Temperature characteristics of small signal gain for Nd/Cr:YAG ceramic lasers

T. Saiki a,⁎, K. Funahashi b, S. Motokoshi a, K. Imasaki a, K. Fujioka b, H. Fujita b, M. Nakatsuka a,b, C. Yamanaka a

a Institute for Laser Technology, 1-8-4 Utsubo-honmachi, Osaka, Osaka 550-0004, Japan
b Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan

Article info
Article history:
Received 5 August 2008
Received in revised form 14 October 2008
Accepted 15 October 2008

Keywords:
Lamp light
Solar-pumping
Nd/Cr:YAG
Ceramic lasers
Cr co-doping
Small signal gain
High temperature

ABSTRACT
Thermal dependence on the small signal gain of Nd/Cr:YAG (yttrium aluminum garnet) ceramics was observed experimentally. Usually, Nd:YAG crystal and ceramics have remarkable gain reduction when optical pumping is performed and the temperature of the laser media is upped to 373 K. A CW laser light generated in a 1064 nm Nd:YAG laser oscillator was amplified by Nd/Cr:YAG ceramic amplifier, and the output power was measured at non-saturation level. Laser small signal gain of the ceramic disk was kept to 470 K. This property was remarkably different from one of Nd:YAG crystals or ceramics. The peak shift of the fluorescence was observed experimentally when the temperature is high.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Until now, Nd:YAG has commonly been used with flash lamps. We recently used a laser diode as a pump source, but it was a conventional laser for industrial and research use. Nd/Cr:YAG crystal was developed by Duncan in 1964 to improve the conversion efficiency of flash lamp-pumped lasers [1]. But, because the Cr3+ ions change to Cr4+ ions in the YAG crystals and the Cr ions have large radii, Cr ions cannot be correctly set on Al sites in YAG crystals. Pure Cr3+ doped Nd:YAG crystal can not be obtained. After that, Cr and Nd co-doped gadolinium scandium gallium garnet (GSGG), gadolinium gallium garnet (GGG), and yttrium scandium gallium garnet (YSGG) were developed, and some improvement due to Cr doping was observed. However, the low stimulated cross-section at lasing wavelength and the low thermal conductivity result in poor laser performance [2].

Our group recently developed Nd/Cr:YAG ceramic sintered pure Nd/Cr:YAG crystal powder using the sol–gel method. This powder contains pure Cr3+ ions and a very low concentration of Cr4+ ions. We then observed laser oscillations [3,4]. Flash lamp or sunlight pumped lasers using Nd/Cr:YAG ceramics have already been reported [5–7]. A remarkable improvement in the optical–optical conversion efficiency of over 40% from lamplight to laser was also reported [8]. The small signal gain of the ceramic disks was measured in experiments on laser oscillations in Nd/Cr:YAG ceramics [4]. The optical property is very different from the Nd:YAG. The effective stimulated emission cross-section and the effective lifetime at the Nd upper level is improved remarkably due to excited Cr3+ ions pumped by ark lamp, flash lamp or sunlight [9], and a high small signal gain is obtained when the irradiated power density of the lamp light or the sun light on a ceramic disk is low. We developed a theory to explain the energy transfer mechanism from Cr ions to Nd ions of Nd/Cr:YAG ceramics [9]. Some advantages of the Nd/Cr:YAG ceramic are below. (1) Thermal conductivity is high compared to Nd:GSGG or Nd:GGG. (2) The effective stimulated emission cross-section and the lifetime is large compared to them. (3) The absorption bands of Nd:YAG is improved by Cr3+ ions doping and they match the solar spectrum.

It is good for design that the laser system has no cooling system because the system is simplified and having low cost. A space solar power station (SSPS) is the facility to supply energy from a satellite on the geostationary orbit above the equator about 36,000 km. For SSPS using laser system (L-SSPS), the solar power concentrated by lens is absorbed to the laser medium, converted directly into laser. The generated heat in the laser media of the L-SSPS system will be removed to the space. This heat removal mainly depended on the black-body radiation. If the temperature of the coolant is high, the black-body radiation increase and the ability of the heat removal will be improved because the radiation power is proportional to T⁴. Therefore, it can be expected to reduce the size of the radiator and the weight of the satellite.

