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Laser output power losses in ceramic Nd:YAG lasers due to thermal effects

Duck-Lae Kim [a],*, Byung-Tai Kim [b]

[a] Seeker & EO/IR R&D Lab, LIG Nex1, Yongin 446-912, Korea
[b] Department of Laser & Optical Information Engineering, Cheongju University, Cheongju 360-764, Korea

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ABSTRACT

Laser output power losses in a ceramic Nd:YAG laser with a doping rate of 2 at.% Nd^{3+} due to thermal effects were analyzed. The ceramic Nd:YAG laser output power losses due to thermal birefringence effects and thermal lens effects were measured via changes in the output power of the ceramic Nd:YAG laser. At a pump power of 12 W, the total laser output power loss, the loss due to the thermal lens, and the loss due to thermal birefringence were found to be 68.7%, 48.1%, and 20.6%, respectively.

1. Introduction

Thermal effects in laser media constitute the greatest factor that reduces the performance of high-output-power solid lasers. When pump light is incident into the medium, part of the pump light is absorbed by the medium and is converted into heat, producing thermal lens effects and thermal birefringence effects. The thermal lens effects are generated by changes in the refractive index of the medium according to its temperature and associated thermal stress. Thermal lens effects cause resonating laser beams to converge, changing their optical paths and thereby decreasing laser output power and beam quality [1–4]. Thermal birefringence effects are produced when the refractive index of the medium has been changed by the pump power, which leads to phase differences between two intrinsic polarized light components. When the beam polarization has been changed to elliptical polarization by thermal birefringence, the S-polarized light component of the beam causes reflections in the resonator that reduce laser output power [5–7].

According to the results of a previous study, in a ceramic Nd:YAG laser, as the pump power increased, thermal lens effects and thermal birefringence effects appeared [8,9]. As a result of thermal lens effects, a ceramic Nd:YAG laser with a doping rate of 2 at.% had a maximum output power of 2.2 W and an output power efficiency of 36.1% at a pump power of 6.2 W. The laser output power rapidly decreased as the pump power increased and completely disappeared when the pump power was 15 W or higher. This decrease was due to the fact that the absorption rate increased as the doping rate of the laser medium increased, so temperature differences easily appeared in the medium [8]. With respect to thermal birefringence effects, when changes in the quantity of light of the probe beam relative to the pump power were measured, the phase difference in the ceramic Nd:YAG material with a doping rate of 2 at.% was determined to be 38.9° for the circularly polarized probe beam under a pump power of 12 W [9]. Ceramic YAG and (111)-cut YAG single crystals with the same Nd^{3+} doping rates showed similar depolarization characteristics because the ceramic YAG has many single crystal grains sized approximately

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* Corresponding author.
  E-mail addresses: duckiboy@hanmail.net (D.-L. Kim), btkim@cju.ac.kr (B.-T. Kim).

Fig. 1. Experimental setup for measuring the thermal effects in a laser material.
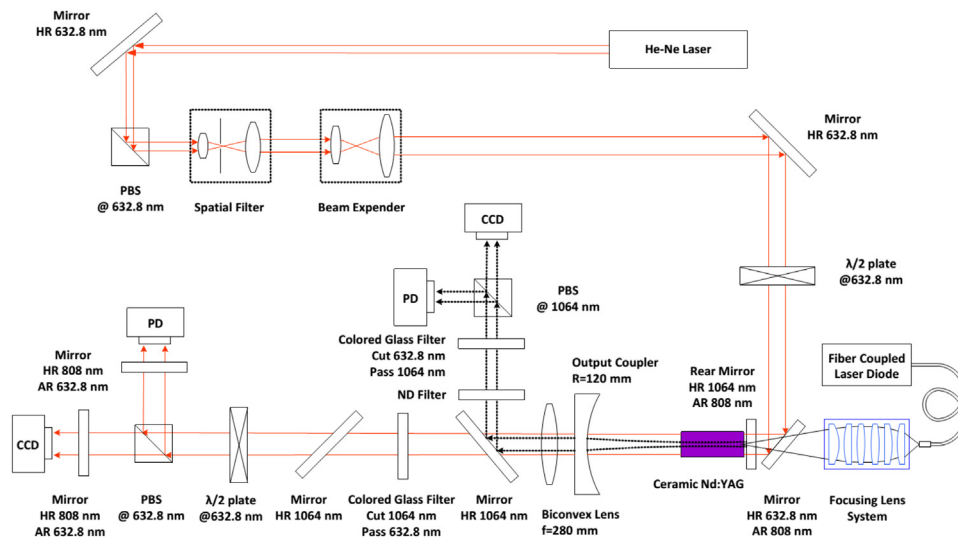
30–100 μm organized in irregular directions. Therefore, the birefringence effects in ceramic YAG are equal to the average of the birefringence effects that appeared in many individual grains. This characteristic is inherently different from the characteristics of YAG crystals. In addition, even at the same pump power, depolarization increased as the Nd^{3+} doping rate increased, which was attributed to increases in thermal loading [10–14]. Because laser output power losses due to thermal effects are caused by the simultaneous occurrence of thermal lensing and thermal birefringence, the two effects cannot easily be measured separately. Thermal lensing and thermal birefringence that affect laser output power losses in highly doped ceramic Nd:YAG have not been extensively studied.

