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Research Article

Q-Switched and Mode-Locked Nd/Cr:YAG Ceramic Pulse Laser

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A mode-locked and Q-switched short pulse laser using the Nd^{3+}/Cr^{3+}:YAG ceramic has been constructed with a SESAM and Cr^{4+}:YAG crystal optical switch based on excite state absorption (ESA). Laser oscillations of the pulse laser were observed experimentally. The Nd/Cr:YAG ceramic laser has a high conversion efficiency from white light (such as lamp light or solar light) to the laser. The Nd/Cr:YAG ceramic has a higher laser gain than the Nd:YAG laser for the same pumping power. The laser oscillation can be obtained very easily. A single-mode-locked laser pulse with fast modulation on the order of 100 ps was obtained in some pump power regimes when using the Cr^{4+}:YAG crystal. The obtained pulse duration of the short pulse was a few hundred ps. A maximum peak power of 60 kW was obtained when using a SESAM. The same level of peak power (60 kW) was also obtained when using the Cr^{4+}:YAG crystal.

1. Introduction

An ultrashort pulse laser with the pulse width of the laser is extremely short and has momentarily high intensity. It is hard to use a laser pulse with a pulse width such as an ultrashort pulse fs to apply heat to an object, and it can also cause a chemical reaction. Various applications to perform processing with low thermal strain and processing of waste fluid using laser-induced atomic conversion exist in the industry.

Nd^{3+}/Cr^{3+}:YAG ceramic materials, which are laser media for white light-pumped lasers such as solar light and flash lamps, have been developed. Various ceramic lasers have been reported to date, such as free-running and Q-switch pulse oscillation with flash lamps [1, 2], solar light excitation [3–5], and active mirrors as the laser amplifier [6]. The advantages of using the Nd^{3+}/Cr^{3+}:YAG ceramic are that the oscillation threshold is low. The required pumping power is 100 W/cm^2, while the required pumping power is a few kW/cm^2; the pumping power for generating a laser can be reduced by an order of magnitude [6].

A prototype for generating an ultrashort pulse laser with a few picoseconds of the pulse width has been constructed, and Q-switching and self-mode-locking using a Cr^{3+}:YAG crystal have been used to generate short laser pulses. No mode-lock oscillation using this material has been reported until now.

2. Experimental Setup

We obtained laser oscillation by both Q-switching and self-mode-locking using a Cr^{4+}:YAG crystal. The experimental configuration for the laser oscillation is shown in Figures 1(a) and 1(b). The Nd/Cr:YAG ceramic rod (Konoshima Chemical Co., Ltd.) was of size $4 \times 4\ mm^2 \times 47$ mml. The concentrations of the Cr and Nd ions were 0.1 and l at.%, respectively.

The bandwidth and pulse duration of the calculated transform-limited pulse (TLP) for Ti:sapphire, Nd:YAG, Nd:YVO_4, and Nd/Cr:YAG ceramic are shown in Table 1. Also, the fluorescence spectrum of the Nd/Cr:YAG ceramic around 1064 nm is shown in Figure 2. The fluorescence spectra of Nd:YAG ceramics and Cr 3 at.% doped and Cr 0.1 at.% doped Nd:YAG ceramics are shown in Figure 2. The doped Nd ion density was all 1 at.%. The dashed line shows that of the Nd:YAG ceramics [9], and the solid ones show that of Nd/Cr:YAG ceramics. The bold line shows the case of the Cr 3 at.% doped Nd:YAG ceramics. The excitation

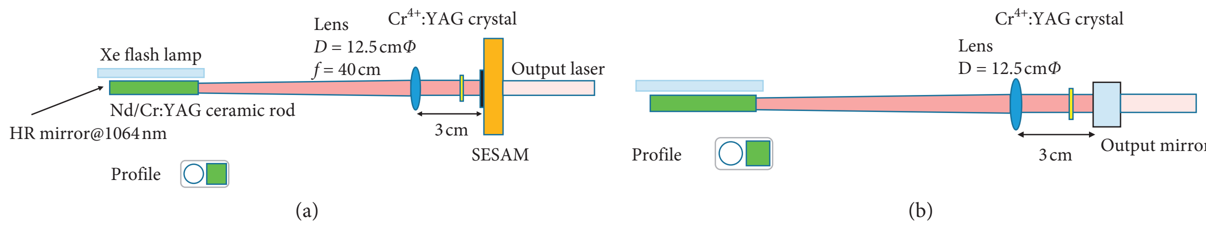

Figure 1: Experimental setup (a) using a SESAM and (b) using only a Cr^{4+}:YAG crystal.

