DEVELOPMENT OF Yb LASER FOR HIGH POWER ULTRA-SHORT PULSE*

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Abstract

Ytterbium (Yb) lasers have good thermal and optical properties. The Yb lasers can be pumped by laser diodes. The oscillation wavelength is near the excitation wavelength. Yb can be highly doped in YAG crystal, so Yb-doped crystal has large gain even if the crystal is thin. These properties are advantages for high power operation. Additionally, because of broad emission spectrum of Yb, the passively mode-locked Yb lasers can easily generate femtosecond pulse at high repetition rate. The Yb lasers have been applied to many fields such as optical frequency comb and X-ray generation. Now, femtosecond pulse of much higher energy at high repetition rate is being required for dielectric laser accelerator (DLA) and lasertron. We have developed high power mode-locked Yb laser, and aim to generate 500 fs pulse of 500 W average power at 50 Hz. In this research, e acheived 20 W mode-locked Yb fiber laser amplification system at 1MHz. We report this achievement and the structure of our Yb laser system to achieve our final goal.

INTRODUCTION

Passively mode-locked lasers can easily generate femtosecond pulse at high repetition rate. The femtosecond pulses have been used in many scientific fields. In the accelerator field, femtosecond pulse of much higher energy at high repetition rate is required for new acceleration technologies such as DLA [1], lasertron [2] and laser wakefield plasma acceleration.

Yb lasers have many advantages for high power operation. Yb can be pumped directly by laser diodes (LD), which can convert electricity into light with as high efficiency as 60 percent. Since the difference between the oscillation wavelength and the excitation wavelength is as low as 90 nm, the quantum efficiency of Yb is very high. Furthermore, Yb can be doped in YAG crystal with high concentration, which enables thin disk lasers. The large surface to volume ratio of the thin disk enables efficient heat removal from the laser material and decreases the wavefront distortion due to the thermal lens effect.

Although the Ti:Sapphire lasers excel at less than 100 fs pulse generation, the Yb lasers have advantages over the Ti:Sapphire lasers when we need several hundreds fs pulse generation for high power operation.

In this research, we have developed a high power mode-locked Yb laser, and are aiming to generate 500 fs pulse with 500 W average power at 50 Hz for the new acceleration applications.

CPA SYSTEM OF YB LASER

To achieve the generation of 500 fs pulse of 500 W average power at 50 Hz, CPA was adopted. The schematic layout of the Yb laser is shown in Fig. 1. For amplification, Yb fiber and Yb:YAG lasers were used. The Yb fiber lasers have higher gain than the Yb solid lasers, and fibers can be cooled sufficiently by air. However, LDs for fiber lasers cost more than those for solid lasers, and power scaling cannot be applied for the fiber lasers. Additionally, the fiber lasers can't amplify high intensity pulse because of its damage threshold. For these reasons, the Yb fiber amplifiers were adopted at the first half part, while the Yb:YAG amplifiers were adopted at the second half part.

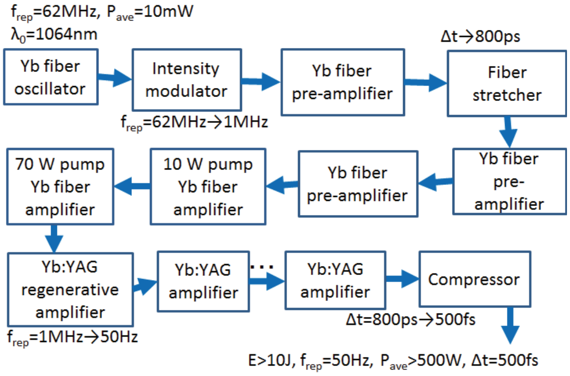

Figure 1: Schematic layout of Yb CPA system.

The ultra-short pulse at 62 MHz was emitted from a Yb fiber oscillator. After that, the pulse was picked up from the pulse train by an electro-optical (EO) module. The repetition rate was reduced from 62 MHz to 1 MHz. Then, the pulse was stretched to 800 ps by a fiber Bragg grating (FBG) stretcher. Through these fiber modules, the power of the pulse decreased. Therefore, three small Yb fiber pre-amplifiers were equipped. These pre-amplifications were needed to suppress amplified spontaneous emission (ASE) at the next amplifiers. After the three pre-amplifiers, the pulse was amplified up to several μJ by two Yb fiber amplifiers pumped by 10 W and 70 W LDs. Next amplifications are done by Yb:YAG lasers. A regenerative amplifier reduces repetition rate from 1 MHz to 50 Hz while amplifying the pulse. Finally, the pulse is amplified up to 10 J by

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the sequent Yb:YAG amplifiers. A grating pair and double prism pair are being considered as a compressor candidate. Whether the compressor is the grating pair or double prism pair, the pulse is compressed from 800 ps to 500 fs, and 500 fs pulse of 500 W average power at 50 Hz is generated by this Yb laser system.