The temperature dependency of the small signal gain for Nd:YAG crystal has already been clarified [10,11]. The decrease
of the small signal gain of Nd:YAG as a function of temperature has been already observed. It is recognized that the main causes of the gain reduction are (1) an increase of number densities at the under level of Nd:YAG and (2) a peak shift of the stimulated emission cross-section at lasing wavelength. The temperature dependency of laser gain for Nd/Cr:YAG crystal or Nd/Cr:YAG ceramics had not been researched at all until now as we know. Thus, the temperature dependency of the small signal gain for Nd/Cr:YAG ceramics had been investigated experimentally.

2. Experimental setup

Fig. 1 shows the experimental setup. A disk-type Nd/Cr:YAG ceramic was used this experiment. The diameter of the disk-type Nd/Cr:YAG ceramic was 9.5 mm, 2 mm in thickness, and 3% in the Cr density and 1% in the Nd density. Arc-metal-halide lamp was used to excite the laser material. The correlated color temperature is 6000 K at a electrical input power is 1.2 kW. The lamp light was used to excite the laser material. The correlated color temperature of the small signal gain of Nd/Cr:YAG ceramics had been already observed. It is recognized that the small signal gain was kept up to 500 K at 300 K [9].

\[
\sigma_l(T) = \sigma_l(T_0)[1 + A]
\]

(4.1)

\[
\tau_{\text{Nd}}(T) = \tau_{\text{Nd}}(T_0)[1 + A(\beta + 1)]/[1 + A]
\]

(4.2)

\[
A = \tau_{\text{Nd}}(T)/\tau_{\text{Nd}}(T_0)
\]

(4.3)

\[
\tau_{L}(T) = \tau_{L}(T_0) \exp[-\sigma_l(T - T_0)].
\]

(5)

\[
\tau_{L}(T) = \tau_{L}(T_0) \exp[-\sigma_l(T - T_0)].
\]

(6)

\(\tau_{\text{Nd}}\) is the lifetime at the Nd-upper level, having a dependence on temperature. \(\tau_{\text{Nd}}\) is 1.1 ms at \(T_0\) of 300 K for 3% Cr ions doping [9]. \(\tau_{\text{Nd}}\) is the life time of the Cr upper level. \(\tau_{\text{Nd}}\) is set to 0.005 to match the experimental data [10]. \(\tau_{L}\) is the feeding time and changes as a function of the media temperature. We consider that the spectral peak does not change until 600 K in the calculation because the measured spectral bandwidth of 3.16 nm at 1064 nm for Nd/Cr:YAG ceramics with 3% Cr ions doping at 300 K and the bandwidth will be broaden at 600 K. We deal with \(\sigma_l\) as a parameter here.

3. Small signal gain of Nd/Cr:YAG ceramics

Here, we consider the small signal gain of the Nd/Cr:YAG ceramics. Small signal gain coefficient of Nd/Cr:YAG ceramics is given by

\[
G_0 = \frac{\sigma_l(T)}{N_2 - n_1}.
\]

(1)

\(N_2\) is the population inversion number density of the Nd-upper level is given by

\[
N_2 = \Delta N_p \cdot \tau_{\text{Nd}}(T)
\]

(2)

\(\Delta N_p\) was calculated with the pumping power and absorption efficiency of 70%. The number density at the Nd-lower level of 2011 (cm\(^{-1}\)) as a function of the normal Boltzmann distribution is given by

\[
n_1 = \frac{1}{N_0} \exp \left[-\frac{\Delta E_1}{kT}\right]
\]

(3)

where \(\Delta E_1\) is set to 2111 (cm\(^{-1}\)), \(N_0\) is the number density of the Nd ions. \(N_0\) is \(1.7 \times 10^{20}\) (1/cm\(^3\)) and \(n\) is the split number at the Nd-lower level. Here, \(n\) is set to 6. \(\sigma_l\) is the effective stimulated cross-section at 1064 nm wavelength with a dependence of temperature. Here, \(\sigma_l\) is set to \(2.3 \times 10^{-18}\) [cm\(^2\)] for 3% Cr ions doping at \(T_0\) of 300 K [9].

