Efficient amplification of a femtosecond Ti:sapphire laser with a ring regenerative amplifier

Wei Zhang,[1] Hao Teng,[1,*] Zhaohua Wang,[1] Zhongwei Shen,[1] and Zhiyi Wei[1,2]

[1]Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

[2]e-mail: zywei@iphy.ac.cn

*Corresponding author: hteng@iphy.ac.cn

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A high-stability and high-efficiency ring Ti:sapphire regenerative amplifier is demonstrated based on a double-gating pulse picker at a repetition rate of 1 kHz. Pulse energy up to 5.7 mJ is obtained using a pump energy of 20.0 mJ at 527 nm, corresponding to a relatively high slope efficiency of 30.3%. After a grating compressor, the laser pulse is compressed to 37.2 fs with an energy of 4.1 mJ. The beam quality factors M^2 are 1.4 and 1.3 in tangential and sagittal directions, respectively. The measured root mean square energy stability is better than 0.31% over an 11 h period.

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1. Introduction

With the development of the Kerr-lens mode-locked technique over the last two decades, it has been possible to directly produce a sub-10 fs laser pulse at nanojoule energy level from a Ti:sapphire oscillator. In general, the femtosecond laser pulse with nanojoule energy has limited its applications. With the invention of chirped-pulse amplification (CPA) technology [1], the energy of the femtosecond laser was greatly increased, and peak power up to petawatts (PW, 10^{15} W) has been realized in many laboratories [2,3]. Recently, CPA is playing a more and more important role in the development of ultrahigh-intensity lasers widely used in many promising fields, such as atomic physics, material science, ultrafast phenomena, and high field physics [4]. It is also responsible for many new research fields, such as attosecond physics [5,6], four-dimensional images [7], micromachining [8,9], etc. In addition, as a beneficial tool for high-precision microsurgery on biological tissue, the femtosecond laser is recognized as a safer tool for refractive surgery [10–12].

There are two kinds of amplifiers mostly applied in the CPA system to boost peak power to the terawatt (TW, 10^{12} W) or even PW scale [13–16]: regenerative and multipass amplifiers. The regenerative amplifier usually has better beam quality and higher stability. Therefore, it is often employed as a prestage amplifier at high repetition rate, such as at kilohertz rate. Until now, the linear cavity has mostly been utilized as a regenerative amplifier because of its simple configuration and easy operation. Although the regenerative amplifier with a ring cavity is rather complicated in configuration and more difficult to perform [17], it has several irreplaceable advantages compared to the linear cavity regenerative amplifier for the CPA system. First, a ring cavity has a larger mode size to support higher energy for a given damage threshold. Second, according to the approximation expression of $I_{\mathrm{ASE}} \sim 1/L$ (I_{ASE} is the intensity of amplified spontaneous emission (ASE), L is the cavity length), as an important specification for a high-power femtosecond laser [3], the contrast ratio of the ring amplifier is higher because the ASE can be greatly suppressed due to longer cavity length [18].

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Third, the amplified pulse propagates in one specific direction in the ring cavity. The directionless ASE and the amplified pulse from the amplifier could not go back to the oscillator to break down the mode-locking state because the isolator [Pockels cell (PC) or Faraday rotators] can suppress them to a large extent. So a ring cavity will provide more secure isolation from the oscillator [19].

In this paper we report on a highly efficient regenerative amplification of the femtosecond Ti:sapphire laser with a ring cavity. Compared to normal regenerative amplifiers [20,21], a double-gating PC is employed in the cavity for pulse picking. A theoretical simulation with consideration of a different thermal lens in Ti:sapphire crystal is performed to choose proper concave mirrors and optimize spot size. Based on the simulation, we have successfully constructed the ring cavity regenerative amplification. Amplified laser pulses with energy up to 5.7 mJ are experimentally obtained with a maximum pump energy of 20.0 mJ at a repetition rate of 1 kHz, corresponding to a slope efficiency of 30.3%. At the output of the compressor, amplified pulses are compressed to 37.2 fs with energy of 4.1 mJ, and the energy stability is 0.31% [root mean square (RMS)] over more than 11 h. Many experiments, such as ophthalmic surgery, optical-parametric amplification (OPA), and terahertz emission in lithium niobate crystal, have been successfully carried out based on this ring amplifier femtosecond laser, and the obtained results have proved its high efficiency and the stability of this design.

