A 12.4 W Ti:sapphire Based Regenerative Amplifier System with 200 fs Pulse Width at 50 kHz Repetition Rate

Tomohiro IMAHOKO,^{1,2} Norihiro INOUE,¹ Kazuya TAKASAGO,¹ Masanao KAMATA,¹

Tetsumi SUMIYOSHI,¹ Hitoshi SEKITA,¹ and Minoru OBARA²

¹ Cyber-Laser Inc, Telecom Center Build. East 2F, 2-38, Aomi, Koto-ku, Tokyo, 135-8070

² School of Integrated Design Engineering, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama-shi, 223-8522

(Received January 17, 2008)

We have developed a cryogenically cooled Ti:sapphire regenerative amplifier at the repetition rate of up to 100 kHz which was pumped by the intracavity SHG pulses of Yb:YAG thin disk laser. An electro-optic (EO) switching device employing a β -barium borate (β -BBO) crystal was used for pulse extraction from the amplifier resonator. The maximum average amplified power obtained was 21 W under the two pumping pump powers of 70 W at 50 kHz and 75 W at 100 kHz. The amplified pulse was able to be compressed to 200 fs by a grating pair compressor, and the output power was 12.4 W at 50 kHz. The cryogenic cooling system made Ti:sapphire crystal capable to be pumped with over 70 W SHG power in order to keep the stable condition of the regenerative amplifier resonator.

Key Words: Femtosecond, Amplifier, Ti:sapphire, Glass, Scribing

1. Introduction

High precision material processing with femtosecond laser pulses has been attracting many interests from industries. To realize cost effective productions using femtosecond lasers, one of the critical technical issues is a processing speed. The pulse energy in excess of 100 μ J at 50–100 kHz is necessary for advanced industrial materials processing such as a flat panel display (FPD) glass scribing without heat accumulation effects¹⁾. And its pulse width is required to be shorter than 500 fs for suppressing the heat affected zone (HAZ) because the energy relaxation time of many industrial-use materials from electron to phonon (lattice) is a few picoseconds. For this purpose, we have developed a 50 kHz, 12.4 W femtosecond laser system and demonstrated a flat panel display (FPD) panel scribing at a high speed of 300 mm/s that is comparable to the current speed achieved with scribing wheels.

2. Development of 12.4 W femtosecond laser system with 200 fs pulse width at 50 kHz

Figure 1 shows a schematic of the developed system based on a chirped pulse amplification (CPA) system consisting of a seed laser, a fiber pulse stretcher, a regenerative amplifier and a pulse compressor.

In order to generate femtosecond pulses with an output power exceeding 10 W at 50 kHz in a Ti:sapphire based chirped pulse amplifier, a green pump power is required to be higher than 70 W. Moreover, the focal beam diameter on the incident surface of a Ti:sapphire crystal should be smaller than 220 μ m to demonstrate larger pump fluence than 2 J/cm². As such a pump laser, we have developed a highly stable Yb:YAG thin disk green laser with high beam quality²⁾. The maximum power in excess of 90 W has been obtained as shown in Fig. 2.

The thermal lens induced in a Ti:sapphire crystal is critical to

the resonator conditions and the crystal should be well thermally managed in terms of heat generation and its dissipation during such high power operation. We employed a cryogenically cooling system for thermal management in the Ti:sapphire crystal^{3,4)}. Figure 3 shows the calculation result of focal length of thermal lens as a function of crystal temperature at pump fluence of 2 J/cm². The thermal conductivity of the Ti:sapphire crystal was dramatically improved by cooling the crystal around the temperature of 100 K and the focal length was estimated as short as 600 mm in the case of a 70 W pump power at 50 kHz. Additionally, we designed a resonator to have a high tolerance for the variation of the thermal lens by placing the Ti:sapphire at the beam waist position of the resonator beam mode. Even if the focal length of the thermal lens becomes shorter, 300 mm in the worst case in our estimation, the cavity creates oscillation mode still in a stable state with the slight change of the mode size of less than 5% in the crystal.

Fig. 1 Schematic of the developed high power system.

Fig. 2 Plots of SHG power as a function of LD power.

At 100 kHz repetition rate operation, an acousto-optic (AO) switch is frequently used for regenerative amplifier⁵⁾. AO devices have the ability of high repetition operation in excess of 200 kHz but are not suitable for the case of high gain cavity because its diffraction efficiency is not unity and hence some fraction of the amplified pulse energy is left in the cavity, causing a low extraction efficiency and low post pulse extinction ratio. On the other hand, an EO switcher can extract almost all energy of the amplified pulse at each round trip. The repetition rate had been limited to be on the order of 10's kHz by high voltage electronic driver for the EO switcher and also by the Piezo ringing effect of Pockels cells. Recently, a 1 MHz cavity dumped oscillator and a 200 kHz regenerative amplifier with EO switch has been reported^{6,7)}. From such a technical background we used a BBO Pockels cell (Lightgate 4, Cleaveland Inc.) to inject seed pulses and to switch out the amplified pulses. Due to its negligible Piezo ringing effect the pre/post pulse extinction ratio could be successfully obtained to be higher as high as 200. The maximum repetition rate determined by the performance of the high voltage driver employing metal-oxide semiconductor field effect transistor (MOSFET) is limited to 100 kHz with an applied voltage of 3 kV. The rise time and fall time are less than 4 ns which is enough to inject and eject stretched pulses in the regenerative amplifier with the cavity length of 2.6 m.