Table 1: Bandwidth and TLP for each laser material.

	Ti:sapphire	Nd:YAG [7]	$Nd:YVO_4$ [7, 8]	Nd/Cr:YAG ceramic Cr 0.1 at.%
Bandwidth (nm)	230	0.45 [7]	0.8 [7]	1.7
Calculated pulse duration of the TLP (ps)	0.0036	3.7	2.1	0.98

TLP: transform-limited pulse. Spectral emission waveform: Gaussian shape was assumed.

wavelength was 590 nm, and the spectrometer used was SS-25 (JASCO Corp.). The spectral resolution was 0.1 nm, and the estimated bandwidth was 2.0 nm. When the excitation wavelength was 809 nm, only Nd ions were pumped. The normal line shows the case of the Cr 0.1 at.% doped Nd:YAG ceramics pumped with the CW arc-metal-halide lamp. The spectral resolution of the infrared spectrometer (SM241: CVI) used was 0.2 nm. The estimated bandwidth of the Cr 0.1 at.% doped Nd:YAG was 1.7 nm.

In general, a laser using a laser medium having a wider bandwidth can generate a pulse laser having a shorter pulse width. At first glance, the Nd/Cr:YAG ceramic seems unsuitable for generating short pulse lasers due to its short bandwidth. However, compared with Ti:sapphire, there is an advantage in that the light intensity required for excitation is one order of magnitude smaller. In addition, since the output power is large, it is possible to differentiate at that portion. The bandwidth of the fluorescence spectrum for the Nd/Cr:YAG ceramic is four times wider than that of Nd:YAG, so it should be possible to generate shorter pulses than when using the Nd:YAG ceramic or crystal. Also, the laser gain at 1064 nm for the Nd/Cr:YAG ceramic is one order higher than that of the Nd:YAG ceramic, the Nd:YAG crystal, or Ti:sapphire when the power of the pumping light is the same. This makes it easy to obtain the laser oscillation.

The absorption spectrum of the Nd/Cr:YAG ceramic is shown Figure 3. The Nd/Cr:YAG ceramic was developed. The Nd/Cr:YAG ceramic is a new material that can add high concentrations of Cr^{3+} ions. By adding Cr^{3+} ions, the absorption band broadens, and this enables the absorption of the broad spectrum of sunlight. In conventional YAG crystals, it is difficult to add Cr^{3+} ions due to the large radius of Cr ions in the structure, and a large laser crystal has never been produced. However, it is possible to add Cr^{3+} ions by ceramicizing the laser crystal, and energy transfer from Cr to Nd ions [10–14] can be actively performed such that a high laser gain with lower solar light excitation density than that of conventional materials can be achieved. Several studies have succeeded in doing so, and it is said that the light-to-light conversion efficiency from sunlight

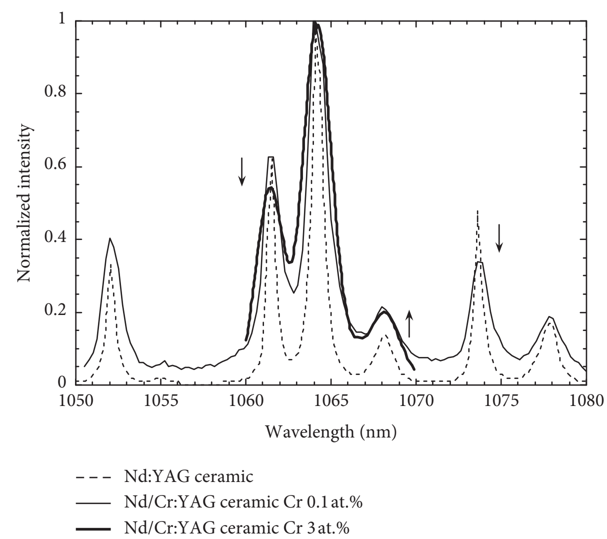

Figure 2: Fluorescence spectra of Nd:YAG and Nd/Cr:YAG ceramics. The doped Nd ion density was 1 at.%, and the doped Cr ion density was 0.1 or 3 at.%.

