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Highly Efficient and Stable Ring Regenerative Amplifier for Chirped-Pulse Amplification at Repetition Rate 1 kHz *

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A highly efficient and stable ring-cavity regenerative amplifier for chirped-pulse amplification at a 1 kHz repetition rate, with slope efficiency up to 40% and output pulse-to-pulse energy-jitter less than 1.25%, is demonstrated. The pulse energy as high as 2.4 mJ is obtained.

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Femtosecond Ti:sapphire oscillator–amplifier systems using the technology of chirped-pulse amplification (CPA) have become standard top table sources of ultra-high-intensity laser pulses.[1] In general, a typical CPA system is composed of an oscillator, a stretcher, amplifiers and a compressor, so far peak power as high as multi-100TW has been obtained by several groups over the world with this way.[2] For such facility with ultraintense power, the stage of pre-amplifier are often pumped by the frequency doubled Nd:YAG laser at a repetition rate of 10 Hz.[3] Because such Nd:YAG laser is pumped by flash lamps, both the beam pattern and stability of pulse-to-pulse energy are limited by the thermal effect. In recent years, LD pumped lasers at repetition rates 1–5 kHz are widely used for pumping the pre-amplifiers. Compared to pump laser with the flash-pump at low repetition rate, better beam-quality and more stable pulse-to-pulse energy are demonstrated. Moreover, such ultra-fast laser with peak-power up to TW and repetition rate to kilohertz is more attractive to generate coherent soft x rays[4] and solid spectroscopy.

Linear cavities are mostly utilized in regenerative amplifiers.[5] Ring cavities, which are more complicated and harder to align than linear ones, are not used widely. However, they have several inherent advantages over linear designs for applications in CPA lasers. First, due to the special cavity geometry, a ring cavity can allow optical elements inside it to be far away from the position of beam waist, which ensures a high damage threshold. Second, amplified spontaneous emission (ASE) always exists in a regenerative amplifier, which limits the intensity contrast of the amplifier because it overlaps with the amplified pulse in time domain and can not be removed by external Pockels cell. With the approximation[6] $I_{\mathrm{ASE}} \sim 1/L$ (L is the cavity length), the ring cavity has higher intensity contrast relative to ASE compared with the linear one with the same footprint. In addition, only ASE propagating in the same direction of the main pulse contributes to the intensity contrast in a ring cavity while it does in both directions in a linear cavity. As a result, an intensity contrast of about 10^8 for ring regenerative amplifier is obtained while the reported value for the linear one is about 10^6.[7] Third, in contrast to a linear cavity, the ring cavity can provide a more secure isolation from the oscillator which will be discussed in details later. Therefore, the ring cavity is preferable in regenerative amplifiers. In this Letter, we present our self-designed ring regenerative amplifier for CPA technique. The ring cavity is optimized by theoretical calculation, and slope efficiency up to 40% and pulse-to-pulse energy jitter less than 1.25% are achieved in the amplifier.

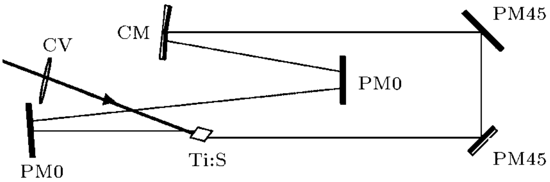

Fig. 1. Ring cavity scheme without Pockels cell and thin-film polarizer. CV: convex lens, PM0: flat mirror with high reflection for 0° incidence, PM45: flat mirror with high reflection for 45° incidence, CM: curved mirror, Ti:S: Ti:sapphire crystal.

Figure 1 shows a ring cavity scheme without Pockels cell and thin-film polarizer. It is made up of a curved mirror (CM) with radius of curvature (ROC) $R = 2\,\mathrm{m}$, four flat mirrors with high reflection (two for 0° and two for 45° incidence), and a Brewster-cut Ti:sapphire crystal with length of 10 mm. The 527 nm

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*** Permanent address: Beijing University of Technology pump laser is focused into the Ti:sapphire crystal through a convex lens with focal length $f = 500\,\text{mm}$.

