A 40-J class Laser Oscillation of Nd-doped Silica Glass with High Thermal Shock Parameter

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INTRODUCTION

High-average-power and high-peak-power lasers are widely applied for material processing, thin film fabrication with ablation, generation of extreme ultraviolet (EUV) light sources for lithography, pump sources and various scientific research, such as high energy physics and particle acceleration. Since there are so many applications for high-power lasers, the demand is growing rapidly for more powerful lasers. Therefore a laser medium used in high-average-power operation should withstand the thermal stress due to a large amount of heat accumulation generated by repetitive high-power pumping.

The silica glass has many attractive properties for a laser medium: the high thermomechanical properties, the high transmittance from ultraviolet to near-infrared, the low nonlinear refractive index, the chemical durability, and the large scalability. Three glass fabrication techniques, such as conventional melting, chemical vapor deposition and sol-gel method, have been demonstrated to fabricate Nd-doped silica glass (NdSG)[1-3] The samples fabricated by the three methods were tested to demonstrate laser oscillation, but all the samples did not show an input/output characteristics of laser oscillation.

In this paper, we demonstrate a 40-J class laser output energy from a NdSG oscillator system. The output energy is progressed to about 260 times larger value than previously reported one. We also discuss to establish more powerful laser with NdSG, for instance, a 100-J class and repetitive operation.

EXPERIMENTAL

An NdSG sample used in following experiments was fabricated by zeolite method [4]. The final composition of the sample was measured by x-ray fluorescence analysis (Rigaku: ZSX-100e) and was determined as follows; Nd2O3: 1.34 wt%, Al2O3: 2.13 wt% and SiO2: 96.53 wt%. A fluorescence peak of NdSG existed at 1062 nm with the FWHM of 51.7 nm and the lifetime was 376 μs [5]. The stimulated emission cross section was calculated to be 1.4×10⁻²⁰ cm² by Judd-Ofelt method [6], which is smaller than that of Nd:YAG (2.8×10⁻²⁰ cm²) [7]. The thermal shock parameter was evaluated to be 12.0 W/cm, which is 1.5 times larger than that of Nd:YAG crystal [5].

The sample was cut and polished to a rod shape with a diameter of 30 mm and a length of 300 mm. Both end surfaces were polished in parallel with antireflection (AR) coating at 1062 nm of the center wavelength. We also did a laser oscillation experiment using the sample without AR coating to analyze the loss effect on the extracted energy. Single-pass transmittance of the NdSG rod with or without AR coating were evaluated to be 77.7% or 73.0% at 1064 nm, respectively. The effective loss coefficients of the sample with or without AR coating, which including end surface reflection losses, were calculated to be 0.0084 cm⁻¹ or 0.0105 cm⁻¹, respectively. The loss coefficient with AR coating is reduced to be one third of the previously reported one [8].

The optical gain property and the laser output energy of NdSG were measured by the same configuration described in Ref.5 except increasing the maximum electrical input energy up to 18.6 kJ. The pumping house has six flash lamps whose arc lengths are all 300 mm, but the 280 mm of the NdSG rod was effectively pumped because of the shadowed area due to fixing. The optical noises due to ASE or flash lamp light are carefully eliminated on the optical gain measurement and the oscillation experiment. After this confirmation, we measured the optical gain and the laser output energy with increasing the electrical input energy between 8.4 and 18.6 kJ. The optical resonator is designed as follows. The NdSG rod was set between a highly reflecting mirror (99.9%) with concave radius of 3000 mm and an output mirror with 30% transmittance. The both mirrors were set at 130 mm from the each end surface of the rod.

Fig. 1 Input-output characteristics of the laser oscillation on optically pumped NdSG rod with AR coating.
RESULTS
The maximum small signal gain was achieved to be 3.75 at the electrical input of 18.6 kJ. Thus its gain coefficient was calculated to be 0.047 cm⁻¹. The maximum stored energy in the rod was estimated to be 124 J that means 0.63 J/cm² of the stored energy density was obtained. And then the pumping efficiency (stored energy/electrical input energy) was evaluated to be 0.67%, which is a reasonable value on the flash lamp operation [9].

Figure 1 shows the characteristics of laser output vs. pump input. The maximum output energy of 37.3 J was obtained with AR coating. The output energy increases linearly with increasing electrical input energy. The threshold pumping energy is obtained to be 5.86 kJ by extrapolating the linear part of Fig. 1. Since any parasitic oscillation was not observed at the maximum pumping, higher stored energy density is expected to achieve in NdSG, in other words, the output energy can be increased by more powerful pumping without any change of the resonator configuration.

\[ E_{ext} = E_{st} \cdot \left(1 - \frac{(2aI + L_{st})}{2gL^2}\right)^2 \]  

where \( E_{st} \) (= 124 J) is the stored energy in NdSG rod, \( I \) is the gain coefficient, \( L_{st} \) is the gain length and \( L_0 \) is the loss at mirrors due to absorption, diffraction, and scattering; in this calculation, in this case, we assume \( L_0=0 \). Figure 2 shows the relation between the loss coefficient and the expected output energy. Two points show the measured output energies in the present experiments: (a) 37.3 J output with AR coating at effective loss coefficient of 0.0084 cm⁻¹ (b) 29.0 J output without AR coating at effective loss coefficient of 0.0105 cm⁻¹. A solid line indicates the calculated curve using Eq. (1). Each of the output energy is well agreed with calculated value. From Fig.2, it is expected that the output energy will be increased up to 100 J (80% extraction), if the internal loss of the gain medium is decreased below 0.001 cm⁻¹. Commercially supplied laser glasses typically have an unpumped absorption loss of less than 0.0015 cm⁻¹ at 1μm. The total static absorption loss in laser glass at 1μm is sum of contributions due to Nd ions thermally populating the terminal laser level (\( ^4I_{13/2} \)), impurities of transition metal or rare earth ions, and residual hydroxyl groups. The absorption loss of the Nd ions thermally populating at \( ^4I_{15/2} \) is calculated to be 0.00019 cm⁻¹ at room temperature [10]. Therefore, it is expected that the 100 J at repetitive operation (~10Hz) can be established, if the absorption coefficient is reduced below 0.001 cm⁻¹ by eliminating the metal impurities or hydroxyl groups, because the NdSG has a good thermal shock parameter of 12.0 W/cm².

CONCLUSIONS
We demonstrate a 40-J class (37.3 J) laser output energy from a NdSG oscillator system. We also discuss about a possibility of a 100-J class repetitive operation if the loss coefficient is reduce until 0.001 cm⁻¹.

REFERENCES

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