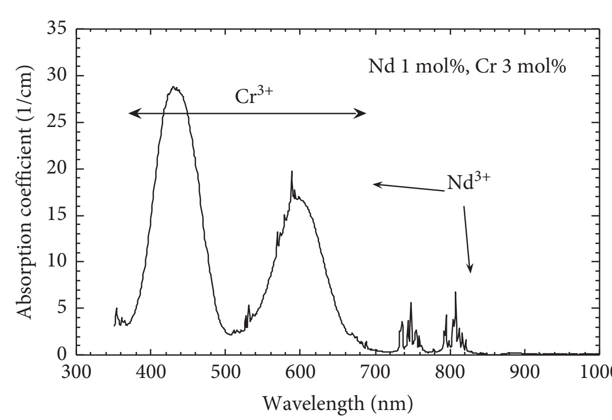

Figure 3: Absorption spectrum of the Nd/Cr:YAG ceramic.

to the laser is up to around 50% [6]. When we compare the Nd/Cr:YAG ceramic with Nd:YAG, there are two key advantages: First, it can produce a high gain with a small excitation power. This is because the effective stimulated emission cross section is large [13] and the effective fluorescence lifetime of 1.1 ms is longer than that of Nd: YAG, which is a general solid-state laser material [14]. Then, the effective stimulated emission cross section of the Nd/Cr:YAG ceramic is very close to that of Nd:YVO_4 [7, 8]. Thus, the laser oscillation threshold is low. This is because a high gain can be obtained with a small excitation power, which makes laser oscillation easy.

A laser oscillation using both Q-switch and mode-lock was performed by a single shot. A modulated Q-switched short laser pulse was obtained. A 210 μF capacitor was used for the flash lamp charging circuit. The input voltage to the capacitor ranged from 220 to 280 V. This charging circuit applies a voltage to turn on the flash lamp. The maximum electrical input energy was 8.5 J. The conversion efficiency from electricity to the lamp light of the xenon flash lamp was 16%. The flash lamp was placed parallel to the ceramic laser rod. The excitation light source of the laser medium in our experiments was a 40 mm xenon flash lamp. The flash lamp and laser medium were surrounded by an aluminum sheet to absorb the lamp light efficiently. The Cr^{4+}:YAG crystal with the diameter of 10 mm was set near the output coupler. The initial transmittances of the Cr^{4+}:YAG crystal were set to 70, 80, 90, and 95%. A SESAM with an output coupler for mode-lock oscillation was installed at the tip of the irradiated surface of the Nd/Cr:YAG ceramic rod. A lens was placed between the two, and a Cr^{4+}:YAG crystal was placed between the lens and the SESAM, as shown in Figure 1(a). Two types of SESAMs were used. The shape of the aperture was a circle, and the diameter was 4 mm. One had the absorption of 2.7%, transmittance of 3.2%, and reflectance of 97%, with a recovery time of 1 ps. The other one had 8% absorption, 6% transmittance, 86% reflectance, and 1 ps recovery time. In this experiment, we measured the resonator length at 20, 35, and 50 cm. First, the laser medium is excited by the light of the flash lamp, but the laser oscillation is inhibited by the Q-switch. When a certain amount of energy is stored, a Q-switch pulse is generated. After that, reflection is repeated with a high-reflection mirror and a saturable absorber, and a laser that reaches a certain light intensity passes through the saturable absorber (SESAM) and is subjected to mode-lock modulation.

Also, a modulated Q-switched short laser pulse was obtained using only a Cr^{4+}:YAG crystal, as shown in Figure 1(b) [15, 16]. The reflectivity of the output coupling mirror in the self-mode-locked oscillation was 90%.

We used a photodetector (DET02AFC, Thorlabs) to observe the temporal waveform. The pulse width of the Q-switch and mode-lock pulse is so short that it cannot be observed by a photodetector with low temporal resolution. However, a modulated Q-switch and mode-lock pulse can be observed by this photodetector. The oscilloscope was Tektronix TDS7104 with a sampling rate of 10 GS/s. This value indicates how many times conversion from an analog signal (observed signal) to a digital signal is performed per second. In other words, the larger the value, the more accurate the waveform drawn on the oscilloscope screen.

3. Results and Discussion

3.1. Using the SESAM. Figures 4 and 5 show the results of the laser output energy with respect to the charging energy, which was tested with an initial reflectivity of the SESAM set to 97% and 86%, respectively.

The maximum averaged output laser energy was 9 mJ and 11 mJ when using the SESAM set to 97% and 86%, respectively. The maximum single output pulse energy was 3 mJ when using the initial reflectivity of 97% and 86%. The shape of the beam profile for the output laser was a square.