The following method was proposed to analyze the effects of thermal lensing and thermal birefringence on output power in ceramic Nd:YAG lasers. Assuming that laser output power linearly increases with pump power, the amount of output power losses due to thermal lens can be quantitatively analyzed by excluding the amount of output power losses due to thermal birefringence from the decreased amount of laser output power. When the S-polarization component of laser output beams is measured using a polarizer, if the S-polarization component of laser output beams decreases with the pump power, the decreases can be attributed to both thermal lens effects and thermal birefringence effects because thermal lensing changes the resonance mode regardless of changes in the polarization of the laser output beam, causing losses, while thermal birefringence changes the polarization of the laser output beam, causing losses. Here, laser output power is in the state of unrestricted, unpolarized light. The laser output power is reduced to half when the polarizer has been inserted into a resonator and reduced further when resonator loss occur due to thermal birefringence effects. Analyzing changes in the intensity of laser output beams due to thermal birefringence effects is important, and these changes can be predicted using circularly polarized probe beams, as changes in the intensity of laser output beams due to thermal birefringence effects are equal to changes in the intensity of circularly polarized probe beams.

In the present study, laser output power losses due to thermal lensing and thermal birefringence in an end-pumped ceramic Nd:YAG laser were analyzed through changes in the polarized light component of laser output beams due to thermal effects and changes in the intensity of polarized probe beams.

2. Experiment setup

Fig. 1 shows the experimental setup for measuring the thermal birefringence in ceramic Nd:YAG. He-Ne laser beams were used as probe beams to determine the characteristics of thermal birefringence in the laser material. The probe beams were S-polarized by reflection on PBS with an extinction ratio of 1000:1, and the beam diameter was made similar to the diameter of the laser medium by passing the probe beams through a spatial filter and a beam expander. Then, the probe beams were converted into circularly polarized probe beams using a quarter-wave plate. A fiber-coupled laser-diode (Apollo Ins.; F25-808-4P) was used as an optical pumping source. The optical fiber core diameter is 400 μm and the numerical aperture is 0.22. The laser diode was maintained at a temperature of 27.5 °C. The laser diode was connected to a power supply (HP; 6011A) for laser beam operation, and at an operating current of 45 A, a light emission spectrum with a central wavelength of 809 nm, a full width at half maximum of 3.2 nm and an output power of 27.5 W was produced. The pump power was focused into the laser medium with an optical focusing system with a spot diameter of 380 μm at an effective focal length of 10.9 mm. A resonator was configured with a $10 \times 20 \times 2\,t$ mm sized dichroic coated plane mirror with an AR 808 nm, an HR 1064 nm and an output coupler with a radius of curvature of 120 nm and a reflectivity of 90% at 1064 nm. A 5 nm diameter

and 10 mm long ceramic Nd:YAG (Baikowski) with 2 at.% neodymium concentration was used as a laser medium. The laser output beam was reflected using the HR 1064 nm mirror and attenuated using the ND filter; only a 1064 nm laser beam was allowed to pass through the color filter (Newport; KG3). After transmitting through the color filter, the laser beam was split into P-polarized light and S-polarized light using a polarizing beam-splitter. The transverse mode and the intensity of the laser were measured using a CCD camera and a photodetector (Thorlabs; DET 110). The probe beam was adjusted to collimated rays by placing a convex lens with a focal length of 280 nm in front of the output coupler. Only the probe beam was allowed to pass through the color filter and the HR 1064 nm mirror. The polarized light of the probe beam was rotated using a half-wave plate and made to pass into the polarizing beam-splitter to divide it into P-polarized light and S-polarized light. To remove the effects of the pump light when the transverse mode and the intensity of the probe beam were measured, a mirror dichroic coated with HR 808 nm and AR 632.8 nm was installed in front of the CCD camera (Sony; ST-50) and photodetector (Thorlabs; DET 110).