The round-trip length of the cavity is 2.8 m, less than twice of the CM ROC. Thus it must be a stable cavity. We assume that the optical length from CM to the centre of Ti:S, through two PM0 mirrors is L1, through two PM45 mirrors is L2, and the folding angle at CM is θ (shown in Fig. 2(a)), vertical height of Ti:S is H (shown in Fig. 2(b)), refractive index of Ti:S is n. If the centre of the Ti:S is the starting point, the ABCD matrix of the beam round trip in the cavity is

$$M = \begin{bmatrix} A & B \\ D & D \end{bmatrix} = \begin{bmatrix} 1 + (\mathcal{L}_2)T & T(\mathcal{L}_1)(\mathcal{L}_2) + (\mathcal{L}_1) + (\mathcal{L}_2) \\ T & 1 + (\mathcal{L}_1)T \end{bmatrix}, \quad (1)$$

$$\mathcal{L}_1 = L_1 + N, \quad \mathcal{L}_2 = L_2 + N$$

where

$$T = \begin{cases} -2/R\cos(\theta), & \text{tangential plane,} \\ -2\cos(\theta)/R, & \text{sagittal plane,} \end{cases} \quad (2)$$

$$N = \begin{cases} H\sqrt{n^2+1}/(2n^4), & \text{tangential plane,} \\ H\sqrt{n^2+1}/(2n^2), & \text{sagittal plane.} \end{cases} \quad (3)$$

The ROC of equiphase surface at the centre of the Ti:S crystal is

$$r = \frac{2B}{D - A}. \quad (4)$$

If the beam waist occurs here, then $r = \infty$ and $A = D$ according to Eq. (4). From Eq. (1) we obtain $A = 1 + (L_2 + N)T$ and $D = 1 + (L_1 + N)T$. Therefore, $L_1 = L_2$ can be easily reached. To increase the gain efficiency, it is preferable to keep the beam waist existing in the Ti:S crystal. Then there is $L_1 = L_2 = 1.4\,\text{m}$.

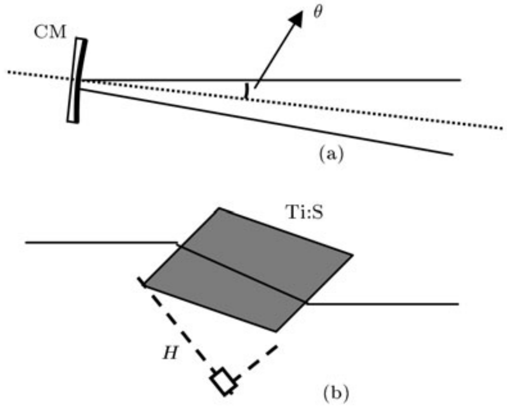

Fig. 2. Definition of θ and H.

Analytical formula of the beam waist is

$$\omega_0 = \sqrt{\frac{\lambda|B|}{\pi\sqrt{1 - A^2}}}. \quad (5)$$

From Eq. (1), we can also obtain $B = T(L_1 + N)(L_2 + N) + (L_1 + N) + (L_2 + N)$. With $\theta = 5°$, $n = 1.76$, $H = 8.66\,\text{mm}$, $\lambda = 800\,\text{nm}$, we can calculate the radius of the beam waist 481 μm on the tangential plane and 484 μm on the sagittal plane. The radius of focusing spot of 527 nm pump laser in the Ti:S crystal is about 500 μm and the maximum energy is 20 mJ, so the maximum energy density of pump laser in the Ti:S crystal is $2.6\,\text{J/cm}^2$, which is less than the damage threshold of Ti:S ($5\,\text{J/cm}^2$). Thus the spot size of pump laser is safe for the Ti:S crystal and also matches well with that of 800 nm laser in the crystal.

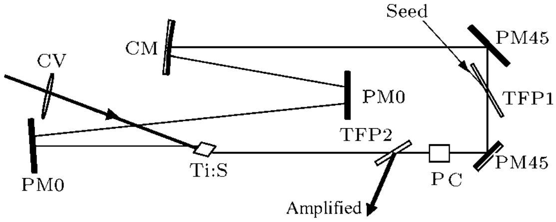

Fig. 3. Ring regenerative amplifier scheme.

