MHz-Repetition-Rate Yb:YAG Thin-Disk Ring Oscillator Pumped by 969nm Zero-Phonon-Line for Intra-Cavity High Harmonic Generation

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Abstract: We developed a high power storage ring oscillator using a Yb:YAG thin-disk gain medium pumped with 969nm absorption line. The intra-cavity average and peak power of 1kW and 200MW were attained, respectively at 14MHz operation. © 2020 The Authors

1. Introduction

For applications such as photoelectron spectroscopy or photo-chemical studies, multi-MHz rate highly coherent XUV sources are demanded. Such coherent XUV radiation is obtained through high harmonic generation (HHG) process when intense laser pulses are focused to gaseous targets [1]. One way of achieving this is intra-cavity HHG with high power laser oscillator. Yb:YAG thin-disk lasers are very suitable for the pumping of such high repetition rate XUV radiation. We already succeeded in generating HH fields with the repetition rate of 3 MHz at the University of Tokyo “Photon Ring” facility [2]. To get brighter XUV radiation, we need to boost the peak power inside the oscillator. A new scheme of pumping with 969 nm absorption line (i.e. Zero-Phonon-Line: ZPL) of Yb:YAG was tested with a more compact ring oscillator constructed at RIKEN.

With Yb:YAG media pumped by conventional 940 nm region laser diode (LD), we succeeded in demonstrating stable Kerr lens mode-locking (KLM) in the thin-disk oscillator of ring configuration for the first time [3]. Later, we improved the laser performance using a diamond heatsinked thin-disk which has higher thermal conductivity and its pulse could result in 128 MW intra-cavity peak power, 68 μJ energy (3.8 μJ for output) with 470 fs pulse duration at 15 MHz operation when the input was 290 W [4]. However, further scaling was prevented by wavefront distortion on the thin-disk due to heat induced by high power pumping. To reduce the thermal load, another pumping scheme of ZPL which has lower quantum defect can be utilized. The ZPL wavelength for Yb:YAG is around 968.8 nm with FWHM of 1~2 nm at room temperature [5]. Therefore, we need to tune it carefully in the very narrow spectral range for efficient pumping. For this purpose, we introduced VBG-locked LDs as fiber-coupled 969 nm pump sources and successfully improved the laser performance further.

2. Experiments and Results

The oscillator design is based on that reported in Refs. [3,4]. We used a diamond heatsinked Yb:YAG thin-disk (Dausinger+Giesen GmbH, TDM1.0) as the gain module. The diameter of the disk is 12 mm, the thickness is 220 μm, and the Yb dope is 7 at.%. The thin-disk was pumped by fiber-coupled 969nm VBG-locked LDs produced by Hamamatsu Photonics. The diameter of the pump region on the disk was set to 3.7 mm. It delivers a pump density >5 kW/cm^2 at the maximum pump power of 550W available.

The cavity was constructed with about 25 cavity mirrors including broadband Gires-Tournois-Interferometer (GTI) mirrors to compensate for the nonlinear phase shift accumulated during the propagation in transmitting materials and air inside the cavity. We can optimize the total amount of the negative GDD per round trip by changing the number of GTI mirrors discretely. The repetition rate was kept almost the same as before to around 14 MHz and the corresponding cavity length was ~21 m for better comparison to the previous scheme of pumping with 940 nm region.