The observed single laser pulse generated by Q-switch and mode-lock oscillation is shown in Figures 6 and 7. Each resonator length is the same: 20 cm. Figure 4 shows the result when using the SESAM reflectivity of 97%. Figure 5 shows the result when using the SESAM reflectivity of 86%. From these figures, we can see that one pulse generated by the Q-switch is modulated by mode-locking and a shorter pulse is generated. It was found that the modulation pulse width was several ps and the modulation rate was about 40%. The modulation pulse width in Figure 6 was found to be several ps and the modulation degree was about 60%. As shown in Figure 4, when the charging energy was 8 J, the laser output energies in Figures 4(a)–4(c) were 8.9, 7.0, and 3.0 mJ. In Figure 5, when the charging energy was 8 J, the laser output energies in Figures 5(a)–5(c) were 11, 7.8, and 3.0 mJ. The oscillation threshold values for the electric input energy were 4.0, 4.3, and 6.8 J, respectively. The maximum laser peak power was estimated to be 60 kW.

For the output laser, the evaluated pulse duration was 250, 230, and 200 ns when SESAM $R = 97\%$ and initial transmittance of Cr^{4+}:YAG T was 95, 90%, and 80% (corresponding to Figure 4), respectively. On the contrary, the evaluated one was 250, 100, and 50 ns for SESAM $R = 86\%$ and T was 95, 90%, 80%, and 70% (corresponding to Figure 5), respectively.

The average laser output power for T was estimated, as shown in Figure 8, when the cavity length L was 20 cm. The average laser output power became maximum when L was 20 cm.

For SESAM $R = 97\%$ (corresponding to Figure 4), the energy of one pulse for the mode-lock and Q-switch laser was 0.35, 0.4, and 0.6 mJ for $T = 90\%$; 0.73, 0.86, and 1.2 mJ for $T = 80\%$; and 1.2, 1.5, and 1.9 mJ for $T = 70\%$, respectively. For SESAM $R = 86\%$ (corresponding to Figure 5), the pulse energy was 0.6, 0.7, and 0.9 mJ for $T = 90\%$; 0.9, 1.1, and 1.7 mJ for $T = 80\%$; and 2.0, 2.2, and 2.8 mJ for $T = 70\%$. The maximum of the average laser output power was evaluated to be 9.5 kW and 56 kW for SESAM $R = 97\%$ and SESAM $R = 86\%$ when T was 70%, as shown in Figure 8.

3.2. Using the Cr^{4+}:YAG Crystal. The experimental results of the measured output laser energy for the Q-switched and self-mode-locked laser oscillation are shown in Figure 9. The obtained maximum output laser energies in the free-running mode were 75 mJ when the electrical input energy was 8 J, as shown in Figure 9(a).

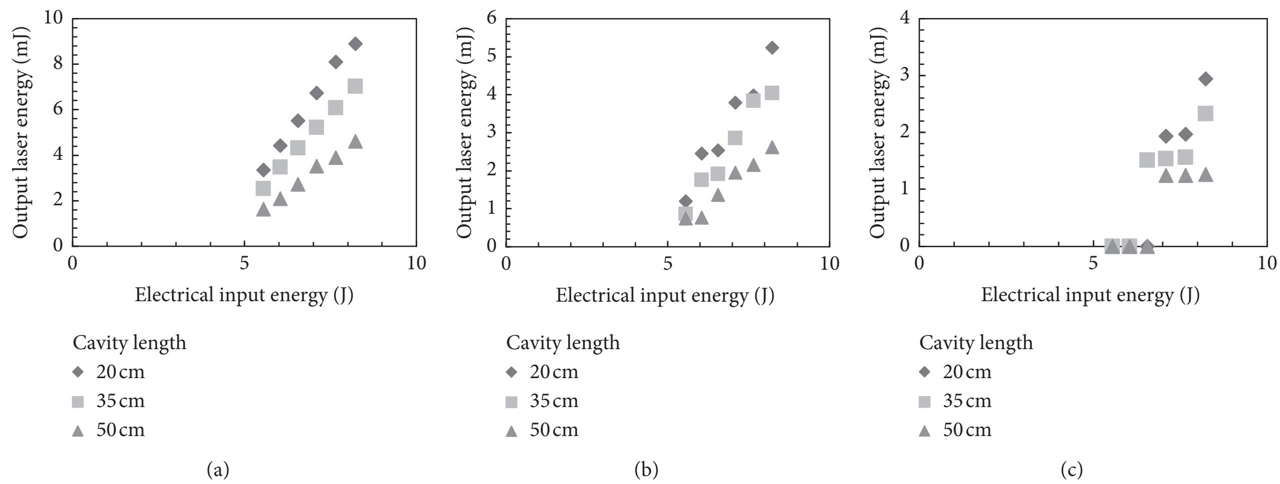

Figure 4: Output laser energy (SESAM $R = 97\%$): (a) Cr^{4+}:YAG $T = 90\%$; (b) Cr^{4+}:YAG $T = 80\%$; (c) Cr^{4+}:YAG $T = 70\%$.