3. Experimental results

Fig. 2 shows changes in the intensity of the S-polarized light of the laser output beam. Fig. 2(a) shows a case where the pump power is 2 W in which it can be observed that the intensity of the S-polarized light increased greatly when pumping began and decreased when pumping was finished. The intensity of the laser output beam changed little over time, and the transverse mode was also shown to be constant. Fig. 2(b) shows values measured at a pump power of 6 W. Significant changes in the intensity of the laser output beam can be observed around the time pumping began. These changes can be attributed to the fact that the sudden increase in the pump power caused significant changes in the refractive index of the medium, leading to changes in the polarized light components of the laser output. No significant changes occurred after approximately one minute had passed, and thermal equilibrium was achieved when 10 min had passed, as the intensity was shown to be almost constant. Fig. 2(c) shows values measured at a pump power of 10 W. The intensity of the laser output increased around the time point of beginning of pumping and decreased thereafter, which can be attributed to the fact that thermal birefringence effects and thermal lens effects appeared simultaneously due to the high pump power. The laser output beam decreased from when 200 s. of pumping time had passed until the pumping was finished. This decrease is attributed to the fact that thermal lens effects affected the output power more than did thermal birefringence effects. The great increase in the intensity around the time of the end of pumping is likely due to the fact that the thermal lens effects momentarily decreased due to the decrease in the pump power, so the laser output increased. Accordingly, the pump power changed the refractive index of the laser medium to affect the polarized light component of the laser output beam and thermal equilibrium was achieved when a certain time had passed, and the output power was stabilized. High pump power causes thermal lens effects, leading to decreases in output power. Changes in the polarized light component of laser output beams according to pump power – and the results of thermal birefringence in a previous study [9] – can be analyzed to discriminate between the laser output power losses due to thermal lens effects and thermal birefringence effects.

Fig. 3 shows laser output power versus pump power. In Fig. 3, values indicated by ■ are the results of a previous study [8] which indicated that the laser output power linearly increased with the pump power until the pump power reached 6.1 W and decreased thereafter due to thermal lens effects. To predict laser output power excluding the effects of thermal birefringence and thermal lens, the measured values from when the pump power was not higher than 6.1 W were linearly fitted. These fitted values were used as reference output power to analyze the effects of thermal birefringence and thermal lensing. To compare the S-polarization output power and the reference output power, the unit of the laser output power was normalized. In Fig. 3, ● shows the S-polarization component of the laser output power according to the pump power. The S-polarization output power linearly increases until the pump power reaches 4 W, then increases at a lesser rate until the pump power reaches 8 W due to losses caused by thermal birefringence effects, and rapidly decreases thereafter due to losses caused by not only thermal birefringence effects but also thermal lens effects.

Fig. 4 shows laser output power losses due to pump power. In Fig. 4, ■ shows total losses including thermal birefringence effects and thermal lens effects, and indicates the differences between the reference output power and the S-polarization output power shown in Fig. 3. Laser output power losses appeared at a pump power of 4 W with a total loss of 0.7%, but the total loss rapidly increased to 23.6% when the pump power was 6 W or higher and increased to 68.7% at a pump power of 12 W. In Fig. 4, ● and ▲ represent losses due to thermal birefringence effects and thermal lens effects, respectively. The losses due to thermal birefringence are the results of a previous study that measured changes in the probe beam. Changes in the probe beam due to thermal birefringence were shown to be 0.2%, 0.7%, 2.7% 7.7%, 10.3%, and 20.6% at pump power 2 W, 4 W, 6 W, 8 W, 10 W, and 12 W, respectively [9]. Output power losses due to thermal lensing could be obtained by excluding the amount of change due to thermal birefringence from the total loss. The output power loss due to thermal lensing was shown to be 2.1% at a pump power of 4 W, and rapidly increased to 20.8% at a pump power of 6 W and 48.1% at a pump power of 12 W. Laser beams generated using ceramic Nd:YAG with Nd^{3+} dopant concentrations of 2 at.% show losses due to thermal lens effects that are approximately three times larger than losses due to thermal birefringence effects.