2. Experiment and Discussion

The femtosecond laser system consists of an oscillator, a stretcher, a ring cavity amplifier, and a compressor, and all of parts are integrated into one optical breadboard, as shown in Fig. 1. 80 MHz seed pulses from the Ti:sapphire oscillator have full width at half-maximum (FWHM) of 60.9 nm and a pulse duration of 20 fs. Before the pulses are injected in the amplifier, the seed pulses are first stretched to 200 ps with a Martinez grating (1200 lines/mm) stretcher, rotated to vertical polarization and then injected into the regenerative amplifier by mirror M5 and Glan prism P1. In order to realize multimillijoule amplified pulses from only one regenerative amplifier stage, the design of the ring cavity is of key importance to the system, so a simulation of spot size in the cavity is made before the experiment.

Considering different thermal lenses with focal lengths of 500, 1000, 1500, and 2000 mm in Ti:sapphire crystal at −25°C and room temperature under 10–20 mJ pump energy, calculated using the formula in [22], the simulation of spot size in the cavity is carried out using the ABCD matrix. The amplifier cavity finally chosen consisted of four concave mirrors with radii of curvature of 2000 mm (M1 and M4) and 3000 mm (M2 and M3), two Glan prisms (P1 and P2), a Brewster-cut Ti:sapphire crystal with a length of 20 mm, and a double-gating PC (OG8/1-2, Avesta Inc.). The crystal is mounted on a fixed copperplate in a vacuum chamber, cooled by a water chiller and a thermoelectric cooling (TEC) system down to about −25°C. As shown in Fig. 2, the simulation shows that the spot size in Ti:sapphire crystal will decrease with increasing thermal effect. The strongest thermal effect will result in a 500 mm thermal focal length for Ti:sapphire crystal under a pump energy of 20 mJ without TEC cooling. In such case, the spot size in the crystal, which is also the waist of the cavity, is about 610 μm in diameter, and the spot size is enlarged to 1.6 mm in diameter on the surface of the PC. For a pulse energy of about 6 mJ, the fluence on the PC is 0.30 J/cm^2, far below the damage threshold of 5 J/cm^2 for DKDP crystal in PC. This can ensure the PC and other components work properly without damage. When the crystal is cooled down to −25°C, the thermal focal length is increased to 2000 mm and the spot size in Ti:sapphire crystal and PC are 800 μm and 1.1 mm in diameter. The fluence is also below the damage threshold. To optimize the overlap between the laser and the pump, the pump beam is collimated and focused by an $f =$ 350 mm lens, which can be move back and forth to get a minimum 740 μm focus spot. Even for a pump

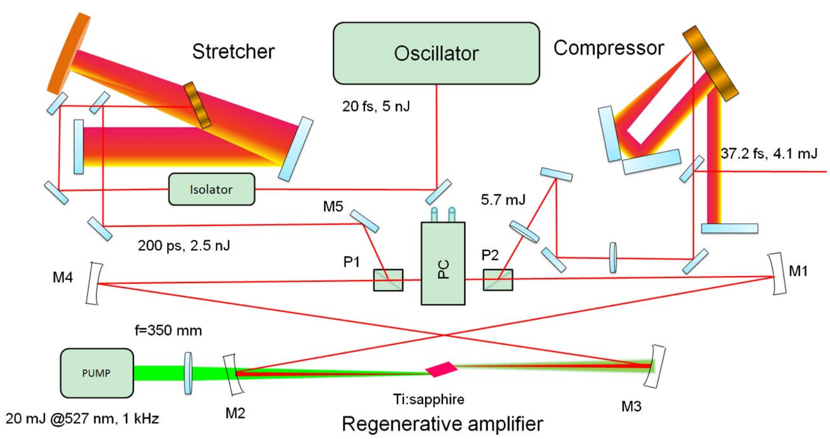

Fig. 1. (Color online) Schematic of the ring regenerative amplifier system, a femtosecond Ti:sapphire laser oscillator, a stretcher, and a compressor are drawn in this figure.

