusion and perspectives

In conclusion, we have demonstrated a direct amplification of femtosecond pulses with the Yb: CALYO bulk crystal based two-stage travelling-wave amplifier. Meanwhile, the amplification properties of Yb: CALYO crystal for two polarizations of π and σ were investigated. High brightness pumping and a four-pass configuration in the first stage resulted in an output power of 25.4 W, which corresponds to an optical-to-optical efficiency of 15.2%. The beam quality remains excellent with M^2 values of 1.16 for the x-axis and 1.22 for the y-axis. In addition, the higher output and conversion efficiency were obtained in the second stage due to the increased seed energy. The 39.4 W and 54.4 W average powers of π- and σ-polarization amplification were obtained at pump power of 125 W, corresponding to the optical-to-optical efficiency 16.3% and 28.3%, respectively. These are to the best of our knowledge the highest value achieved with Yb: CALYO amplifier so far. It is worth noting that there is a certain spectral blue-shift to around 1030 nm and 1032 nm, accompanying by a slight gain narrowing. This allows our system to be used not only as a next-stage power amplifier but also as a high-power seed source for Yb:YAG based amplifier. The pulse duration of 166 fs and the output power of 51.8 W were obtained after compression. The beam was TEM_{00} with the spot ellipticity of 0.92 up to full output power, with M^2 parameters <1.30 along each axis. Compared to Yb:YAG amplifiers, the main advantage of Yb: CALYO crystal is that it provides both short pulse duration and high efficiency leading to a very compact amplifier geometry.

Furthermore, the seed laser will be replaced with a home built Yb: CALYO regenerative amplifier with a repetition rate of 10 kHz output power of 28.7 W [17]. It is believed that this amplification scheme based on Yb: CALYO crystal could be functional for sub-200-fs pulses with more than 100-W average power, corresponding to a pulse energy of 10 mJ.

Funding. National Key Basic Research Program of China (No. 2022YFA1604202); National Natural Science Foundation of China (No. 61975071, No. 62105253); the Science and Technology Program of Xi'an (No. 202005YK01); the Natural Science Foundation of Shannxi Province (No. 2023-JC-YB-485).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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