Q-switched and Mode-locked Nd/Cr:YAG Ceramic Pulse Laser

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Abstract

A mode-locked and Q-switched short pulse laser using Nd^{3+} /Cr^{3+}: YAG ceramic has been constructed with a semiconductor 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 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 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 Cr^{4+}:YAG crystal.

１.Introduction

An ultra-short pulse laser with the pulse width of 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 the 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 laser amplifier [6]. The advantages of using 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 ultra-short pulsed 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 has 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 Fig. 1(a) and (b). The Nd/Cr:YAG ceramic rod was sized 4 × 4 mm^2 × 47 mml. The concentrations of the Cr and Nd ions were 0.1 and l atm.%, respectively.

Table.1. Bandwidth and TLP for each laser materials

	Ti:Sapphire	Nd:YAG[7]	$Nd:YVO_4$ [7,8]	Nd/Cr:YAG Ceramic
Band width (nm)	230	0.45[7]	0.8[7]	1.8[9]
Calculated pulse duration of TLP (ps)	0.0036	3.7	2.1	0.92

TLP: Transform-Limited Pulse. Spectral emission waveform: Gaussian shape was assumed.

The bandwidth and pulse duration of calculated transform-limited pulse (TLP) for Ti:Sapphire, Nd:YAG, $Nd:YVO_4$, and Nd/Cr:YAG ceramic are shown in Table.1. 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, 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 Nd:YAG ceramic or crystal. Also, the laser gain at 1064 nm for Nd/Cr:YAG ceramic is one order higher than that of Nd:YAG ceramic, Nd:YAG crystal, or Ti: Sappire 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 Fig. 1. Nd/Cr:YAG ceramic was developed. 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 [9-13] can be actively performed such that a high laser gain with lower solar light excitation density than 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 to laser is up to around 50% [6]. When we compare 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 [12] and the effective fluorescence lifetime of 1.1 ms is longer than that of Nd:YAG, which is a general solid-state laser material[13]. The effective stimulated emission cross section of 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.

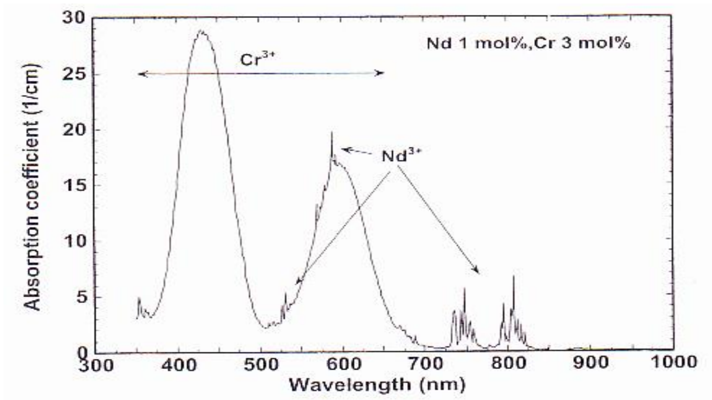
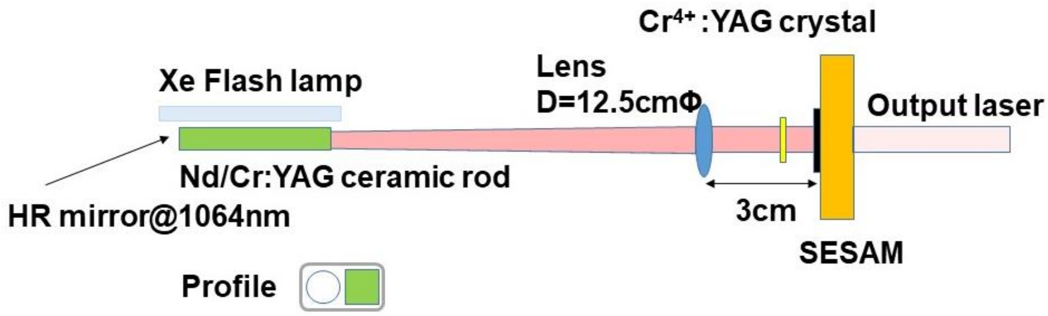


Fig.1. Absorption spectrum of Nd/Cr:YAG ceramic.

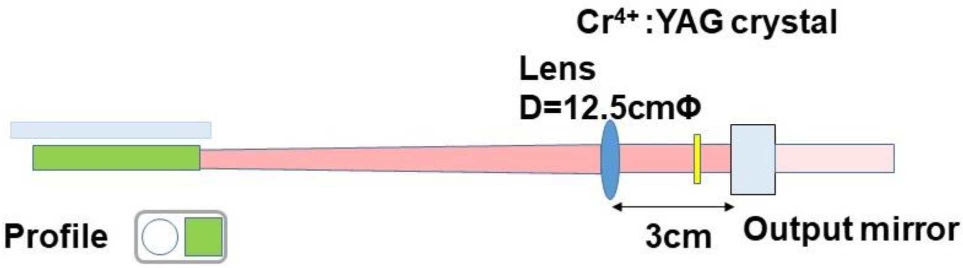
A laser oscillation using both Q-switch and mode-lock was performed by single shot. A modulated Q-switched short laser pulse was obtained. A 210-μF capacitor was used for the flash lamp charging circuit. The input voltage to the capacitor ranged from 220 to 280V. This charging circuit applies a voltage to turn on the flash lamp. The maximum electrical input energy was 8.5J. 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. 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 Fig. 2(a). Two types of SESAM were used. The shape of the aperture was a circle, and the diameter was 4mm. 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 Cr^{4+}: YAG crystal, as shown in Fig. 2(b) [14,15]. The reflectivity of the output coupling mirror in the self-mode-locked oscillation was 90%.

