New Concept of Laser Fusion Energy Driver Using Cryogenic Yb:YAG Ceramics

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Abstract. We have proposed a cryogenic Yb:YAG ceramics as a novel reactor laser material instead of a conventional Nd:glass. Our researches on the cryogenic Yb:YAG revealed that both of the stimulated emission cross section and the thermal conductivity can be tuned well by controlling the material temperature. Also, using our diode-pumped oscillator with a cryogenic Yb:YAG disk, the highest optical-optical slope efficiency of 90% has been demonstrated. The heating of the laser material is one third of that in the conventional Nd:glass. Using the obtained laser parameters in our experiments, a new diode-pumped reactor laser system has been conceptually designed with the cryogenic Yb:YAG ceramics. A 1.1-MJ compression laser and a 0.1-MJ heating laser operate at a 16-Hz repetition rate. The overall electrical-optical conversion efficiency is numerically calculated as high as 12%. The compact main amplifier with less than 3000 m^3 volume size would be realized by using an active mirror architecture.

1. Introduction

Recently, the huge laser facilities of NIF and LMJ are under construction for mega-joules pulse energy to ensure compressive central heating. A 10-kJ short-pulse heating laser has been developed for fast ignition in our FIREX-project. Such high-pulse-energy lasers are single-shot systems for IFE researches. For a reactor laser, in addition to high pulse energy, repeatable operation and high electrical-optical efficiency are needed. Our rough specification for a fast-ignition-based reactor laser is 1-MJ output power at 16-Hz repetition rate with more than 10% efficiency. A diode-pumped solid state laser is a prior candidate today. One of the most significant issues in its realization is laser material. Three important factors are strongly required for the reactor laser material. First, production capability of large-aperture materials is necessary for high pulse energy. Then, high thermal strength enables repeatable operation. Finally, proper stimulated emission cross section optimizes both of the laser efficiency and the system size. A large-aperture Nd:glass material has been used in the single-shot laser systems. The poor thermal strength is, however, wrong for the repeatable reactor laser. A new material of Yb:S-FAP in the Mercury program is well suited for diode pump due to a long emission lifetime. [1] The large-aperture material productivity is inferior to the glass materials and the thermal strength is not enough. We have proposed a cryogenically cooled Yb:YAG ceramics as a reactor laser material for the first time. A fast-ignition-based reactor driver has been designed conceptually with an active-mirror amplifier architecture.

2. Properties of Cryogenic Yb:YAG Ceramics

An Yb-doped material is one of the most promising laser materials for the next generation of efficient high power lasers, due to superior availability of diode-pump, high storage-energy capability and low thermal loss. Among various kinds of Yb-doped materials, Yb:YAG has been focused on due to its high thermal strengths in thermal shock parameter and thermal conductivity. Then, Yb:YAG ceramics with a laser-grade quality is recently obtainable, which enables large-aperture material production.[2] The stimulated emission cross section is, however, too small at room temperature to extract the storage energy efficiently with commercial optics. Tuning of the stimulated emission cross section can be realized by controlling the material temperature. According to our spectroscopic researches [3], the preferred temperature is between 150 K and 270 K, shown in FIG. 1. Also, the cryogenic Yb:YAG has two additional advantages. One is improving the thermal strengths of higher thermal conductivity, [4] lower thermo-optic coefficient (dn/dT) [5] and lower coefficient of thermal expansion [5] than those at room temperature. These result in reducing the thermal effects such like thermal lensing and thermal birefringence. The other is dramatic increase of effective laser gain.[3] Much re-absorption of lower levels in a laser transition becomes a considerable gain loss in a quasi-three-level laser system of Yb-doped materials at room temperature. Decreasing the temperature, the re-absorption reduces rapidly to increase the effective laser gain like a four-level laser system.