PRESENT EXPERIMENTAL RESULTS

In this section, the experimental results and present laser status are described.

Yb Fiber Oscillator

The Yb fiber oscillator was mode-locked by nonlinear polarization rotation (NPR). Its structure was almost same as typical NPR mode-locked Yb fiber lasers [3]. However, the polarization beam splitter was not used as an output component because the output from it includes more ASE than that from other components in principle. In our oscillator, the reflected light from a grating was used for output. The power of it was 10 mW and the repetition rate was 62 MHz. The central wavelength was 1060 nm, and FWHM of the spectrum was 49 nm.

EO Fiber Module, FBG Stretcher and Preamplifiers

A part of the 62 MHz optical pulse was captured by a photodiode. The frequency of photodiode signal was reduced from 62 MHz to 1 MHz. The delay and voltage of 1 MHz signal was adequately adjusted for the EO module. Figure 2 describes the result of intensity modulation. The pulse was picked up from the pulse train as shown in Fig. 2. The SN ratio after the pre-amplifiers was about 100.

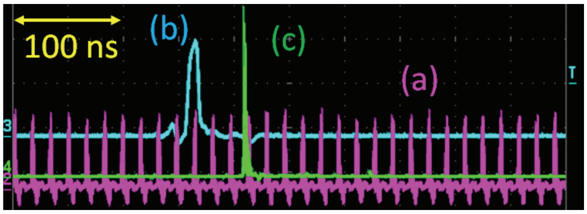

Figure 2: Intensity modulation result. (a) The pulse train from the oscillator, (b) The electric pulse applied on the EO module, (c) The pulse picked up by the EO module

A FBG has periodic refractive index in a fiber, and reflects light at designed wavelength. A FBG stretcher reflected light at different positions according to the wavelength, and gave the pulse positive dispersion. The pulse was stretched to 800 ps here.

The pulse was attenuated through the EO module and at the reflection of the stretcher. In order to suppress ASE at the Yb fiber amplifiers, one Yb fiber pre-amplifier was equipped after the EO module and two were after the stretcher, which were pumped by LDs of 150 mW, 150 mW and 200 mW respectively. By equipping these preamplifiers, the input power to the first Yb fiber amplifier was improved from 0.1 mW to 137 mW.

Yb Fiber Amplifiers

Two Yb fiber amplifiers amplified the pulse after the preamplification. The first amplifier consists of 10 W LD and 4 m long 10 μm-core Yb double cladding fiber. The second amplifier consists of 70 W LD and 2 m long 25 μm-core Yb double cladding fiber. The structure of them is described in Fig. 3. The edges of the fibers were cut at the angle of 8 degrees to reduce Fresnel reflection. The 70 W LD was so strong that the fiber chuck had heavy thermal load. For this reason, all-metal chucks were adopted for the both sides of the second amplifier. Additionally, the fiber chuck mounts were large, so they acted as good heat sink and reduced the thermal load of the fiber and fiber chucks.

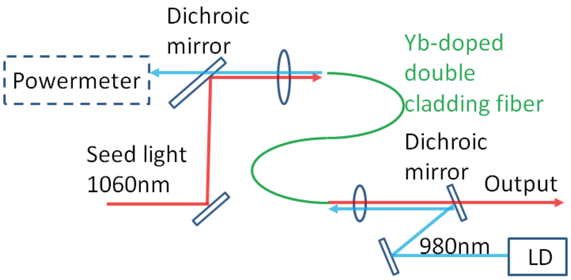

Figure 3: The structure of the Yb fiber laser amplifier.

Figure 4 shows the amplification result from the second amplifier. The 70 W LD was cooled by water, but the water temperature wasn't controled (was controled at room temperature). The maximum output power was 18.0 W then.

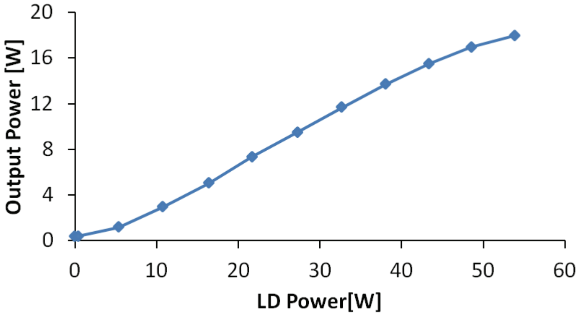

Figure 4: The output power from the second Yb fiber amplifier. The 70 W LD was cooled by water, but the water temperature wasn't controled.

