10 kHz 54 W Ti:sapphire regenerative amplifier
as a pumping laser of a laser-plasma X-ray source

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ABSTRACT

We are developing a multi-kHz repetition rate high-average power Ti:sapphire regenerative amplifier as a pumping laser of a laser-plasma X-ray source. With an optimally designed ring resonator with a cryogenically-cooled laser rod, the average output power of 54 W before compression was achieved when pumped by a 180-W green laser at 10 kHz repetition rate. The focusability of the output beam was better than two times of the diffraction limit and can be compressed to 82 fs. Possibility of scaling to higher output power is discussed.

Keywords: Ti:sapphire laser, regenerative amplifier, kilohertz repetition rate, high average power

1. INTRODUCTION

We are developing applications of a laser-produced plasma (LPP) as an intense short-wavelength-radiation source. As an excitation laser for producing a plasma, a multi-kHz repetition rate high-average-power Ti:sapphire (Ti:S) laser is being developed.

1.1 Laser-plasma light source

Laser produced plasma is a high-brilliance X-ray and extreme ultraviolet (EUV) source. We have been developing many applications making use of it, including EUV lithography, biological and medical applications. Merits of a laser-plasma light source are its small size, high brilliance, and short-pulse duration. These properties are important for high-spatial-resolution measurements.

1.2 Applications and multi kHz repetition requirement

A laser-plasma light source can explore many applications. We are developing our original applications.

The main application of LPP we are developing is EUPS (Extreme Ultraviolet excited Photoelectron Spectroscopy), which is a novel surface analysis using an EUV emission from a LPP. Photoelectrons from a sample excited by EUV light are energy-analyzed with a time-of-flight (TOF) method by taking advantage of a pulsive nature of a LPP. We have demonstrated that the energy resolution of EUPS is better than 0.3 eV. EUPS has a capability of ultra-high spatial resolution, and the spatial resolution better than 1 µm has been demonstrated. The present energy resolution of 3eV at 1 µm spatial resolution will be improved to sub-eV in very near future. Just as a reference, in conventional x-ray photoelectron spectroscopy (XPS), the energy resolution is approximately 0.8 eV and the spatial resolution is several tens of µm.

We demonstrated that the time-average photon flux on a sample can be ten times higher than that available from a bending magnet synchrotron radiation. We plan to replace a 100-Hz YAG laser (Continuum, Infinity) presently employed for producing the LPP source of EUPS with a 1 kHz Ti:S laser (Spectra Physics, Hurricane) for high throughput analysis. For a higher throughput we plan to increase the repetition rate to a level higher than 10-kHz.

We are also developing other LPP applications such as an EUV source3 and defect inspection4 of multi-layered mask blanks, both for EUV lithography, and x-ray microscopy of living cells5. In many applications, multi kHz repetition-rate operation is required for high throughput analysis.

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1.3 Requirements of lasers for x-ray generation

The source in EUPS is required to have a temporal duration shorter than a few ns for a decent energy resolution in TOF analysis. In generating x-rays, an excitation laser is required to exhibit the pulse duration shorter than 1 ns to achieve high peak-power and produce a high temperature plasma. On the other hand, the pulse duration should not be in the order of several tens of femtoseconds. The reason is that highly ionized ions are required for emitting EUV and x-rays, where the ionization time cannot be shorter than 1 ps, and the duration of the heating source should be longer than a few tens of a ps.

In our LPP generation experiment, using a commercial 1 kHz Ti:S laser (Spectra Physics, Spitfire), EUV radiation of a wavelength longer than 10 nm was strong enough for EUPS when a laser pulse of 1 mJ was focused to a few tens of a µm on a rotating rod target. However, the intensity of x-rays of a wavelength shorter than a few nm was found to be very weak for both stretched and compressed pulses. Thus, we found that the pulse energy needs to be larger than several mJ for generating x-rays. That is, a Ti:S laser for generating a LPP x-ray source should operate at multi-kHz repetition rates, with a pulse energy of several mJ and with good beam focusability to tens of a µm in diameter. Additionally, not fully-compressed femtoseconds pulses but slightly stretched picoseconds pulses should be employed for generating a LPP x-ray source.