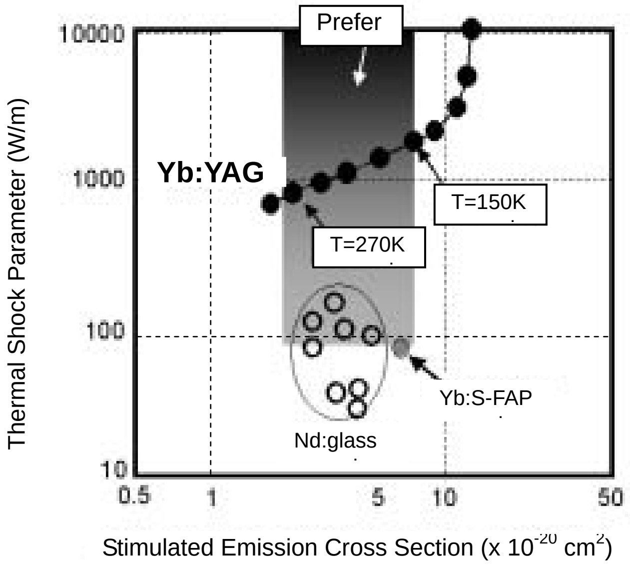
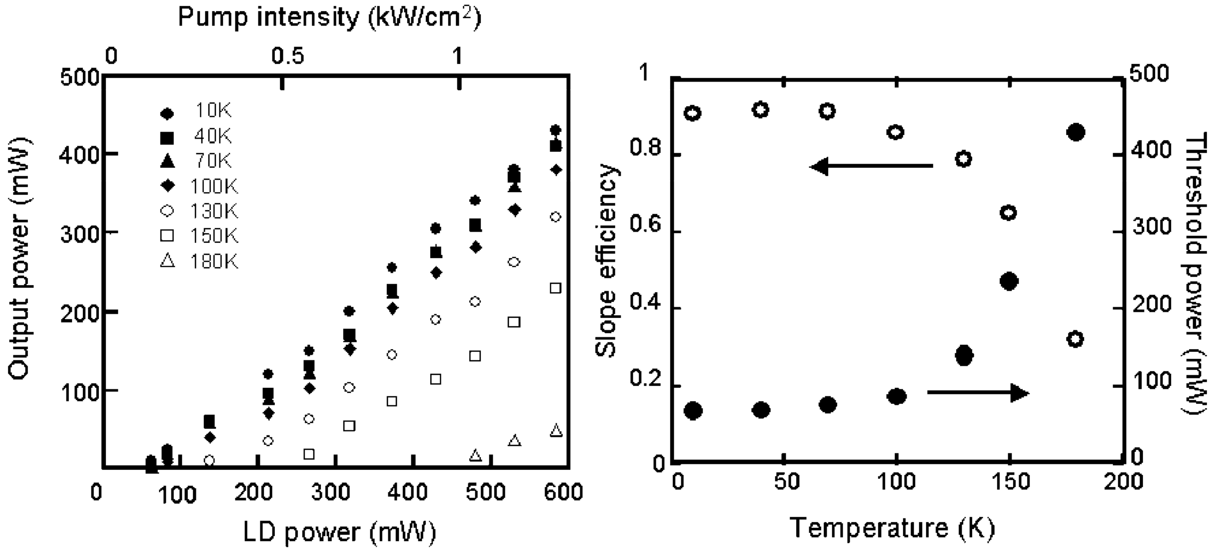


FIG. 1 Emission cross section of IFE laser materials.

3. Laser Demonstration with Active-Mirror Amplifier

A short-cavity diode-pumped cw laser oscillator has been developed with an Yb:YAG at liquid nitrogen temperature to ensure its excellent material properties.[3] FIG. 2(a) shows the laser output power as diode pump power. Cooling the material, the threshold pump power of laser oscillation is decreasing and the slope efficiency is increasing. Both of them are constant below 100K in FIG. 2(b), which means construction of four-level laser system. The highest slope efficiency of 90% almost equals to the theoretical limit ($h\nu_{Laser}/h\nu_{LD}$).[3] The material heating is only 10% which is one third of that of the Nd:glass. An optical-optical efficiency is up to 80% at pump intensity of 1.4 kW/cm^2. The low pump intensity is obtainable even by using stacked laser diode arrays, which enables us to realize the power scaling. The experimentally obtained small signal gain is high at g_0=8cm^{-1} at maximum. Our numerical calculation by the observed stimulated emission and absorption cross sections agrees well with the experimental results. When the pump intensity and the material temperature are given, laser amplification can be numerically estimated.



(a)

(b)

FIG. 2 (a) Laser output power as diode pump power and (b) slope efficiency as Yb:YAG temperature.

An active-mirror architecture, which has double functions of laser amplification and laser beam reflection, is adopted in a diode-pumped Q-switch oscillator in Fig. 3. The active mirror is an Yb:YAG ceramics disk with an anti-reflection (AR) and high-reflection (HR) coatings on its optical surfaces. Both of diode emission and laser beam are at the same side. A seed pulse is going into an Yb:YAG disk and reflected at the back surface of the material, then, amplified again. The seed pulse experiences two-pass amplification at each disk to extract the stored energy efficiently. That results in less pass number in amplification, leading to relax restrictions of the system design. The disk contacts with a cooling plate thermally conductively to remove heat efficiently. As the heat flow or the thermal distribution is perpendicular to the optical surfaces, there is no spatial difference in the optical phase shift of the laser beam and the spatial beam quality is kept. Power scaling can be easily achieved by enlarging the pump cross section without thermal condition changes. The output power of 30W was obtained at 10 kHz repetition rate in FIG. 4, corresponding to a high extraction power density from a unit volume of the Yb:YAG ceramics of 20kW/cm^3. The slope efficiency of 71% is high in pulse operation.