4. Conclusion

Laser output power losses in a ceramic Nd:YAG laser due to thermal lens effects and thermal birefringence effects were analyzed in this study. The relative amounts of laser output power losses were determined by comparing changes in the
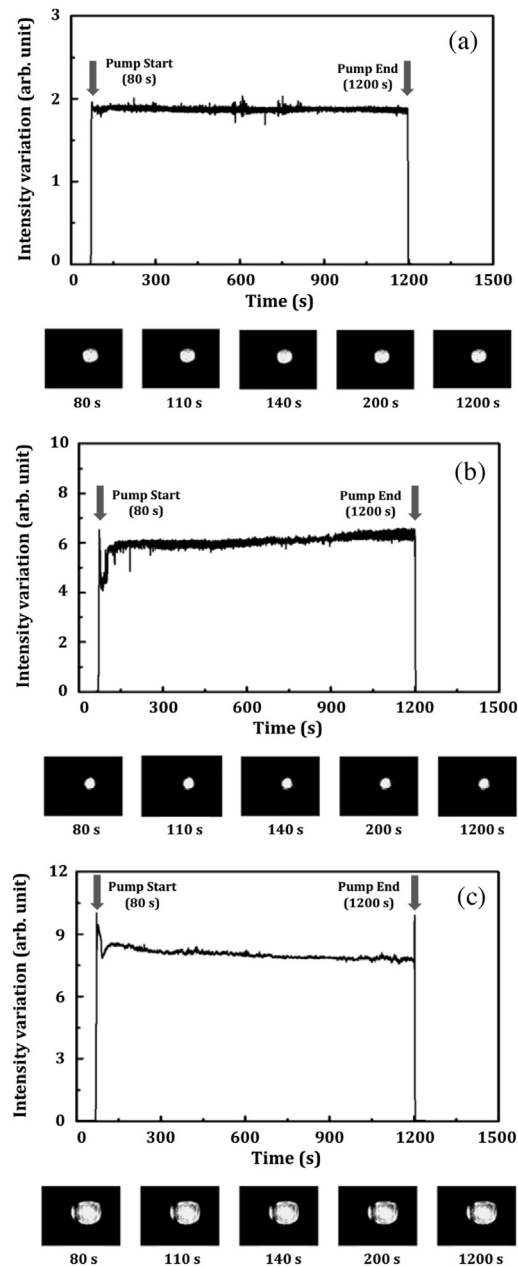
Fig. 2. Variation in the intensity of the S-polarized light component of the laser output beam.

fraction of the laser output S-polarized by pump power and changes in polarized light due to thermal birefringence effects on the basis of laser output power. At pump power not exceeding 6.1 W, these lasers are almost free of thermal lens effects and thermal birefringence effects. According to our analyses, S-polarization output power linearly increased until the pump power reaches 4 W, then increased at a lesser rate until the pump power reaches 8 W due to losses caused by thermal birefringence effects, and rapidly decreased thereafter due to losses caused not only by thermal birefringence effects but also by thermal lens effects. Therefore, laser beams generated using ceramic Nd:YAG showed output power losses due to thermal effects. The total laser output power loss at a pump power of 12 W was shown to be 68.7% and losses due to thermal lensing and thermal birefringence were shown to be 48.1% and 20.6%, respectively. Laser beams generated using ceramic Nd:YAG with a doping rate of 2 at.% Nd^{3+} show losses due to thermal lens effects approximately three times larger on average than the losses they show due to thermal birefringence effects. To enable broader use of the ceramic Nd:YAG, further study should be conducted into these thermal effects in a Q-switched Nd:YAG ceramic laser using information from this study.
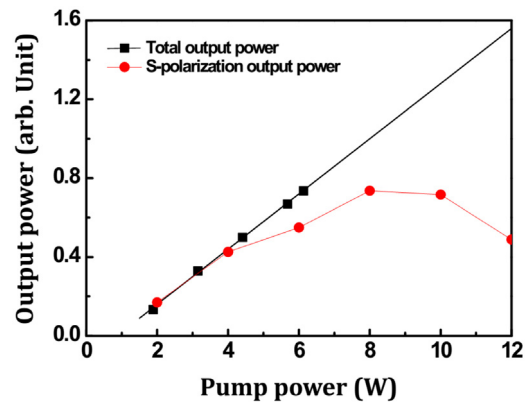
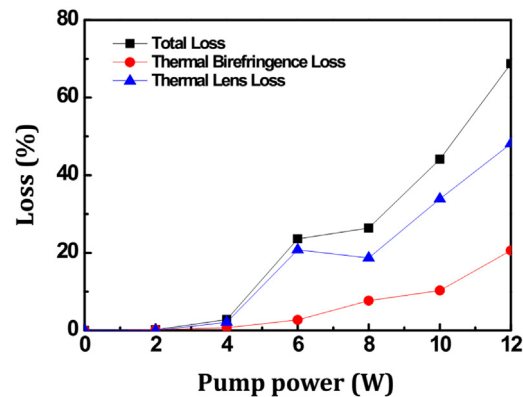**Fig. 3.** Laser output power according to pump power.

Fig. 4. Laser output power losses according to pump power.

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