First, to check the effectiveness of the ZPL pumping scheme, we increased the pumping power to get a higher mode-locking output as much as possible by accordingly selecting several out-coupling (OC) rates. As expected, power scaling was done by its less wavefront distortion due to the reduction of accumulated heat on the thin-disk. We obtained stable KLM at 14 MHz operation and could sustain it over 10 minutes until air turbulence interrupted. Table 1 shows the mode-locking results obtained for each OC cavity. Figure 1 shows obtained pulse characteristics at the intra-cavity peak power of 198 MW with the 5.5% OC case. Autocorrelation trace and spectrum show 280 fs pulse duration with sech^2 fit and the bandwidth of 4.0 nm (FWHM), respectively, and the time-bandwidth product was 0.315 indicating Fourier transform limited pulse. In the case of the OC of 9% transmission the power extracted from the oscillator was 74.9 W and the intra-cavity average and peak power were 832 W and 162 MW, respectively. When the OC rate was decreased to 5.5% and 3.7%, we could increase the intra-cavity values as shown in Table 1. Although the obtained intra-cavity peak power level of 200 MW was almost the same for 5.5% and 3.7% OC cases, the required input pump power decreased by one fourth, which means it could be more efficiently stored inside the laser cavity. This is in turn as we construct a system for HHG much more efficient one we could achieve.

Table 1. Mode-locking results and parameters for different OC rate cavities.

OC rate	9.0 %	5.5 %	3.7 %
GDD per round trip (fs^2)	-23,000	-18,000	-23,000
Input power (W)	481	416	319
Average power (W) [extra / intra]	74.9 / 832	49.8 / 905	36.7 / 992
Pulse repetition rate (MHz)	14.6	14.4	14.4
Pulse energy (μJ) [extra / intra]	5.1 / 57	3.5 / 63	2.5 / 69
Pulse duration (fs)	310	280	299
Peak power (MW) [extra / intra]	14.6 / 162	10.9 / 198	7.5 / 203

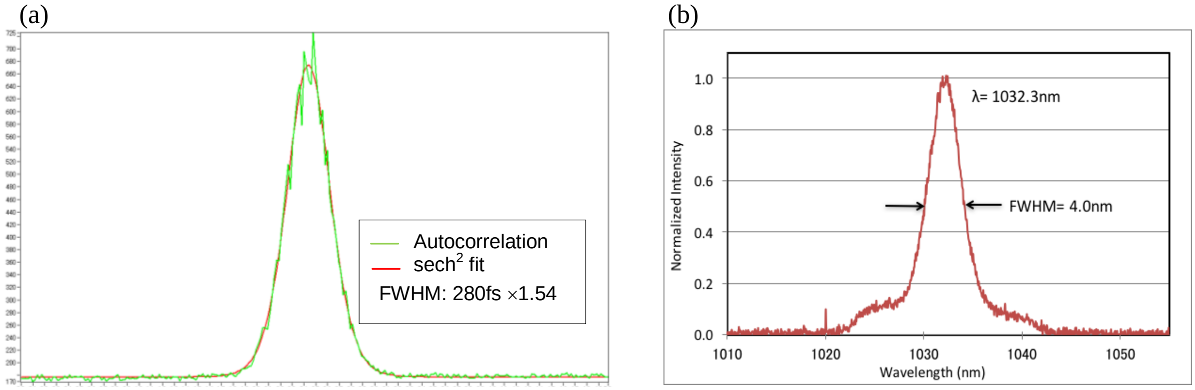

Fig. 1. Pulse characteristics in the case of intra-cavity peak power of 198 MW. (a) Autocorrelation trace with a sech^2 fit showing 280 fs pulse duration, and (b) spectrum showing bandwidth of 4.0 nm (FWHM) and its pedestal feature due to strong SPM effect.

3. Conclusion

We applied the ZPL pumping scheme to our thin-disk ring oscillator and successfully improved the laser performance in terms of intra-cavity peak power and pulse duration. Now, the highest peak power of 203 MW at a repetition rate of 14.4 MHz and average power of about 1kW were attained with just below 300 fs pulse duration in the case 3.7% OC rate and total GDD value of -23,000 fs^2 in atmospheric condition. If we focus the beam to 25 μm mode diameter, the peak intensity of 8×10^{13} W/cm^2 is obtained and is already high enough to generate HH inside the oscillator. Further peak power scaling is expected by extension of cavity length and reducing the pulse repetition rate, and also by fine tuning of the intra-cavity SPM and GDD values. To achieve this, it is more preferable to place the oscillator in the vacuum condition similar to the Photon Ring, which should lead to a more stable performance of the system as well.

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