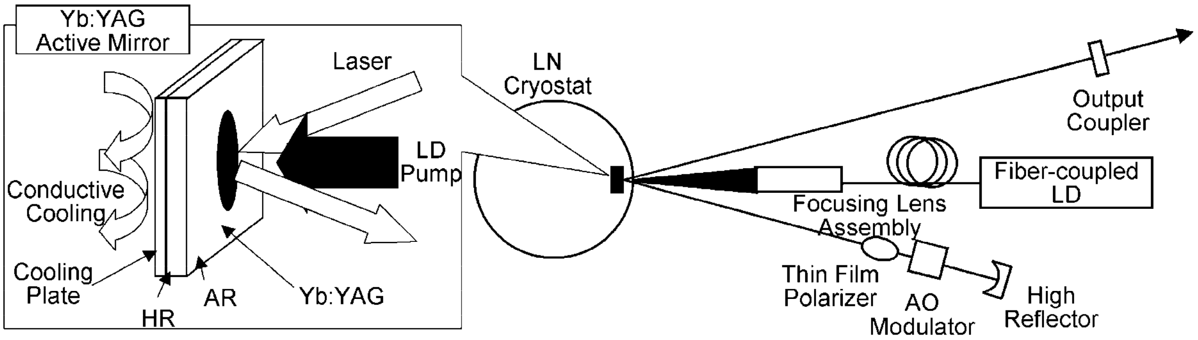


FIG. 3 Diode-pumped Q-switch oscillator with Yb:YAG active mirror.

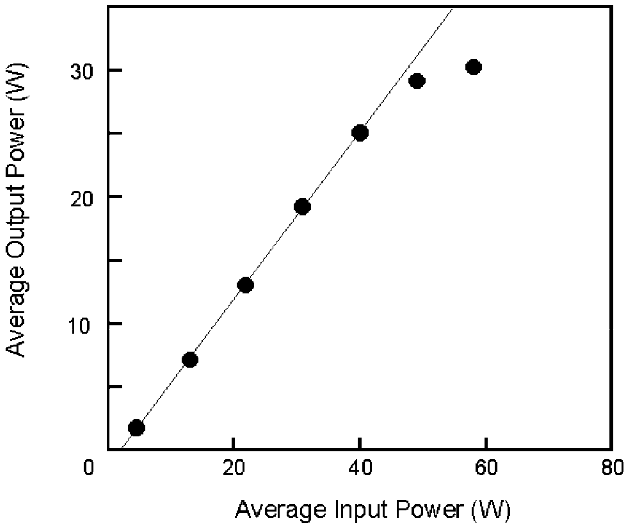


FIG. 4 Average output power of the active mirror oscillator.

4. New Conceptual Design of Laser Driver

Using a cooled Yb:YAG ceramics, a new reactor laser has been conceptually designed. The construction of the laser system is shown in FIG. 5. A small-energy nano-second pulse with a good beam quality in temporal and spatial region is generated at an oscillator. The near-infra-red (NIR) pulse is amplified to kJ class at the pre-amplifiers. The amplified pulse is divided into 40 beams and each beam grows up to 64 kJ at the main amplifier. Then, the 32 laser beams are frequency-converted to blue and the total output of 1.1 MJ is obtained as a nano-second compression laser. The rest of 8 beams are frequency-converted to green. The green laser beams are used as a pump source for optical parametric chirped-pulse amplification (OPCPA) to obtain a 100 kJ pico-second heating laser. The main amplifier consists of 40 polygonal modules. One polygonal module is shown in FIG. 6. The figure shows five disks in simplicity, nine disks are, in actual, set at the vertices of the polygon. The Yb:YAG ceramic disks are pumped by stacked laser diodes which set at the center of the module. The Yb:YAG disks are used as active mirrors. About 10-J input seed pulse is going via nine active mirrors and turned back along the same pass by an end mirror. The 64-kJ pulse energy is generated for each module at a NIR spectral region. The ceramics disk is attached to a thermally conductive plate with the HR-coated surface and a fluorinert flow unit removes the heat from the plate. The ceramic disk is cooled at 200 K, considering the system efficiency on a balance between the extracted laser energy and the electric power demands for cooling. The overall electrical-optical efficiency is estimated at 12% including the electric power for the disk cooling, shown in table I. The average heat density is 16 W/cm^2, which is much smaller than our small-power laser demonstration. The calculated disk temperature rise of 30K is so small that no significant fractures occur in both of the laser profile and the Yb:YAG disks. The amplifier module is compact with 8m-diameter and 1.4m-thickness. The volume of all 40 modules is less than 3000 m^3.

