10 kHz 40W Ti:sapphire regenerative ring amplifier

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Abstract

With a cryogenic-cooled Ti:sapphire regenerative ring amplifier, 37% conversion efficiency at 1 kHz operation and 40 W output power at 10 kHz operation are achieved.

We are developing EUV (extreme ultraviolet) photon excited photoelectron spectroscopy (EUPS) for the analysis of surfaces with a laser-produced plasma (LPP) EUV source. One-micron spatial resolution has been demonstrated with our EUPS. In order to improve spatial resolution below 0.5 µm and to shorten the exciting EUV wavelength, we need to increase repetition rate of a LPP source to multi kHz from the present rate of 100 Hz. A sub-ns duration EUV source is required in the EUPS application, and we are developing a multi-kHz repetition rate Ti:sapphire regenerative amplifiers. In many other applications of LPP X-ray source as well, high repetition-rate operation is required for high throughput, and a laser power is required to be as high as possible to generate shorter wavelength x-rays.

To our knowledge, the maximum conversion efficiency of a regenerative amplifier at a few watt output level was around 31% at 1kHz operation, and the maximum power was 16 W before compression at 10 kHz. In this paper, we report the achievements of 37% conversion efficiency at 1 kHz repetition rate, and 40 W at 10 kHz operation.

In the development of a multi-kHz repetition rate Ti:sapphire laser, overcoming the thermal lens effect of a Ti:sapphire laser rod which becomes serious at multi-kHz operation, high density pumping for saturation lasing, and minimizing the cavity loss for high extraction efficiency of the stored energy are the most crucial issues. The technology of cryogenic cooling a Ti:S laser rod has been demonstrated to solve the thermal lens effect, and we adopt the cryogenic cooling method. To achieve a near diffraction limit beam and the low cavity loss, we adopt a ring resonator.

A Ti:sapphire laser rod (6x6x25 mm Brewster-cut, 0.1wt% doped) was held in a copper mount with liquid nitrogen cooling. The laser rod and the copper mount were enclosed in a vacuum cell of 10⁻⁷ Pa pressure with Brewster windows to prevent frosting of the surfaces of the optics. The temperature of the mount was kept lower than 100 K degree. A convex lens of f=1 m was inserted in the ring resonator so that the beam waist comes at the laser rod. The round trip length of the resonator was 3.6 m. In this configuration, the beam waist of TEM₀₀ resonator mode is calculated to be 780 µm. Optical switch consisting of a Pockels cell, a thin-film polarizer and a half-wave plate switched out a pulse from the resonator.

For 1-kHz repetition rate operation, the laser rod was pumped by the second harmonics (527nm) of a diode-pumped Nd:YLF laser (Evolution30). The measured M² of the pumping

Fig. 1. Schematic layout of 10kHz 40W Ti:sapphire regenerative amplifier
laser was 31.4. For the best match between the pumping beam and the resonator mode, a focusing lens of 300-mm focal length was placed 1.42 m from the pump laser. Fine adjustment of the lens position was performed by maximizing the output power. The measured absorption of the pump laser beam in the rod was 97%. With a beam size of 1340 × 780 µm² in the rod after horizontal magnification of 1.72 times due to Brewster incidence, the stored fluence was estimated 1.7E₀ for a pulse energy of 20 mJ, where E₀ is the saturation fluence of 0.9 J/cm².

A stretched pulse of 0.8 nJ from a mode-locked Ti:sapphire oscillator (Spectra Physics, Tsunami) of 22 fs (FWHM) pulse width was injected as a seed pulse. The pulse was switched out from the ring resonator after a 14-round trip amplification. By fine adjusting the amplifier for realizing high pumping fluence and low roundtrip loss, we achieved average output power of 7.4 W for a pump laser power of 20 W with the conversion efficiency of 37%, which is the maximum reported value to our knowledge.

To obtain much higher average power, a 10-kHz system is under development. At higher repetition rate, because the energy of a single pulse is small, a pumping laser beam is required to have a good focusability to achieve high pumping fluence required for high conversion efficiency. The measured pump beam quality of our pumping laser, the second harmonics of diode-pumped Nd:YAG laser (Powerlase AO2/G) was M² = 23.5. The laser rod was pumped by two lasers each emitting 90 W output power with the maximum total pumping power of 180 W.

Figure 1 shows the schematic layout of the 10 kHz regenerative amplifier. Although some of optical components were changed or modified, the ring resonator is essentially the same as that of the 1-kHz system. The pump beams are injected from the both ends of the rod.

The seed pulse was amplified about 22 round trips. So far, 40 W has been observed before compression for the pumping power of 180 W. A far-field image of the output pulse at the average output power of 35 W is shown in Fig. 2, which was recorded by a CCD camera placed at 5.7 m from the laser beam output by focusing the beam with a lens of 1m focal length. Figure 2 (b) shows the intensity traces across the peak. The theoretical beam waist diameter of the TEM₀₀ mode was 180 µm at 1/e² intensity in this measurement setup. The corresponding Gaussian curve is drawn as a dotted line in Fig. 2 (b). The observed beam was well focused as M²<1.2.

Autocorrelation trace of the pulse compressed from 4% power of the amplified beam shown in Fig. 3 indicates a FWHM width of 58 fs. The pulse-compressed power was 20 W when the output power form the regenerative amplifier was 30 W. The beam diameter was 8 mm. At this power density, thermal distortion of the compressor grating became obvious, and we realized we need to increase the beam size for higher power compression.

In summary, we constructed a ring resonator Ti:S regenerative amplifier with the rod cooled to 100 K, and output power of 7.4 W was achieved with the conversion efficiency of 37 % when pumped by 20W 1kHz repetition rate pumping laser. When the regenerative amplifier was operated at 10 kHz pumped by a 180 W laser, the output power of 40 W was obtained. The output beam was near diffraction limit, M²<1.2, and FWHM of the compressed pulse was 58 fs.

References