4. Experimental results

Fig. 3 shows the temperature dependency of small signal gain. It was recognized that the small signal gain was kept up to 500 K at an injected lamp light power density of 10.0 W/cm\(^2\) and up to 430 K at an injected lamp light power density of 2.0 W/cm\(^2\). At a power density of lamp light of 10.0 W/cm\(^2\), a gradual decrease of
the small signal gain was observed. It was found that the thermal property of the Nd/Cr:YAG ceramics is largely different in the case of Nd:YAG. As increasing the injected lamp light power, the temperature at which the laser media keep small signal gain improved highly.

The dashed line and solid line show the calculated results of small signal gain coefficients using Eqs. (1)–(3), (4.1)–(4.3), (5), (6). The dashed line shows the results under assumption that the $\sigma_{l}'$ and $\tau_{md}'$ is independent from temperature. The solid line shows the results with considering the thermal dependence of the $\sigma_{l}'$ and $\tau_{md}'$. The calculated results with considering thermal dependence have good consistence with the experimental results.

Fig. 4 shows the temperature dependence on the peak shift of the fluorescence of Nd/Cr:YAG ceramics at 1064 nm. In this experiment, it was found that the spectral shift was 0.8 nm per 200 K for 3% Cr ions doping. This result is close to one in a reference for Nd:YAG [12].

5. Discussion

We had investigated the temperature dependency of the small signal gain for Nd/Cr:YAG ceramic. It had been clarified that small signal gain of Nd/Cr:YAG ceramic can be kept up to high temperature of more than 473 K in spite of the spectral peak shift.

It was considered that main cause of the gain reduction is the increasing of the population inversion density at the Nd-under level. It has been recognized this laser media can be operated at over 500 K. At an injected lamp light power of 10 W/cm² (67 SUN, 1 SUN is the solar power density of 0.14 W/cm² in the space) if the allowance of the gain reduction ratio was assumed to 80% under CW laser operation.

Under CW operation, the improvement on the effective stimulated cross-section and the effective lifetime of the Nd upper level of Nd/Cr:YAG ceramic lasers were observed theoretically and experimentally. It was found that the gain reduction is reduced due to the longed effective lifetime of the Nd-upper level, which is contrary to in the case of the Nd:YAG. The lifetime of Nd:YAG is 230 μs and the effective life time of Nd/Cr:YAG ceramics are more than 1.05 ms. Moreover, the slight increasing of the effective stimulated cross-section and the effective lifetime of the Nd-upper level as a function of the temperature may be observed in this experiment. High power density irradiation of the lamp light or solar light and operating at high temperature may results in the increasing of the laser gain due to the increasing of $N_{2}–N_{1}$. Optical–optical conversion efficiency may be improved. Gain reduction at an injected lamp light power of 10 W/cm² at 500 K will depend on the spectral peak shift of the fluorescence at more than 450 K but not due to the increasing of the population number density at the Nd-lower level.

6. Conclusion

Thermal dependence on the small signal gain of Nd/Cr:YAG ceramics was observed experimentally. 1064 nm Nd:YAG laser was amplified by Nd/Cr:YAG ceramic amplifier. High laser small signal gain was kept to media temperature of 470 K at an injected lamp light power of 10 W/cm² (67 SUN). The temperature dependency of the gain reduction shows a remarkable difference to Nd:YAG crystals or ceramics. More high power density irradiation of the lamp light or solar light will improve the thermal property.

Acknowledgment

This research was supported by the Japanese Aerospace Exploration Agency. The Nd/Cr:YAG ceramics were sintered by Kounoshima Chemical Company.

References