1.4 Previous works

A large scale master-oscillator power-amplifier (MOPA) system can generate a joule-class high-energy pulse of femtoseconds pulse duration.\textsuperscript{6,7} The repetition rate less than 10 Hz is, however, much lower than our requirement. Although recently progressing fiber lasers emit CW output power more than kilo-watts, this was achieved at tens of MHz repetition rate, and the pulse energy has not yet reached to a milli-joule.\textsuperscript{8}

As a multi-kHz repetition rate sub-ps pulse laser, the highest-average-power reported before our work for a single stage Ti:S amplifier system was 11 W, where an output energy of 1.1 mJ was achieved when pumped with a 100 W average-power laser at 10 kHz.\textsuperscript{9} Even using multistage amplifiers, the maximum output power was 37.7 W before compression at 5 kHz and 16 W at 10 kHz.\textsuperscript{10}

1.5 Our achievements

We designed a single stage regenerative Ti:S amplifier for a high efficiency at 10 kHz. Complex multistage amplifier is not preferable for our LPP light source. The output pulse energy was 7.4 mJ before compression at 1 kHz repetition rate when pumped with a 20 W green laser. The realized conversion efficiency of 37% is the highest ever reported.\textsuperscript{11} With the same resonator, the average output power of 40 W was obtained when pumped by a 180 W laser at 10 kHz repetition rate.\textsuperscript{12}

At 180W pumping power, thermal lens effect is significant even for a cryogenically cooled rod. Therefore, to maximize the efficiency, the ring resonator was re-designed by considering the thermal lensing effect under cryogenic cooling of a laser rod. This re-design of the resonator improved the power to 54 W with the conversion efficiency of 30%. The output beam quality of the regenerative amplifier is better than two times of the diffraction limit. The pulse can be compressed to 82 fs. Possibility of higher power will be discussed.

2. RESONATOR DESIGN

A ring resonator was designed as below. A convex lens with a focal length of f was placed in the ring resonator at the symmetric position to the laser rod. We learned this design from ref. 13 and judged it the best to realize a good beam quality.

2.1 High efficiency regenerative amplifier

Low loss and high gain are essential to achieve a high conversion efficiency as mentioned in our previous report.\textsuperscript{11} However, the gain should not be too large to avoid parasitic oscillation. A single-pass small signal gain $g_0$ is given by

$$g_0 = \exp\left(\frac{E_a}{E_s}\right),$$

(1)
where $E_s$ is the stored fluence in the laser rod and $E_s$ is the saturation fluence of 0.9 J/cm$^2$ for the case of Ti:S. To realize a high-stored fluence for a high gain, a pump laser beam is tightly focused in a laser rod, and the resonator mode beam radius should match with the size of the focused pump beam. A laser rod is placed at the beam waist position of the resonator mode beam. The beam waist radius $\omega_z$ is given by \cite{14}

$$\omega_z^2 = \left( \frac{\lambda}{2\pi} \right) \sqrt{(4f - L)L} .$$

(2)

where, $\lambda$ is the laser wavelength of 800nm, $f$ is the focal length of a convex lens inserted in the resonator to adjust beam waist radius, and $L$ is a round trip optical path length of the resonator.

When a pump power of $P_{\text{pump}}$ is focused in a radius of $r_o$ at the rod position, the stored fluence is calculated as

$$E_{at} = \frac{P_{\text{pump}} C_{abs} C_{\text{Stokes}}}{\nu \pi r_0^2 C_{\text{Brewster}}} ,$$

(3)

where, $\nu$ is the repetition frequency, $C_{\text{abs}}$ is an absorption rate of the pump beam in the rod, $C_{\text{Stokes}}$ is a Stokes factor from the pump beam to the amplified beam. The rod is Brewster cut, and $C_{\text{Brewster}}$ is a factor of 1.72 due to Brewster incidence. We achieved the conversion efficiency of 37\%\textsuperscript{14} when $E_{at}$ was 1.7 $E_s$. For high-conversion efficiency, the resonator mode beam radius $\omega_z$ should be equal to $r_o$.

