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Numerical laser gain estimation of cryogenic Yb:YAG ceramics for IFE reactor driver

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Abstract. We have demonstrated regenerative amplifier for various ceramics temperature between 77 K and 200 K. From simple calculation taking into account the re-absorption losses at each temperature, the pump intensity for moderate laser gain is reduced to several kilo-watts per square centimetre below 200 K, and is easy to obtain even with commercial laser diodes, and we obtained G = 1.43 at 185 K for 3 kW/cm².

1. Introduction
In the concept of fast ignition, an inertial fusion energy (IFE) reactor driver requires mega-joule pulse energy at about 10 Hz repetition rate and more than 10 % electrical-optical efficiency [1]. For these requirements a diode-pumped solid-state laser (DPSSL) is the most reliable system. Recently, an Yb:YAG ceramics has become a candidate as a gain medium for reactor driver since it has a high stored energy capability, high thermal shock parameter, and large material production. At room temperature, however, Yb:YAG needs intense pumping in the range of 10 kW/cm² to obtain a moderate laser gain with high efficiency because of much re-absorption of lower laser level which is thermally populated in the quasi-three-level laser system [2]. To reach such intense pumping a lot of diodes are needed and, for example, their considerably large occupation space for the reactor driver is not on reality. We can reduce the thermal population of lower laser level by cooling Yb:YAG below 100 K, leading to dramatic improvements in the disadvantage of the quasi-three-level laser system. In addition, the lower the material temperature is, the larger a stimulated emission cross section is in the range of 1.2 to 9 x10⁻²⁰ cm², and the larger the thermal shock parameter becomes dramatically [1]. We would also reach 12.5 % electrical-optical efficiency in the design of IFE reactor driver using Yb:YAG [3].

Though a cooled Yb:YAG ceramics is another candidate as a gain medium for reactor driver, the quantitative calculation codes taking into account temperature dependences of Yb:YAG with high accuracy will be essential to the amplifier design with a cooled Yb:YAG.
In this paper, we quantitatively calculated laser gain, taking into account the re-absorption losses of Yb:YAG at each temperature and demonstrated regenerative amplifier with Yb:YAG ceramics cooled at various temperature between 77 K and ~200 K.

2. Calculation - Estimation of laser gain variation at low temperature
In this section, we simply calculate the laser gain at low temperature from experimental data of the stimulated emission cross section. In Ref. 4, small-signal gain $g_0$ is given as following,

$$g = \sigma_{em}(\lambda)N_2 - \sigma_{ab}(\lambda)N_1$$  

(1)

$g$ is the small-signal gain, $\sigma_{em}$ and $\sigma_{ab}$ are the stimulated emission cross section and the absorption cross section, $N_2$ and $N_1$ are the population densities of upper and lower manifold, and $\lambda$ is the wavelength of laser emission. The value of $\sigma_{em}$ and $\sigma_{ab}$ are given from the emission and absorption spectroscopy at each temperature and F-L equation [5]. The measured emission and absorption spectroscopy are presented at each temperature in Fig.1. To calculate $N_2$ and $N_1$, we use following expression,

$$N_2 = \frac{I \cdot S \cdot \lambda_p \cdot \eta_f}{h \cdot c \cdot V} \cdot \eta_f$$

(2)

$$N = N_1 + N_2$$

(3)

$I$ is the pump intensity whose temporal and spatial profile is flat-top one, $S$ and $V$ are pump area and pump volume, $t_p$ is the pump duration, $\lambda_p$ is pumping wavelength, $h$ and $c$ are the Plank constant and velocity of light in vacuum, $\eta_f$ is the rate of population left in the upper manifold during pump duration, and $N$ is the total population density contained in the pump volume.

Fig. 1 Measured absorption (left) and emission (right) cross section of 9.8 at.% Yb:YAG ceramics

In addition, we use the absorption coefficient at pump wavelength calculated from absorption spectroscopy at each temperature. To simplify the calculation model, we assume that the radial and axial temperature distribution is not exist or negligible (in most cases, however, it is not proper in the real end-pumped disk laser).
In this calculation, we use parameters of a 9.8 at.% Yb:YAG with a 2-mm thickness and 10 mm-square cross section and pumping and amplifying configurations are end-pumped and active-mirror incident on Brewster angle against Yb:YAG, respectively. The result is shown in Fig.2.

