1J x 100 Hz Cryogenic Yb:YAG Laser Development for Feasibility Demonstration of GENBU Main Laser

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As the first step for GENBU main laser, we have designed a 1 J x 100 Hz nanosecond-pulsed average power laser system in order to demonstrate the advanced technologies such as cryogenic cooled Yb:YAG laser medium, active mirror geometry and scalability of this concept.

Key Words: Cryo-cooled laser, Yb:YAG ceramics, High average power laser.

1. Introduction

Laser systems for pulse operation with high average output power are strongly desired for various industrial applications such as high-energy particle generation, hard x-ray generation and inertial fusion energy driver.[1)] For those applications, there are four desirable factors; high overall efficiency, extraction of a large stored energy from a single aperture, repeatable high average power operation and good beam quality.

The Generation of ENergetic Beam Ultimate (GENBU) laser was conceptually designed on the basis of a diode-pumped cryogenically-cooled Yb:YAG ceramic. [1)] The main laser of the GENBU will have pulse energy of 100 to 200 J in ns pulse duration and repetition rate of 100 Hz. The trivalent ytterbium ion's simple electronic structure, $[Xe]4f^{11}6s^2$, permits diode-pumping with high efficiency. The stokes efficiency of the Yb-doped material is less than 90 % and the heat generation is about one third of Nd-doped materials. Yb:YAG has a long radiative lifetime suited to the large stored energy for high energy pulse. Ceramics as gain media can be made large size media compared with the single crystal. The thermal properties of gain media such as thermal conductivity, thermo-optic coefficient (dn/dT) and thermal expansion coefficient are significantly improved by cryogenic cooling .[2,3)]

As basic studies for GENBU laser, we will develop a laser system with output pulse energy of 1 J, pulse duration of 10 ns and repetition rate of 100 Hz. We will demonstrate advanced technologies as follows: an active mirror chain, verification of the scalability in an active mirror concept, using a flat-top beam form with uniform pumping from the laser diode (LD) stack and a composite design on the ceramic technology. Recently, we demonstrated a diode-pumped picosecond 8-pass amplifier with a liquid-nitrogen cooled Yb:YAG crystal.[4)] An average output power of 23.7 W was obtained at pulse repetition rate of 80 kHz and pulse duration of 11.7 ps. The amplifier produced pulse energies of 0.3-0.97 mJ at repetition rate in the range of 80-20 kHz. This result shows the feasibility of the 1J/10ns at 100 Hz laser system. The pulse energy of 1 J has potential of the damage on the gain media and the optics. The generation of 1 J pulse needs high pump energy. The higher pump energy causes the higher heat generation on gain media. Therefore, we carefully design the laser system with calculation for amplification and thermal analysis.

2. Laser system architecture

The 1 J laser system consists of three-stages; seed oscillator, regenerative amplifier and main amplifier. Parameters of this system are summarized in Table 1. The seed oscillator and the regenerative amplifier have been constructed. The 10 mJ pulse from the regenerative amplifier is amplified to 1 J by using main amplifier.

Initial demonstration with low repetition rate (<100Hz) is examined by using a rod medium in the main amplifier though active mirrors design has more advantageous things. The rod medium is a 5 at.% Yb:YAG with 12 mm in diameter and 6.6 mm in length. The schematic of the system at 1J/10ns with low repetition is shown in Fig. 1. The laser pulse from the

Table 1. 1 J laser system design

Laser stage	Seed oscillator	Regenerative amplifier	Main amplifier
Gain medium	Cryogenic Yb:YAG		
Lasing wavelength	1030 nm		
Repetition rate	1 to 100 Hz		
Pulse width	10 ns		
Pulse energy	100 pJ	10 mJ	1 J
Maximum average power	10 μW	1W	100W
Media design	Disk	Active mirror	Active mirror or Rod
Pumping wavelength	938 nm		
LD power	1.2 W (cw)	140 W (cw)	(1)2.5kW×2 (peak) (2)1.5kW×4 (peak)
LD type	Fiber coupling	Fiber coupling	(1)Fiber coupling (2) Stack