Figure 4 shows plots of amplified power as a function of pump power. A maximum average amplified power obtained was 21 W at the repetition rate of up to 100 kHz. Figure 5 shows the temporal profiles of the build up behavior in the amplifier and the switched off pulse from the amplifier.

Fig. 3 Calculation result of focal length of thermal lens as a function of crystal temperature at a pump fluence of 2 J/cm².

Fig. 4 Plots of amplified power as a function of pump power

The build up time in the amplification was 144 ns and an appreciable ASE was not observed during the build up time. Both the pre-pulse and post-pulse ratio to the ejected pulses measured was less than 1%. The power conversion efficiency of the amplification was obtained to be 30%. The amplified average power at both 50 kHz and 100 kHz resulted in the highest values to our best knowledge in the category of the Ti:sapphire regenerative amplifier.

The amplified chirped pulse was compressed to its pulse duration of 200 fs with a grating pair compressor. The output power was decreased to be 12.4 W due to the grating diffraction efficiency. As shown in Fig. 6, the spectral width of the amplified pulse became narrower than the one of the stretched pulse due to the wavelength dependent gain of the Ti:sapphire amplifier. Since in this experiment we did not compensate for the third order dispersion (TOD) and the spectrum of the stretched pulse was broadened due to a self phase modulation (SPM) in the fiber stretcher, the obtained pulse was not a Fourier transform limited pulse. The Fourier transform limited pulse width calculated with the spectrum of the amplified pulses was 50 fs. Hence, we could easily obtain femtosecond pulses with the pulse width of less than 100 fs if we compensate for the TOD with the grating stretcher, and the grism⁸⁾ compressor or the prism-grating combined compressor. Moreover if we combine our regenerative amplifier and the down chirped pulse amplification (DPA) scheme^{3,5)} the final femtosecond laser power could exceed 20 W.

Fig. 5 Build up behavior in a 21 W amplification at 50 kHz and the ejected pulse profile from the amplifier.

Fig. 6 Spectrum of amplified, stretched and seed pulse.

4. Femtosecond laser FPD glass scribing

We have demonstrated glass substrates scribing using this developed femtosecond laser of 12.4 W, 200 fs at 50 kHz. The used sample glass sheets (Corning eagle 2000) are 200 μm and 700 μm thick which were usually employed for mobile phone display and large size television display, respectively. The scribing speed in both cases was achieved more than 300 mm/s, which was sufficient in comparison to any existing techniques such as mechanical diamond dicer. The scribed glass was easily diced by applying a small mechanical stress along with

the scribed line to be divided to smaller size displays.

5. Conclusion

We have developed the 50 kHz, 12.4 W femtosecond laser system and demonstrated a 300 mm/s FPD glass scribing. In future work, we are going to demonstrate a wide variety of high speed material processing with our developed laser and carry out the reliability test of the laser system in production line.

References

- 1) S. Eaton, H. Zhang, P. Herman, F. Yoshino, L. Shah, J. Bovatsek, and A. Arai: *Opt. Exp.* **13** (2005) 4708.
- 2) T. Imahoko, K. Takasago, M. Kamata, J. Sakuma, T. Sumiyoshi, H. Sekita, and M. Obara: *Appl. Phys. B* **89** (2007) 217.
- 3) D. M. Gaudiosi, A. L. Lytle, P. Kohl, M. M. Murnane, H. C. Kapteyn, and S. Backus: *Opt. Lett.* **29** (2004) 2665.
- 4) I. Matsushima, H. Yashiro, and T. Tomie: *Opt. Lett.* **31** (2006) 2066.
- 5) K. H. Hong, S. Kostitsa, T. J. Yu, J. H. Sung, I. W. Choi, Y. C. Noh, D. K. Ko, and J. Lee: *Opt. Exp.* **14** (2006) 970.
- 6) A. Killi, A. Steinmann, J. Döring, U. Morgner, M. J. Lederer, D. Kopf, and C. Fallnich: *Opt. Lett.* **30** (2005) 1891.
- 7) D. Nickel, C. Stolzenburg, A. Beyertt, A. Giesen, J. Häußermann, F. Butze, and M. Leitner: *Rev. Sci. Instrum.* **76** (2005) 033111.
- 8) E. A. Gibson, D. M. Gaudiosi, H. C. Kapteyn, R. Jimenez, S. Kane, R. Huff, C. Durfee, and J. Squier: *Opt. Lett.* **31** (2006) 3363.