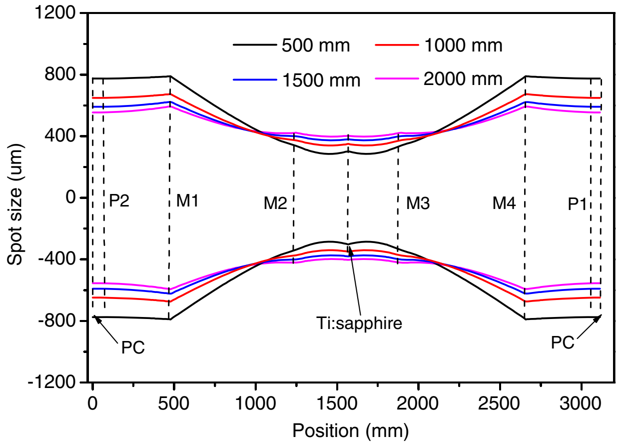

Fig. 2. (Color online) Simulation of spot size in the cavity with different thermal focal length of Ti:sapphire crystal. The straight dashed lines show the internal elements' positions.

energy of 20 mJ, the maximum energy fluence is 4.65 J/cm^2, which is below the damage threshold of Ti:sapphire crystal (10 J/cm^2). From the calculation, the optical component in the cavity will be safe whenever the Ti:sapphire crystal works with or without TEC cooling.

As mentioned above, a double-gating PC is employed in the cavity, and located between the two Glan prisms. The PC can deliver two high-voltage (HV) pulses with duration of less than 10 ns at 10% level. Compared to a normal single-gating PC, these two HV pulses are independent, more flexible, and accurate for adjustment. When the first high-voltage pulse (HV1) delay time changes, the second high-voltage pulse (HV2) delay time will not be affected. Moreover, for a double-pulsed PC, the high voltage does not need to remain until the pulse amplification reaches its maximum. This process often has a time interval of several hundred nanoseconds or even microseconds. For such a long duration, high voltage would cause a more severe thermal effect for high-repetition-rate application, and the laser system needs more time to stabilize—it might even require a water chiller to cool the PC itself. Meanwhile, in a double-pulsed PC system, even in a longer than 1 μs acting time, the coexisting time of two high voltages is only about 20 ns, yielding a much smaller thermal effect, especially in a high-repetition-rate situation. Since there is no disturbance from any other high voltage during the amplification process, the regenerative amplifier can be more stable.

HV1 on the PC is for pulse picking in the pulse train from the oscillator and pulse injecting into the cavity for amplification, while HV2 is for cavity dumping of the amplified pulse when the energy is amplified highly enough. The time interval between these two HV pulses, corresponding to the buildup time of the pulse amplified (from start to dumping) in the cavity, can be adjusted independently from 0 ns to 4 μs with a minimum step of 10 ps. Furthermore, for a seed pulse train with a repetition rate of 80 MHz, corresponding to a 12.5 ns interval between two pulses, only a single pulse will be selected by the high voltage less than 10 ns.

When the stretched pulses pass through the PC, which is adjusted to the static full-wave condition (without any high voltage), the polarization of pulses will not be changed; thus the pulse is switched out of the cavity by the Glan prism P2. But when there is a half-wave HV1 applied to the electro-optical crystal inside the PC, the polarization state of the seed pulse is rotated from vertical to horizontal. The pulse freely passes through the second Glan prism P2 and then injects into the cavity for amplification. Since the duration of HV1 is less than 10 ns and the roundtrip length of the cavity is 3.1 m, only one pulse from the oscillator can be trapped in the cavity and the PC will recover its full-wave state before the second seed pulse reaches the cavity. Therefore, the selected single pulse can continually obtain amplification until the second HV signal is applied on the PC. When HV2 is added to the PC, the pulse polarization is rotated to vertical again. Then the amplified pulse will be reflected and ejected out of the cavity through Glan prism P2. The PC is triggered by a 1 kHz signal that is divided from the 80 MHz repetition rate of the femtosecond oscillator, and the pump laser (Empower-30, Spectra-Physics) is also triggered by the same source. The picked pulse in the cavity can be optimized to obtain high amplification by finely adjusting the synchronization between the pump laser and HV1.

To observe the amplification evolution of the pulse buildup, leaked pulses from the high-reflectivity mirror M1 are detected by a photodiode. Figure 3 shows the temporal profiles of the pulse buildup in the cavity. When the pulse energy reaches the maximum after the necessary round trips, the amplified pulse is ejected by adding HV2 on PC. The interval between the first HV signal and the ejected pulse is less than 350 ns, so amplified pulses can reach the peak after less than 35 round trips. There is no prepulse around the ejected amplified pulse observed, which