### 2.2 Thermal lensing effect

In developing a multi-kHz repetition rate Ti:S laser, overcoming the thermal lens effect of a laser rod is the most important issue. The thermal lens effect can be reduced by cryogenic cooling of a laser rod.\textsuperscript{15} The focal length of the thermal lens $f_T$ is determined\textsuperscript{16} by

$$f_T = \frac{k C_{\text{Stokes}}}{dn/dT E_{at} \nu (1 - C_{\text{Stokes}})} ,$$

(4)

where, $k$ is the thermal conductivity of the rod (W/cm K), and $dn/dT$ is the change of refraction index per unit temperature change (K$^{-1}$). The Stokes factor $C_{\text{Stokes}}$ from a pumping laser, second harmonic of Nd:YAG laser (532 nm), to Ti:Sapphire (800 nm) is 0.67. At 100 K, $k = 4.9$ W/cm K (Ref. 17) and $dn/dT = 3.4 \times 10^{-6}$ (Ref. 18).

A cryogenic cooling system using liquid nitrogen was specially designed to keep the temperature of the rod below 100 K even at the heat load of 200 W. When the repetition frequency $\nu$ is 1 kHz and the stored fluence of $E_{at} = 1.7 E_s$, $f_T = 19$ m, and the thermal lens effect can be ignored. At 10 kHz repetition frequency, however, the temperature at the center of the rod increases and temperature gradient grows to a significant level even under cryogenic cooling because of a finite thermal conductance in the rod. Focal length of the thermal lens will be as short as 1.9 m at 10kHz repetition rate, as seen in Fig.2.

For realizing a stored fluence of $E_{at} = 1.7 E_s$, the pulse energy of a pumping laser needs to be 20mJ when focused to a radius $r_o$ of 390 $\mu$m by taking account the Stokes factor of 0.66 and the absorption efficiency of 0.97 by the rod, and the average pumping power is 20 W at 1 kHz operation. Then, thermal lens effect can be neglected and a ring resonator with a round trip optical path length $L$ of 3.6 m and a convex lens of a focal length $f = 1$ m provides a beam waist radius of $\omega_z = r_o$ for the resonator mode. At 10 kHz operation, the thermal lens is ten times larger than for 1kHz as seen from Eq.(4).

The beam radius $\omega_{zT}$ of the resonator mode at the laser rod is calculated to be

$$\omega_{zT}^4 = \left( \frac{2 \lambda f_T}{\pi} \right)^2 \frac{2f - L/2}{2f_T - L/2} \left( \frac{L/2}{2f + 2f_T - L/2} \right) ,$$

(5)

If the resonator length is fixed, the resonator mode beam radius increases to 440 $\mu$m. Mis-matching of the pump beam radius $r_o$ to $\omega_{zT}$ causes decrease of the conversion efficiency. When a focused diameter of the pumping laser is fixed to keep the optimum stored fluence for high gain, the resonator length $L$ should be increased to 3.8 m according to Eq. (5).
2.3 Amplifier setup

Figure 1 is a schematic of a 10 kHz regenerative amplifier. A Ti:sapphire laser rod (6x6x25 mm Brewster-cut, 0.1 wt. % doped) is held in a copper mount and cooled by using liquid nitrogen. The side wall of the rod is wrapped with an indium foil for better heat conduction. The laser rod and the copper mount are enclosed in a vacuum cell of $10^{-4}$ Pa pressure with Brewster windows to prevent frosting of the rod surfaces. The temperature of the mount is kept lower than 100 K at the maximum heat load of 200 W. This cryogenic cooling system was specially designed with advices from AIST Cryogenic Technical Center. Liquid nitrogen is supplied from a compact liquid nitrogen generator (Iwatani NL-300) capable of supplying 28 liter a day, which is sufficient to keep the rod cool during 12 hours of operation at up to 200 W heat deposition.