The central wavelength of the LD was around 976 nm, but it depended on its temperature. Considering the narrow FWHM of Yb absobtion cross section around 976 nm, it was important to adjust the wavelength by controlling the cooling temperature. The experiment was done by measuring the LD power from the fiber at the seed laser injection side. The powermeter was set behind the dichroic mirror in Fig. 3. The measured power means the power not used for the amplification. Not all the power could be measured because of small diameter of the lens, but that was enough because the temperature to minimize the measured power was only the parameter we needed. From Fig. 5, Cooling temperature of 289 K was the best for over 50 W LD operation. The maximum output power was improved to 20.9 W at 289 K. The SN ratio was measured by a photodiode, and it was about 100. Additionally, the observation of this photodiode signal showed ASE was small. Therefore, the pulse energy could be calculated as 13 μJ when ASE was ignored.

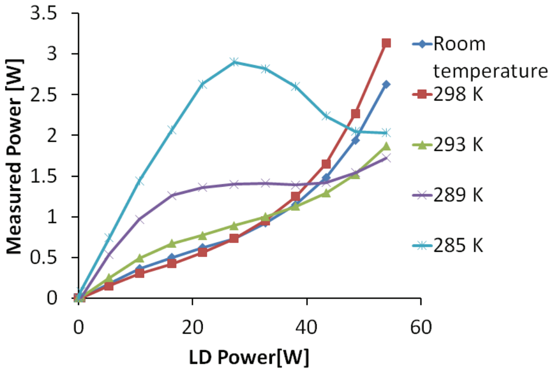

Figure 5: Power measurement experiment by changing cooling temperature.

Yb:YAG Solid Amplifiers

The first Yb:YAG amplifier is a regenerative amplifier. Here, the repetition rate will be reduced from 1 MHz to 50 Hz. The basic experiment was done to check whether a Pockels cell could pick up and dump the pulse. The result of this experiment showed the Pockels cell could pick up and dump it clearly. The SN ratio was over 150.

The final Yb:YAG amplifier is being designed now. Here, 50 pieces of Yb:YAG crystals are arranged symmetrically on the edge of a rotating disk. The seed pulse comes at 50 Hz, but each pulse injects on the different Yb:YAG crystals in 1 second. Therefore, the thermal load per one crystal decreases. The pulse energy will be amplified up to 10 J by 8 modules of 10 kW LD.

Compressor

Two ways to compress the pulse from 800 ps to 500 fs are now being considered. One is transmission grating pair. The other is double prism pair. The grating pair is often used for high intensity lasers. However, its cost is very high and a large vacuum chamber is required. Although the double prism pair cannot give large dispersion, its cost is relatively low and it may not need a vacuum chamber because the prism surface is very plane. To know the required distance for double prism compression, the dispersion was calculated based on Ref. [4]. In this calculation, the laser diameter was considered. The prism material was F2. The wavelength was 515 nm to make the dispersion large. The calculation result are shown in Fig. 6. From this calculation, it was shown that 32 times round trips between 3 m prism pair distance are needed to compress 800 ps pulse when the prism size is 50 mm and the FWHM of spectrum is 10 nm. Therefore, it will be difficult to cmpress the pulse by the double prism pair of 50 mm prisms.

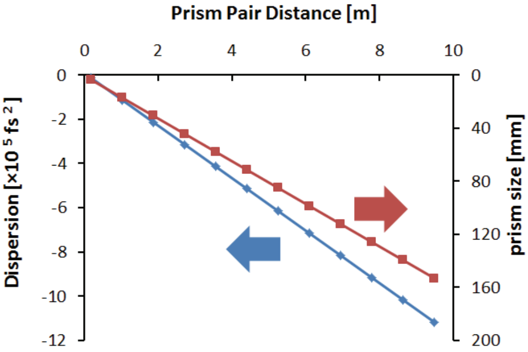

Figure 6: Dispesion and required prism size for the prism pair distance.

CONCLUSION

In this research, we reduced repetition reduction to 1 MHz, amplified the pulse up to 13 W average power without noise pulse, and achieved over 10 μJ pulse energy. The present laser parameters and the goal parameters are compared in Table 1. We will go to the stage of the Yb:YAG amplifiers. In the near future, the generation of 500 fs pulse of 500 W average power at 50 Hz will be achieved.

Table 1: Present Laser Parameters and Goal Parameters

	Present	Goal
Pulse energy	13 μJ	10 J
Repetition rate	1 MHz	50 Hz
Average power	13 W	500 W
Pulse duration	800 ps	500 fs

ACKNOWLEDGMENT

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