Figure 3 shows the ring regenerative amplifier scheme, where PC represents the Pockels cell, TFP1 and TFP2 are the two thin-film polarizers. Seed pulse is injected into the cavity through TFP1 with vertical polarization and amplified pulse is switched out through TFP2 with the same polarization state. If there is no bias voltage added onto the Pockels cell, polarization state of the light passing through it will change 90°, in other words, vertical polarization light will change into horizontal one and vice versa. When a preset bias voltage is added onto the Pockels cell, polarization state of the light passing through it will not change. Therefore, after a seed pulse enters the cavity, the amplifying process is as follows. First, there is no voltage added onto the Pockels cell. When a pump laser pulse goes into the Ti:S crystal, if there is only one horizontal polarized seed pulse existing in the cavity, we can add the preset bias voltage onto the Pockels cell at once to make the light through it while not change the polarization state. Thus, the seed pulse will travel roundly many times in the cavity and its energy will be amplified soon. When the pulse energy reaches the maximal saturation value, we can remove the bias voltage to the Pockels cell promptly. Then the amplified pulse will be switched out of the cavity through TFP2 instantaneously after it passes through the Pockels cell again. When there is a bias voltage existing in the Pockels cell, other seed pulses go out of the cavity through TFP2 directly and cannot be amplified through the Ti:S crystal in the ring cavity.

From the process of regenerative amplification mentioned above, we know that neither seed pulses nor amplified pulses can go back into the oscillator. Moreover, because of the injection of seed pulse, the ASE which propagates against the seed pulse in the cavity has already been very weak. Thus the ASE going back into the oscillator through TFP1 can not change the mode-lock state of the oscillator. Therefore, the ring regenerative amplifier, compared to the linear one, has much better isolation from the oscillator.

It should be ensured that there is only one seed pulse amplified inside the cavity every time; the total length of the ring cavity cannot be too long. Commonly, it should be less than $2D$ (D is the distance between two adjacent seed pulses). The pulse repetition rate of our oscillator is 96 MHz, then $D = 3.125$ m, and the total length of the ring cavity is $L = 2.8$ m, which is much less than $2D$. Thus we can ensure only one pulse amplified inside the ring regenerative amplifier every time.

Figure 4 shows the curve detected by fast-response photodiode which represents the pulse-amplification process inside the ring regenerative amplifier, and we can find that the energy of seed pulse reaches the maximum after at least 30 times rounding trip in the cavity, spending more than 300 ns. The curve shown in Fig. 5 is the electronic signal of amplified laser pulse switched out from the regenerative amplifier. We can find from the figure that there is only one pulse amplified in the cavity and its signal-to-noise ratio is very high. The maximum energy of the amplified laser pulse is up to 2.4 mJ.

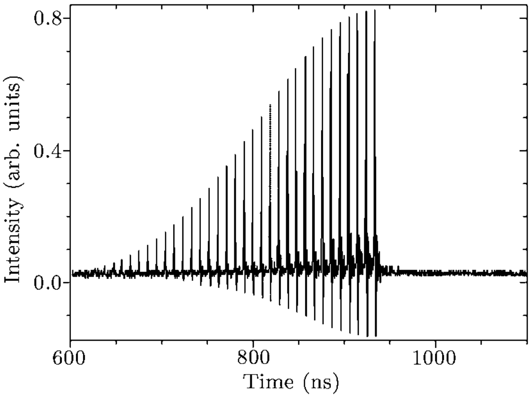

Fig. 4. Amplification process of laser pulse in the cavity.

The calculation formula of the total slope efficiency of the regenerative amplifier is[8]

$$\eta = \eta_e \exp(-n\tau_c/\tau_e) R_p \lambda_p / \lambda, \tag{6}$$

where n is the number of round-trip necessary to reach peak fluence; τ_c is the cavity round-trip time; τ_e is the excited-state lifetime of Ti:S; R_p is the output polarizer reflectivity; λ_p is the pump central wavelength; λ is the lasing central wavelength; η_e is the slope extraction efficiency of the regenerative amplifier, defined by

$$\eta_e = 1 - G_0(1 - T)/(G_0 - 1) \tag{7}$$

with G_0 being the unsaturated gain and T the round-trip transmissivity.

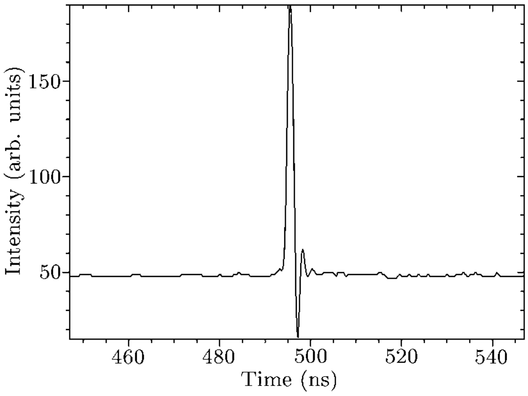

Fig. 5. Amplified pulse switched out of the cavity.