The laser rod is pumped by two second harmonics of diode-pumped Nd:YAG lasers (Powerlase AO2/G). In the experiment described below, the maximum total pumping power was 180 W. The pumping laser beam is required to have a good focusability to achieve high pumping fluence required for high conversion efficiency. The beam quality of the pumping laser was measured to be $M^2 = 23.5$. The pump beams were focused by plano-convex lenses with focal lengths of 350 mm and 500 mm, respectively. In our experiment, due to the available space on our anti-vibration table, beam path length to the laser rod from the two pumping laser were different. Hence the different focal lengths were required to give the same minimum focal spot radius of 300 $\mu$m on the rod. To match the pump beam diameters to the resonator mode, the positions of focusing lenses were fine-adjusted. An optical switch consisting of a Pockels cell, a thin-film polarizer, and a half-wave plate switched out a pulse from the resonator at the best timing.

![Schematic drawing of a ring regenerative amplifier](image)

Fig. 1. Schematic drawing of a ring regenerative amplifier. A cryogenic-cooled Ti:sapphire rod is kept in a vacuum cell and placed at the beam waist for $f = 1$ m intra-cavity lens. M1–M6 are cavity mirrors; $\lambda/2$ is a half-wave plate; PC is a Pockels cell; TFP is a thin film polarizer; FI is a Faraday isolators; and AO2/G is a pump laser.

3. EXPERIMENTAL RESULT

The focal length of the thermal lens was measured as described next. From the measured focal length, we decided that the resonator length of the ring resonator should be changed from $L = 3.6$ m for the 1kHz negligible thermal lens case to $L = 3.8$ m for the 10kHz case. This change improved the output power and the conversion efficiency. The output beam quality and pulse compression ability were also measured.

3.1 Measurement of thermal lensing effect

The thermal lens was measured with a probe beam and the lens power was estimated by the following equation
Here, \( L_d \) is a distance from the rod to a detector (CCD camera), \( \omega_r \) is the probe beam radius at the rod, and \( \omega_d \) and \( \omega_{d0} \) are the beam radii at the detector position in the cases with and without the thermal lens. The results were compared with results by an optical complex amplitude simulation code (Applied Optics Research, GLAD). The observed thermal lens power is shown in Fig. 2.

Calculated values by Eq. (4) shown by dashed lines agree well with the observed values. Agreement is not good for the value of \( 1/f_T \) larger than 2. When thermal lens power is very large, the simple model of Eq. (6) is not applicable. As seen in the figure, even under the cryogenic cooling, the lens power increased and the focal lengths of the thermal lens was 2.2 m at a pump power of 170 W.

\[
\frac{1}{f_T} = \frac{\omega_{d0} - \omega_d}{\omega_r} \frac{1}{L_d}.
\]  

3.2 Seed pulse

A mode-locked Ti:S oscillator (Spectra Physics, Tsunami) is pumped by a 4 W green laser (Spectra Physics, Millenia Vs). The output power of the oscillator is 500 mW with the repetition frequency of 76 MHz. The measured pulse duration was 22 fs. The center wavelength is about 800nm. The mode-locked pulses are stretched to 200 ps using a double-pass, 1200-line/mm grating expander and injected as a seed pulse with the pulse energy of 0.8 nJ.
3.3 Amplification

Firstly, measurements were performed with the resonator length of 3.6 m. If the thermal lens effect can be neglected, the radius of the beam waist of the resonator mode located at the rod position is calculated to be 390 µm. As described above, the best pumping condition, \( E_p = 1.7E_s \), is achieved when pumped with the pulse energy of 20 mJ with focused diameter of 390 µm. In this condition, i.e., 20W pumping at 1 kHz, the conversion efficiency as high as 37% was observed.

When this resonator was operated at 10 kHz repetition rate with a pump power of 180 W, the maximum output power of 40 W was observed, as shown by open circles in Fig. 3. This power is more than three times of that reported previously from a single-stage single rod Ti:S regenerative amplifier\(^9\). However, the conversion efficiency of 22% is lower than 37% achieved for 1 kHz 20W pumping with the same resonator.