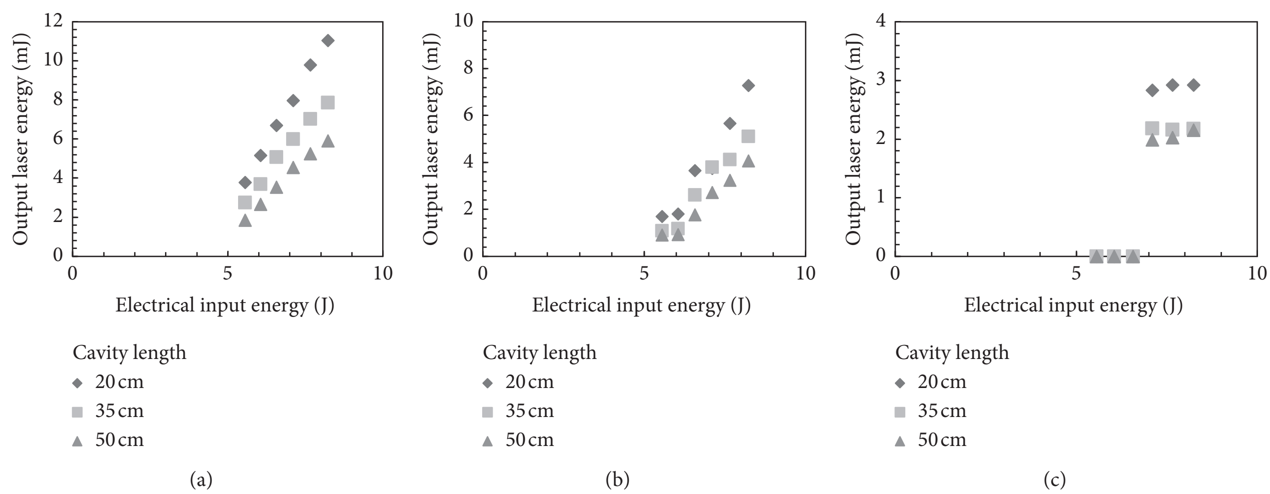

Figure 5: Output laser energy (SESAM $R = 86\%$): (a) Cr^{4+}:YAG $T = 90\%$; (b) Cr^{4+}:YAG $T = 80\%$; (c) Cr^{4+}:YAG $T = 70\%$.

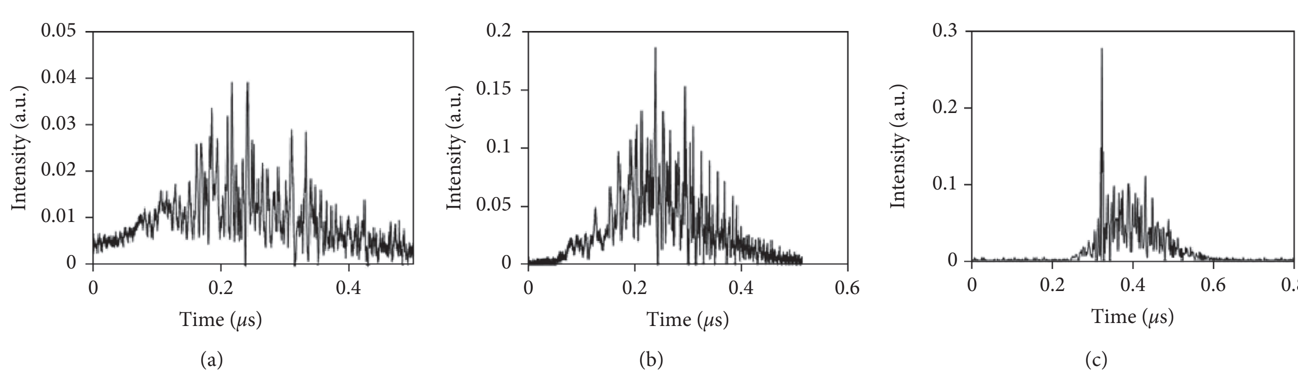

Figure 6: Q-switched and mode-locked pulses (cavity length 20 cm, SESAM $R = 97\%$): (a) Cr^{4+}:YAG $T = 90\%$; (b) Cr^{4+}:YAG $T = 80\%$; (c) Cr^{4+}:YAG $T = 70\%$.