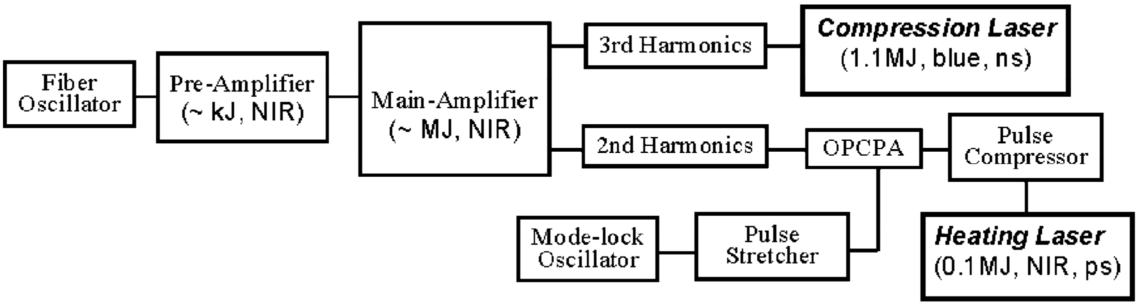


FIG. 5 Construction of the reactor laser system.

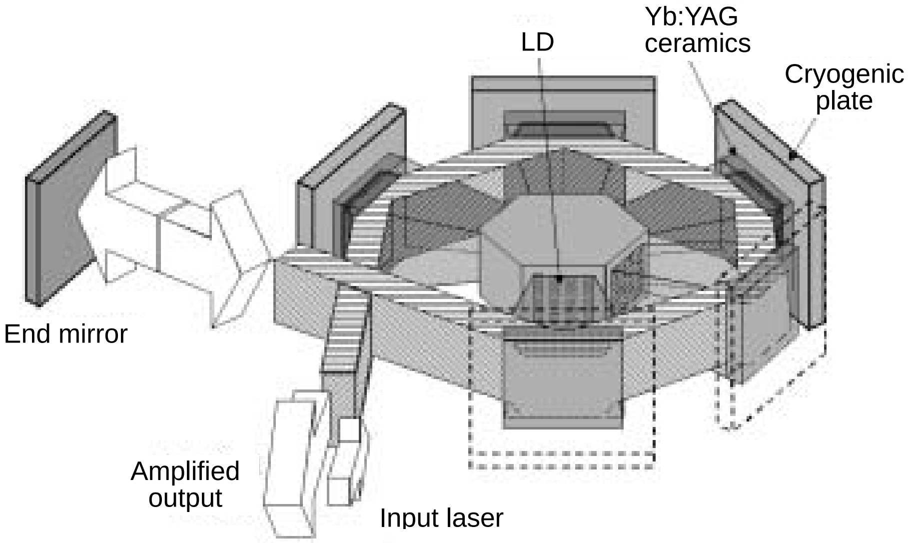


FIG. 6 Polygonal module concept in main amplifier. Five Yb:YAG disks are shown in simplicity.

Table I Estimation of powers and efficiencies.

	Implosion Laser	Heating Laser
Laser Power	18 MW (1.1MJ, 16 Hz)	1.6 MW (0.1MJ, 16Hz)
LD Electrical – LD Optical	60%	
LD Optical – 1ω	42%	
LD Electrical – 1ω	**25%**	
1ω – 3ω	70%	-
1ω – 2ω	-	80%
OPCPA Eff.	-	40%
Pulse Compression Efficiency	-	80%
Transportation Efficiency	90%	90%
Harmonic Generation and Transportation	**63%**	**23%**
Electric Input Power	110 MW	28 MW
Crystal Heating Power	6.6 MW	1.7MW
Cooler Electric Power	22 MW	5.7 MW
Electric Power Demands	132 MW	24 MW
Total Electric Power	166 MW	
Overall Efficiency	**12%**	

5. Conclusion

A new fast-ignition-based reactor laser driver has been conceptually designed with a cooled Yb:YAG ceramics. The output pulse energy is 1.1 MJ and 0.1 MJ for the compression and the heating laser, respectively, at the repetition rate of 16 Hz. The overall electrical-optical efficiency is numerically calculated at 12%. An active mirror amplifier scheme has been adopt. The main amplifier size, which consists of 40 polygonal modules, is compact with a volume less than 3000 m^3.

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