New concept for laser fusion energy driver by using cryogenically-cooled Yb:YAG ceramic

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Abstract. We propose cryogenic Yb:YAG ceramic as a novel reactor laser-driver material instead of conventional Nd:glass. Our research on cryogenic Yb:YAG revealed that both of stimulated emission cross section and thermal conductivity can be tuned well by controlling the material temperature. Using the obtained laser parameters in our experiments, a 1.3-MJ, 16-Hz diode-pumped laser system has been conceptually designed. The overall electrical-optical conversion efficiency is numerically calculated to be as high as 17%. The compact main amplifier with about 3000 m³ volume size would be realized by using the active mirror architecture. In addition, a 1-kJ laser system “GENBU” has been designed as a milestone for the new driver.

1. Introduction

Laser material is one of the most significant research issues for laser fusion energy driver developments. Nd:glass is the most popular laser material for such lasers. Using Nd:glass, mega-joules lasers of NIF and LMJ are under construction for ignition burn demonstration and are single-shot lasers. On the other hand, 10-Hz repeatable lasers of HALNA[1] and Mercury have been developed for 100 J pulse energy with Nd:glass and Yb:S-FAP, respectively, as basic research for reactor laser-drivers. It is, however, difficult to realize both high photon density and high repeatable operation due to poor thermal strength of the laser materials. As the next generation of reactor laser-driver
material, we propose cryogenic Yb:YAG ceramic. Various laser parameters of Yb:YAG were measured as a function of temperature experimentally. Based on them, a reliable diode-pumped reactor driver has been conceptually designed. The output power is 1.3 MJ at 16 Hz repetition rate with an overall electrical-optical conversion efficiency of 17%. In addition, a 1 kJ, pico-second laser system “GENBU” has been designed conceptually as a milestone for the reactor driver.

2. Characteristics of Cryogenic Yb:YAG Ceramic

A diode-pumped solid-state laser is the most promising laser system for a reactor driver due to high pulse energy generation, high operation efficiency, high operation stability and so on. Yb-doped materials are, generally, suitable for diode pump due to long fluorescence lifetime and good spectral overlap between its absorption and high-power diode emission. Also, thermal loading is less than 10% of absorbed pump power, which is one third of that of Nd-doped materials and leads to repeatable operation. Especially, Yb:YAG has been focused on due to its excellent thermal strength of thermal shock parameter and thermal conductivity.[2] Recent ceramic technology realizes Yb:YAG ceramic with laser-grade quality and high pulse energy can be obtained with the large-aperture ceramic.[3] The emission cross section is, however, slightly small at room temperature. Preferable emission cross section is between $2 \times 10^{-20}$ and $7 \times 10^{-20}$ cm$^2$, shown in fig. 1, which is limited by optics damage threshold and parasitic oscillation, respectively. We have proposed tuning of the stimulated emission cross section by controlling the material temperature. Our spectroscopic research shows that the temperature should be between 150 K and 270 K. The cryogenic Yb:YAG shows another improvement of thermal conductivity. There is no difference in both stimulated emission cross section and thermal conductivity between Yb:YAG crystal and ceramic at 100 ~ 300K.

![Figure 1: Stimulated emission cross section and thermal shock parameter of Yb:YAG crystal](image)

3. Laser Demonstration with High Efficiency and High Photon Density

A laser oscillator with cryogenic Yb:YAG ceramic has been developed, and efficient and high-photon-density operations have been demonstrated in cw and Q-switch mode. The highest slope efficiency of 90% was obtained in cw operation.[4] The optical-optical efficiency was as high as 80%. The low diode pump intensity of 1.4 kW/cm$^2$ is easily obtainable even by using stacked laser diode
arrays and enlargement of the pump area enables us to facilitate power scaling. High output power of 75W has been obtained with a near-diffraction-limited beam.[5] The extraction power from a unit volume of the Yb:YAG is as high as 71 kW/cm$^3$. Our numerical calculation of the small signal gain shows a good agreement with the experimental results. When the pump intensity and material temperature are given, laser amplification can be simulated by using the experimentally obtained material parameters.

4. New Conceptual Design for Laser Driver

A 1.3-MJ laser system with 16-Hz repetition rate has been designed conceptually. The main amplifier consists of polygonal modules, shown in Fig. 2. Nine Yb:YAG active-mirror disk units are set at the vertices of the polygon. The disk units are pumped by laser diodes, which set at the center of the polygon, and the disk units are conductively cooled with 200K fluorinert through HR-coated surface of the active mirror. Each disk unit consists of an 8x8 segmented array and the segment size is a 10cm x 10cm x 2cm. The segment generates 1-kJ pulse energy at 1-µm wavelength and 10-ns pulse duration. A 10-J input seed pulse is amplified via nine active mirrors and reflected for the second pass by an end mirror. 64-kJ NIR laser pulses per a module can generate 38-kJ third harmonics in blue. The average heat density is 16 W/cm$^2$, which is much smaller than our small-power laser demonstration mentioned above. The calculated material temperature rise of 13K is so small that no significant wavefront distortion occurs. The overall electrical-optical efficiency is estimated to be as high as 17% including the electric power of the cryostat for laser materials. The amplifier module is compact with 8-m diameter and 1.4-m thickness, and the whole main amplifier volume is as small as 2814($\pi$ x 4 m x 4 m x 1.4 m x 8 modules/tower x 5 towers) m$^3$.

![Figure 2: Conceptual main amplifier with cryogenic Yb:YAG ceramic.](image)

5. “GENBU” Laser Design for 1-kJ Demonstration

1-kJ pulse energy is a basic unit with a Yb:YAG ceramic segment of the reactor laser driver. A “GENBU (Generation of ENergetic Beam Ultimates)” laser has been designed conceptually to
demonstrate 1-kJ output pulse energy as a milestone of the new reactor driver. Another target of the “GENBU” laser is industrial use, especially, neutron source, ion-beam treatment for cancer, positron emission tomography (PET) and so on, and the repetition rate is 100 Hz for their demand. The “GENBU” laser consists of two technical systems, shown in fig. 3. One is a main laser, which is pico-second laser system with 1 kJ pulse energy. New technologies of cryogenic Yb:YAG ceramic and active-mirror amplifier architecture at large-aperture are involved. The other is an optical parametric chirped-pulse amplification (OPCPA) laser, which generates few-cycle pulses with 30-J pulse energy. The peak power reaches multi-peta watts. The pump laser is taken after the first amplifier of the main laser. An advanced technology of a spectrally-wide (> 600 nm) amplification is adopted. The size of the whole laser system is as small as 12 m x 6 m.

6. Summary

A cryogenically-cooled Yb:YAG ceramic has been proposed as a new reactor driver material. Our material researches show that the emission cross section and thermal shock parameter are suitable for them between 150 K and 200 K. High photon-density and efficient laser operations were demonstrated with our developed oscillators and various laser parameters were obtained. A reliable diode-pumped reactor driver has been conceptually designed with cryogenic Yb:YAG ceramic by using them. The output power is 1.3 MJ at 16 Hz repetition rate with the overall electrical-optical efficiency of 17%. The system size is reduced to less than 3000 m³ by using active-mirror amplifier-architecture at large aperture at first. A 1-kJ, pico-second laser system “GENBU” has been designed conceptually as a milestone for the new reactor laser-driver.

References

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Figure 3: Block diagram of “GENBU” laser.