When the initial transmittances of Cr^{4+}:YAG were 90% and 95%, the obtained maximum output laser energies were 40 mJ and 43 mJ when the electrical input energy was 8 J, as shown in Figures 9(b) and 9(c). Also, local increments in the output laser energy for the electrical input energies were observed owing to the cross-relaxation effect of the doped Nd ions [17–19], as shown in Figures 9(b) and 9(c).

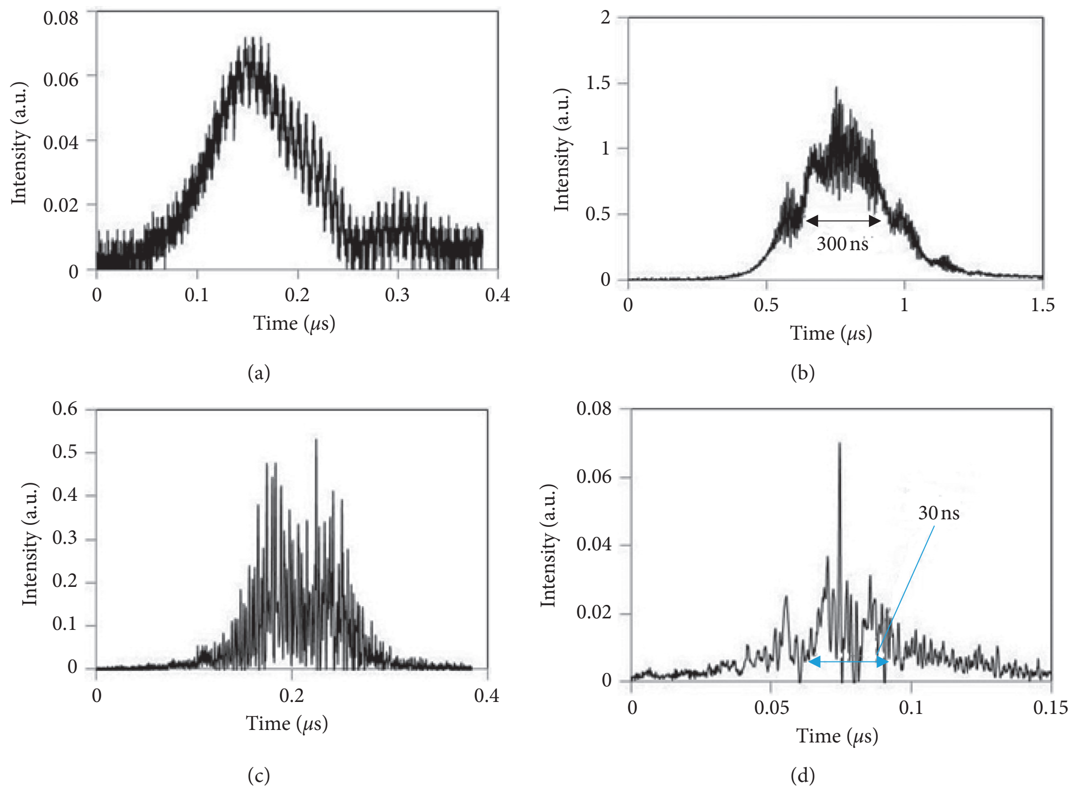

Figure 7: Q-switched and mode-locked pulses (cavity length 20 cm, SESAM $R = 86\%$): (a) Cr^{4+}:YAG $T = 95\%$; (b) Cr^{4+}:YAG $T = 90\%$; (c) Cr^{4+}:YAG $T = 80\%$; (d) Cr^{4+}:YAG $T = 70\%$.