In this experiment, we assume $G_0 = 6$, $T = 82\%$, then $\eta_e = 0.784$. With $n = 32$, $\tau_c = 9.3$ ns, $\tau_e = 3.2\,\mu$s, $R_p = 0.86$, $\lambda_p = 527$ nm, $\lambda = 800$ nm, according to Eq. (6) we obtain $\eta = 40.9\%$. The measured slope efficiency in the experiment is 39.3% (shown in Fig. 6), which is close to the theoretically calculated value 40.9%.

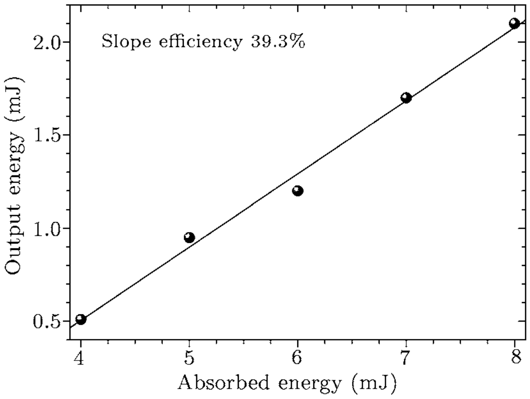

Fig. 6. Regenerative amplifier output energy to absorbed energy.

The output laser from the regenerative amplifier performs a good stability and no obvious fluctuation is observed during the running time of several hours. Figure 7 shows the normalized energy values of one thousand laser pulses measured within one second, which represents the short-term energy stability of laser from pulse to pulse. The result means that energy-jitter is about 1.25%. Considering the electronic noise, the actual energy jitter should be less than the value, which indicates that output pulse energy from the ring regenerative amplifier is very stable.

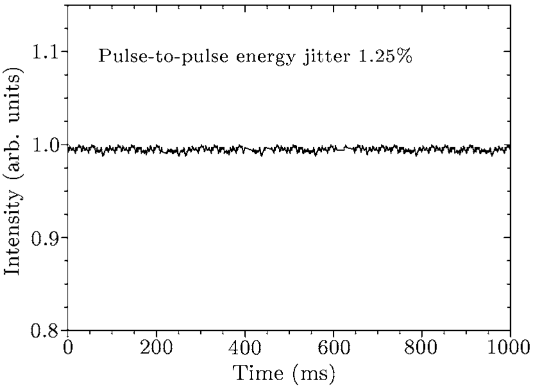

Fig. 7. Short-term stability of pulse-to-pulse energy output from the regenerative amplifier.

In conclusion, we have discussed some special advantages of the ring regenerative amplifier compared with the linear one and presented our self-designed ring regenerative amplifier for chirped-pulse amplification at a 1 kHz repetition rate. The ring cavity is optimized by theoretical analysis and calculation. Experimental result shows that the output laser of the amplifier has very good spot pattern. Moreover, the slope efficiency of the amplifier is up to 40% and pulse-to-pulse energy jitter is less than 1.25%. All these experimental results indicate that the ring regenerative amplifier has a high performance, which is very advantageous for the laser pulse from it to be further amplified in next stage for TW amplification or compressed directly for other physical applications.

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References

[1] Strickland D and Mourou G 1985 *Opt. Commun.* **56** 219
[2] Aoyama Y et al 2003 *Opt. Lett.* **28** 1594
[3] Sun Z P et al 2005 *Chin. Phys. Lett.* **22** 339
[4] Schnurer M et al 1998 *Phys. Rev. Lett.* **80** 3236
[5] LeBlanc C, Curley P and Salin F 1995 *Advanced Solid-State Lasers* **24** 314
[6] Koechner W 1996 *Solid State Laser Engineering* (Berlin: Springer)
[7] Yamakawa K and Barty C 2000 *IEEE J. Select. Topics Quantum Electron.* **6** 658
[8] Yanovsky V, Felix C and Mourou G 2001 *IEEE J. Select. Topics Quantum Electron.* **7** 539