As discussed above, thermal lens effect becomes significant at 10 kHz operation even under cryogenic cooling. Best performance should be realized with a longer resonator for the thermal lens of \( f_T = 2.2 \text{ m} \).

Filled squares in Fig. 3 show the observed power for the resonator of 3.8 m round trip length. The maximum output power increased to 54 W. In our experience, the pulse energy of a few mJ is the threshold for the x-ray generation. Therefore, the pulse energy of 5.4 mJ is significantly important for generation of x-rays.

While the achieved conversion efficiency of 30% in the optimized resonator for 10 kHz is still lower than 37% achieved for 1 kHz operation, this value is higher than those reported by other groups in the past\(^9,\)\(^13\).

![Fig. 3. Output power of the regenerative amplifier at 10 kHz as a function of pump power.](image)

### 3.4 Output beam quality

A far-field image of the output pulse was observed with a CCD camera with a \( f = 1 \text{ m} \) focusing lens. The measured image is shown in Fig. 4. The diffraction limited focal spot diameter (XDL) is 225 µm in this setup. More than 80% of
energy was included within the area of two times of the diffraction limit. The requirement for our laser-plasma X-ray source was well satisfied.

A pulse of 4% power was split from the output beam and compressed by a gold-plated grating of 1500 line/mm. Autocorrelation trace of the compressed pulse indicated a FWHM width of 82 fs.

![Far-field image of the output pulse and intensity traces for the vertical (solid line) and horizontal (dashed line) direction with the output power of 56W.](image)

4. DISCUSSION

In our experiment presented here, the output power was limited mainly by the available pumping power. However, if some people ask us to build a kilo-watt class Ti:S regenerative amplifier by providing us a enough high power pumping laser, it will not be easy to scale up the power.

At 1 kHz repetition rate, the output power of 7.4 W was achieved with a pumping power of 20 W. The conversion efficiency was 37%. When this resonator was operated at 10 kHz repetition rate, the output power of 40 W was obtained for a pump power of 180 W. The conversion efficiency was 22%. With the optimized resonator by taking into account the thermal lens which becomes significant at a pumping power exceeding several tens W, the output power increased to 54 W, and the conversion efficiency was improved to 30%.

Thus, we succeeded in improving the conversion efficiency for 10kHz operation by optimizing the resonator design. However, the efficiency of 30 % was still lower than 37% in 1 kHz. By careful examination of the experimental results, we noticed the efficiency was reduced at a pumping power above 100W. This might be caused by un-known non-linear losses. To scale up the power further beyond 100 W, this un-known non-linear losses which might exist need to be clarified.
5. CONCLUSION

The 10 kHz repetition rate high average power Ti:sapphire regenerative amplifier has been developed as a pumping laser of a laser-plasma X-ray source. Ring resonator is adopted for a good beam quality, and a thermal lensing effect in a laser rod at high power pumping is reduced by cryogenic cooling. With the resonator with which output power of 7.4 W was achieved when pumped by a 20 W laser at 1 kHz repetition rate, output of 40 W was observed when pumped by a 180 W laser at 10 kHz repetition rate.

In order to improve the performance at 10 kHz operation, we measured the thermal lens effect at a pumping power up to 180 W. The thermal lens power was observed to increase with power and reached 1/2.2 m at 170 W. The observed increase of the thermal lens power agreed well with the theoretically expected ones. From this measurement, we found the best performance should be achieved by increasing the resonator round trip length from 3.6 m for a 20 W pumping to 3.8 m at 10 kHz. As expected, the maximum output power was improved by 35% to reach 54 W with the re-designed resonator. Our previous output power of 40 W was three times larger than reports at other institutes. The world record of output power of Ti:S laser was re-written by the present optimization of the resonator design.

The quality of the output beam showed enough performance for our applications. More than 80% of energy was focused within the two times of the diffraction limit. The amplified beam showed the possible compressed pulse duration to 82 fs.

By careful examination of the experimental results reported here, we found there exist non-linear losses. When further scaling-up of Ti:S laser is required, detailed study on this un-known non-linear will be indispensable.

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