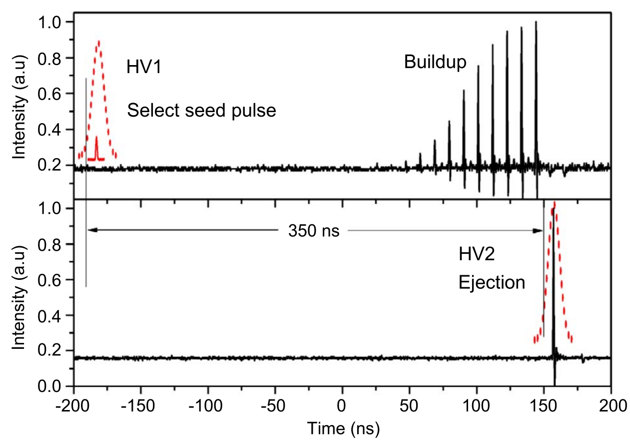

Fig. 3. (Color online) Buildup process of amplification and the dumped amplified pulse from the ring regenerative amplifier. The function principle of double-gating PC is also sketched with a red dashed curve.

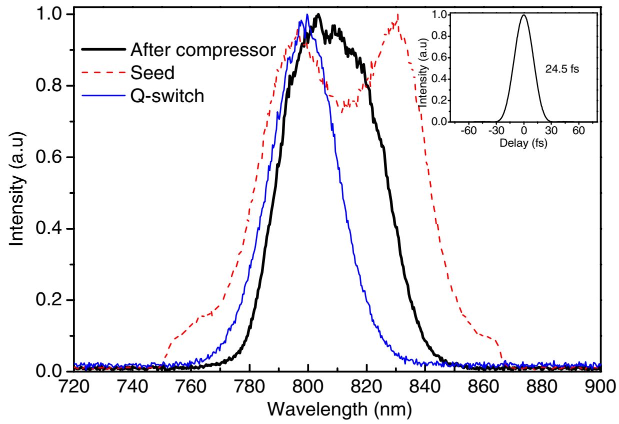

Fig. 4. (Color online) Spectra of seeding laser pulse (dashed curve), Q-switched amplified laser pulse (thin curve), and compressed laser pulse (thick curve). The inset shows transform-limited pulse duration of the amplified laser spectrum.

shows a high signal-to-noise ratio and no appreciable ASE during buildup time.

Figure 4 shows the laser spectra of the oscillator and Q-switched operation both without a seed and amplified with seed injection after the compressor. The corresponding FWHM bandwidths are 60.9, 26.0, and 39.6 nm, respectively. Because of the gain-narrowing effect in Ti:sapphire crystal and the coating bandwidth limit of both the PC and the mirrors, the spectrum of the laser pulse after the compressor is narrower than that from the oscillator and supports a transform-limited pulse as short as 24.5 fs (see the inset in Fig. 4). However, the shortest pulse duration experimentally measured is 37.2 fs with a commercial autocorrelator (shown as Fig. 5), which is longer than the theoretical limit as a result of the incompressible high-order dispersion in the laser amplifier.

The amplified pulse energy as function of the pump energy is illustrated in Fig. 6. The thermal effect often limits the output energy and prevents us from obtaining high beam quality. In order to eliminate the thermal effect and increase output

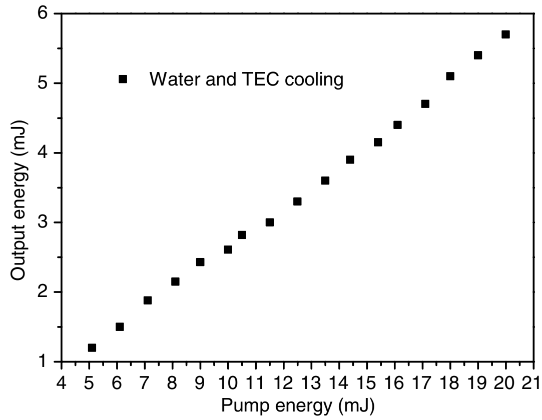

Fig. 6. Output energy extracted from the ring regenerative cavity as a function of pump energy.

energy, the Ti:sapphire crystal is cooled down to −25°C by a TEC cooling system in a vacuum chamber. The measured maximum energy of the uncompressed pulse is as high as 5.7 mJ with a slope efficiency of 30.3%. If higher pump energy is available, the energy of the amplified pulse will be higher. Finally, after expanding the beam to 10 mm in diameter, the amplified chirped pulse is compressed using a four-pass, single-grating (1500 line/mm) compressor, with an overall efficiency of 72%. The energy of the compressed pulse is measured to be 4.1 mJ. We believe that higher energy should be possible by further increasing the pump energy and minimizing the thermal lens effect.