![Graph showing small-signal gain at each temperature against each pump intensity](image)

Fig. 2 Calculated small-signal gain at each temperature against each pump intensity

3. Experimental result - Laser gain at low temperature

In this section, we demonstrate regenerative amplification with Yb:YAG ceramics cooled at various temperature to calculate the small-signal gain at each temperature.

The experimental setup was consisted of seed oscillator, pulse picker and mode-matching telescope, and regenerative amplifier, shown in Fig.3. As nanosecond seed source a diode-pumped cryogenically cooled Yb:YAG laser was used, whose pulses are picked up at 10 Hz using a KD*P-Pockels cell. The pulse energies are about 130 pJ. Pulse durations are as short as 10 ns. The seed pulse was injected into the regenerative amplifier after matching the spatial beam mode with a telescope. To protect the seed laser system, an optical isolator (consisted of a thin film polarizer, a Faraday rotator and a half wave plate,) was used. A regenerative cavity was a 5-m long ring cavity. A laser material was a 9.8 at.% Yb:YAG ceramics with a 2-mm thickness and a 10 mm-square cross section. The ceramics was used as an active mirror with high-reflection coated and non-coated surfaces, which was set at the Brewster angle for the amplified pulse. The material temperature was controlled between 85K and 185 K by using a liquid nitrogen cryostat with an electric heater, shown in the inset of Fig.3. A temperature monitoring unit is buried in the holder near the crystal. The stability of temperature controlled by the heater is ± 0.1 K at the maximum pump power. A pump source was a fiber-coupled 150W laser diode at 940 nm wavelength and the maximum pump intensity was ~3 kW/cm² on the ceramics. More than 90% of the diode emission power was absorbed at any temperature. The typical repetition rate was 10 Hz and the pump duration was 2 ms. A seed pulse was injected as soon as the diode pump was finished. The observed amplified pulse energy at 2 ms pump duration was shown in Fig.4. The output pulse energy was increased linearly with the pump power. The maximum pulse energy was limited to about 10 mJ to avoid optical damage. A small signal gain coefficient \( g_0 \) was estimated at 2 ms pump by fitting our numerical calculations to the experimental waveform of pulse energy growing and decaying in the regenerative amplification with Lowdermilk and Murray’s equation [6], shown in Fig.4. In spite of the low pump intensity of 1–3 kW/cm², a high laser gain was obtained, \( g_0 = 1.4 \text{ cm}^{-1} \) at 85 K for 1 kW/cm² pump intensity and \( g_0 = 0.8 \text{ cm}^{-1} \) at 185 K for 3 kW/cm² pump intensity. The small signal gain calculated in section 2 was shown with a dashed line in Fig.4.
Fig. 3 Schematic of the experimental setup: PC: KD*P Pockels cell, FR: Faraday Rotator, TFP: thin film polarizer, \( \lambda/2 \): half wave plate

Fig. 4 Output pulse energy as a function of diode pump peak power at various temperature (left) Small signal coefficient as a function of Yb:YAG ceramics temperature

4. Conclusion
In this paper, we quantitatively calculated laser gain, taking into account the re-absorption losses of Yb:YAG at each temperature and demonstrated regenerative amplifier with Yb:YAG ceramics cooled at various temperature between 77 K and ~200 K. From calculation of small signal gain and experimental results, at low temperature below 200 K, we obtained higher pulse energy and higher small signal gain at lower pump intensity than at room temperature. \( G = 1.89 \) at 85 K for 1 kW/cm\(^2\) and \( G = 1.43 \) at 185 K for 3 kW/cm\(^2\) are obtained when pulse energies at each temperature are around 10 mJ at 10 Hz repetition rate. Our calculation is not concerned temperature distribution inside ceramics, however, so we need improved calculation to further analysis. We will calculate the small signal gain taking into account temperature distribution inside ceramics and other thermal effects.

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