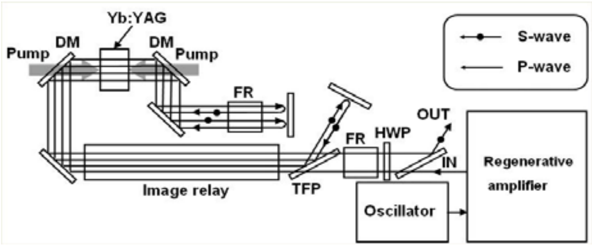

Fig. 1. Schematic of 4-pass rod amplifier

regenerative pre-amplifier is spatially expanded to the full-aperture of 5 mm diameter by using a telescope. The beam image is relayed to the gain medium by using a vacuum telescope with a spatial filter. Both sides of the gain medium are pumped by two fiber-coupling LDs with irradiation optics. The beam passes four times into the rod by using a Faraday rotator (FR), a thin-film polarizer (TFP) and two end-mirrors. The output pulse is ejected by using the FR, half-wave plate (HWP) and the TFP.

3. Calculation for amplification

To achieve the output pulse of 1 J, we calculated amplification on the rod of 6.6 mm in length using the Frantz-Nodvik model.[5, 6)] The diameter of pumping is 5 mm. The transmission loss in the amplifier per 1-pass is 20 %. The spatial coupling rate between seed and pump beam is 90 %. The saturation fluence of Yb:YAG is controlled with temperature change. The parasitic oscillation can be eliminated by adjusting the temperature on the gain medium. Figure 2 shows the calculated temperature dependence of $g_0 \times l_{max}$ for 1 J output. g_0 is the small-signal gain coefficient of the rod and l_{max} is a diagonal length of the rod, 8.3 mm. Assuming the threshold of the amplified spontaneous emission (ASE) is $g_0 l_{max} > 3$, the amplification to 1 J pulse without the parasitic oscillation needs the temperature over 180 K. At 180 K, the extraction efficiency is 66 %, the stored energy is 1.57 J, the necessary pumping peak power is 2.3 kW with the pulse duration of 700 μs and the B-integral is 0.41 rad.

The fluence of a 1J pulse with the beam diameter of 5 mm is 5.1 J/cm^2, which is closed to the damage threshold of the optics. Hence, it is necessary to optimize the sizes of the rod and the beam diameter in future work.

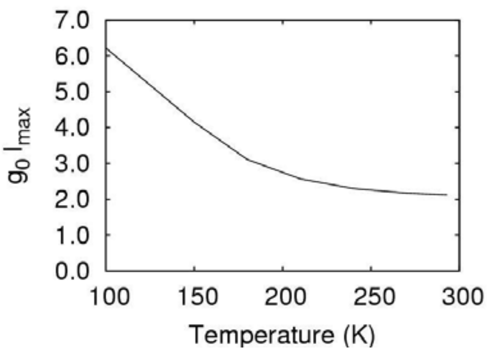

Fig. 2. Temperature dependence of g0lmax

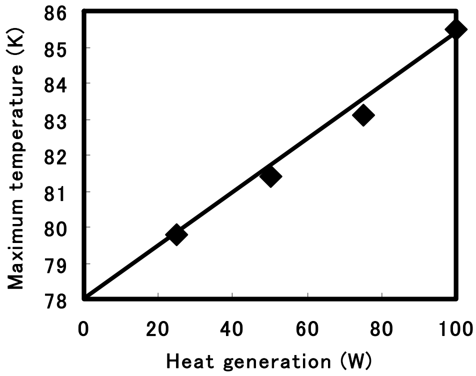

Fig. 3. Result of thermal calculation

4. Thermal analysis

To avoid the material destruction by heat generation from pumping light, thermal analysis is numerically studied using the commercial software, STREAM.* The maximum pumping peak power (two fiber-coupling LDs) is 5.0 kW with the pulse width of 700 μs at the repetition rate of 100Hz. The maximum heat generation is 70 W, 20 % at the average pump power of 350 W. Heat is removed from both end-sides of the rod excluding open aperture of ϕ6 mm. The thermal calculation result is shown in Fig. 3. The cryogen temperature is 78 K with liquid-nitrogen. The variation of maximum temperature is 5 K at the heat generation of 70 W.

5. Summary

Possibility of 1 J output power on the rod gain medium was confirmed by using the amplification calculation at 180 K. The extraction efficiency of this main amplifier was 66 %. The thermal analysis is demonstrated to avoid the material destruction with high-power pumping. Now, we are constructing the main amplifier in this laser system.

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