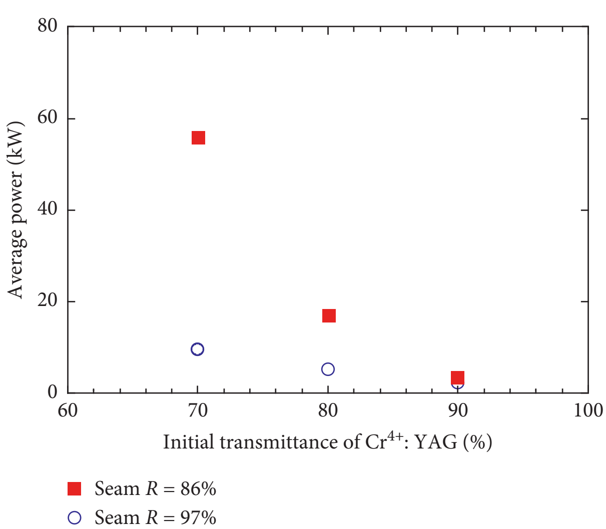

Figure 8: Average output laser power per single Q-switched and self-mode-locked laser pulse for initial transmittance of Cr^{4+}:YAG.

These output laser energies of the single laser pulses were three times higher than the case using the SESAM. The threshold of electrical input energy for laser oscillation was 3 J in the free-running mode and 3.8 J in the Q-switched and mode-locked oscillation, respectively.

The observed temporal waveforms for the Q-switch and self-mode-locked laser oscillation are shown in Figure 10. The electrical input energy was 5.6 J in Figure 10(a), 6.0 J in Figure 10(b), and 6.4 J in Figure 10(c). Q-switch and self-mode-locked laser oscillations were only observed below low electrical input energy of 7.4 J. Here, the maximum laser peak power was estimated to be 90 kW.

For the pulse duration of the output laser, the measured output laser pulse duration was 230 μs when the pulse duration of the lamp light for pumping was 450 μs. Thus, the maximum average power in the free-running mode was 320 W for the maximum laser output laser energy of 75 mJ.

When T was both 90 and 95%, the pulse duration of the Q-switch and self-mode-locked laser changed from 500 ns to 300 ns for increasing excitation energy slightly. When T was both 90 and 95%, the output laser energy per single Q-switch and self-mode-locked laser pulse was 20 and 13 mJ. Thus, the average power was estimated to be up to 67 and 43 kW, respectively.

4. Conclusion

We conducted an experiment on a Q-switched and mode-locked Nd/Cr:YAG ceramic laser. The maximum output laser energies were 11 mJ and 3 mJ with multiple Q-switched pulses when the electrical input energy was 8 J. The obtained pulse duration of the single Q-switched laser pulse was 80 ns, and the modulated pulse width was below 100 ps. The evaluated peak intensity was 60 kW. The maximum output laser energies were 40 mJ and 43 mJ when the electrical input energy was 8 J and when using only a single Cr^{4+}:YAG crystal, respectively. The output