The energy stability of the compressed laser pulse is shown in Fig. 7, which is better than 0.31% RMS over 11 h. To fit the applications for ophthalmic surgery, generation of terahertz radiation, etc., we also measured the spatial profile of the output beam 4 m away from the compressor by using a commercial laser beam analyzer (Spiricon, M2-200s-FW). As shown in Fig. 8, the beam qualities of M^2 factors are $Mx^2 = 1.4$ and $My^2 = 1.3$, respectively, which demonstrate very good beam profiles both at the far field and the near field.

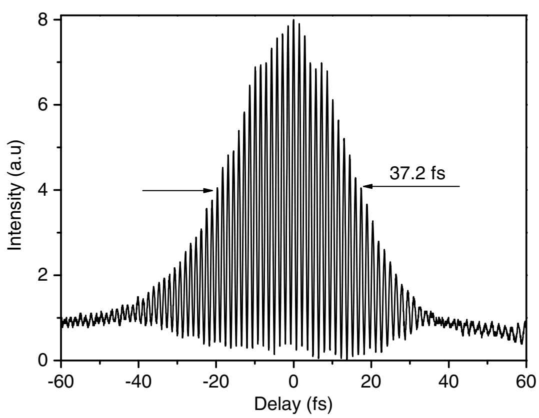

Fig. 5. Interference autocorrelation trace of the pulses after the compressor.

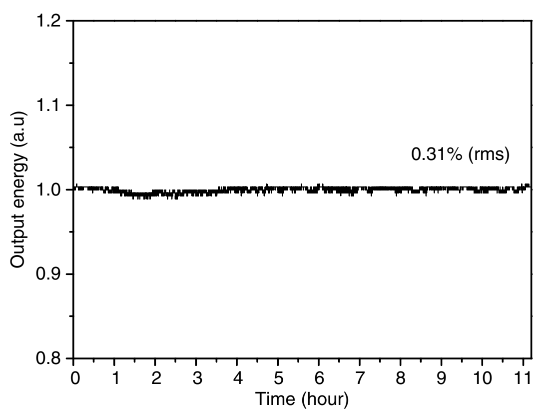

Fig. 7. Energy stability of the pulses after compressor over more than 11 h.

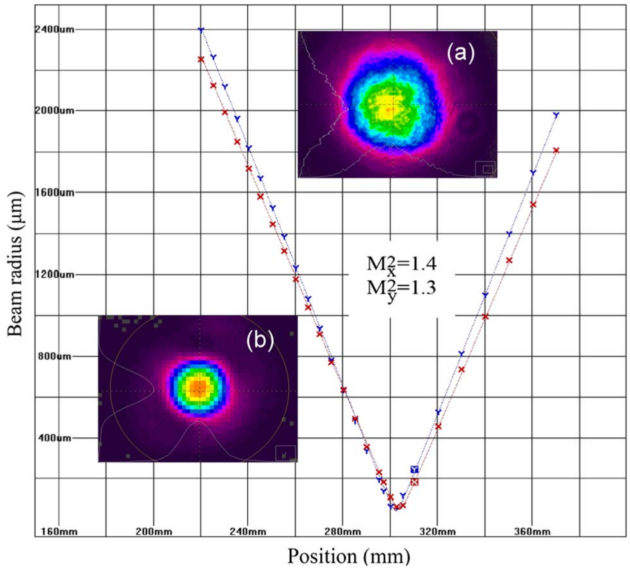

Fig. 8. (Color online) (a) Near-field and (b) far-field beam profiles and M2 factor of the compressed pulse.

Many experiments, such as ophthalmic surgery, generation of terahertz radiation, and OPA, have been successfully carried out based on this laser system. The experimental results demonstrate that the design and performance of the regenerative amplifier based on the ring cavity and double-pulsed gating PC will provide a candidate scheme to study ultrafast phenomena and industrial machining.

3. Conclusion

In conclusion, a high output energy and efficiency compact ring regenerative amplifier has been developed based on a double-gating PC. Amplified pulse energy as high as 5.7 mJ is obtained using pump energy of 20 mJ, and it is only limited by the available pump laser. After the single-grating compressor, the amplified pulses are compressed to 37.2 fs with energy of 4.1 mJ. The measured energy fluctuation of 0.31% RMS over more than 11 h shows excellent stability. We believe that shorter pulses with higher energy can be obtained by this ring regenerative scheme if wider spectral bandwidth seed pulses and a higher-energy pump source are available. The obtained results show that this regenerative amplifier is very favorable for ultrafast application and in further amplification, such as in a TW system.

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