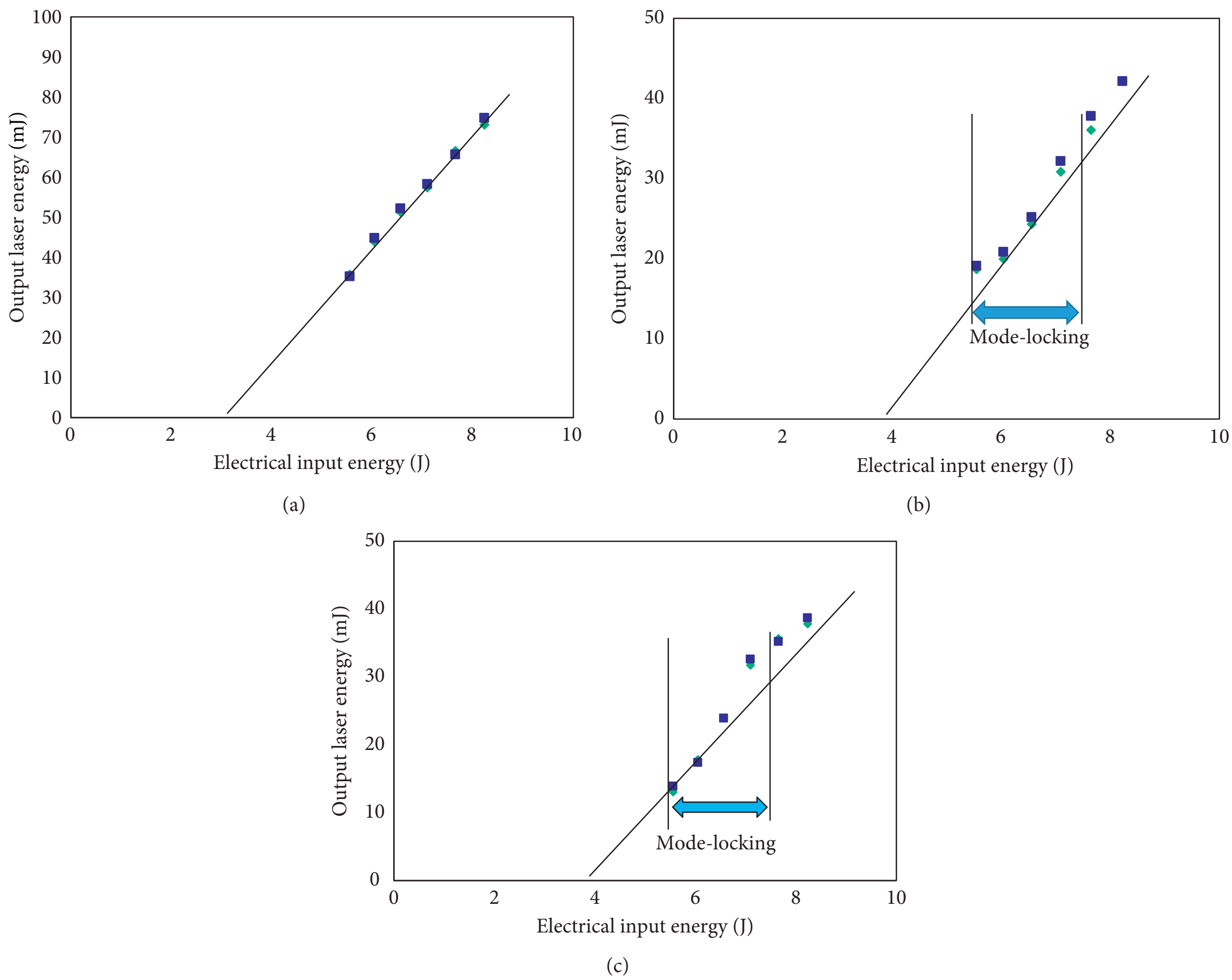

FIGURE 9: Measured output laser energy: (a) free-running mode; (b) Cr^{4+}:YAG $T = 90\%$; (c) Cr^{4+}:YAG $T = 95\%$.

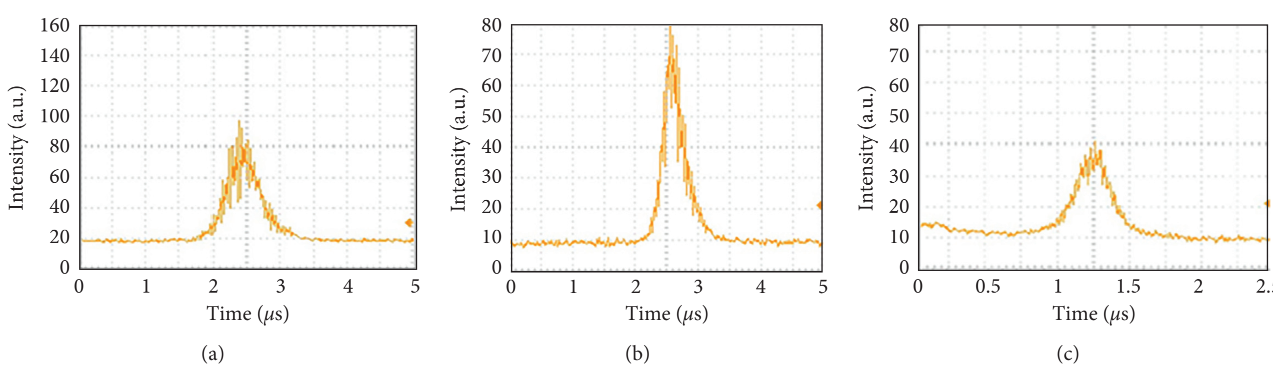

FIGURE 10: Measured temporal waveform of a single laser pulse when Cr^{4+}:YAG $T = 90\%$ and when the electrical input energy is (a) 5.6 J, (b) 6.0 J, and (c) 6.4 J.

energy of the single laser pulse using only a single Cr^{4+}:YAG crystal was three times higher than the case using a SESAM. Also, the output energies of the laser pulse for the Q-switched and self-mode-locked laser oscillation using only a single Cr^{4+}:YAG crystal increased locally for the input electrical energy owing to the cross-relaxation effect of the doped Nd ions.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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