We used a Thorlabs DET02AFC photo detector 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 a 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 this value, the more accurately the waveform can be drawn on the oscilloscope screen.



(a)



(b)

Fig.2. Experimental setup. (a) using SESAM, (b) using only Cr^{4+}: YAG crystal.

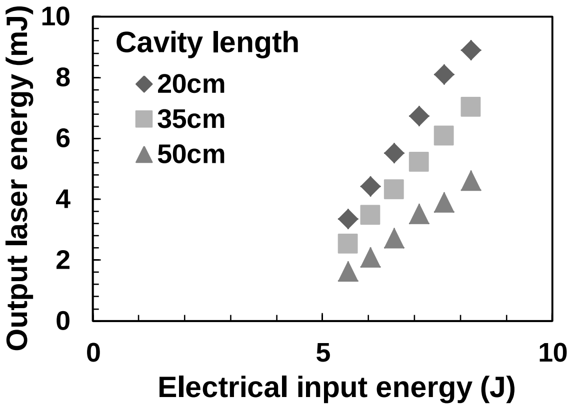
3.Result and Discussion

3.1 Using SESAM

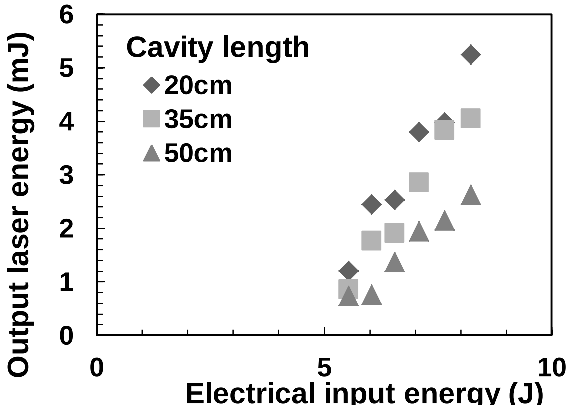
Figures 3 and 4 show the results of the laser output energy with respect to the charging energy, which was tested with initial reflectivity of the SESAM set to 97% and 86%, respectively.

The maximum averaged output laser energy was 9 mJ and 11 mJ when using 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 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 Figs. 5 and 6. Each resonator length is the same: 20 cm. Figure 5 shows the result when using the SESAM reflectivity of 97%. 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 Fig. 6 was found to be several ps and the modulation degree was about 60%. As shown in Fig. 3, when the charging energy was 8 J, the laser output energies of (a), (b), and (c) were 8.9, 7.0, and 3.0 mJ. In Fig. 4, when the charging energy was 8 J, the laser output energies of (a), (b), and (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.



(a)



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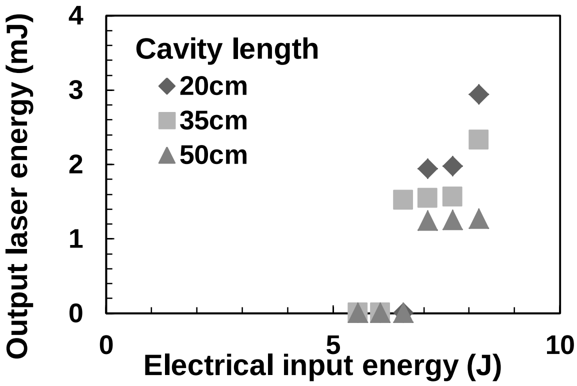
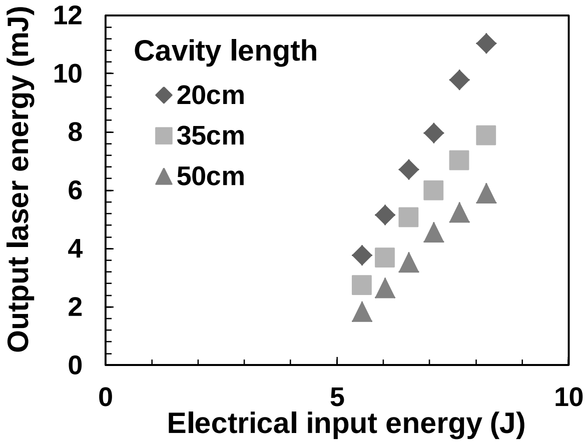
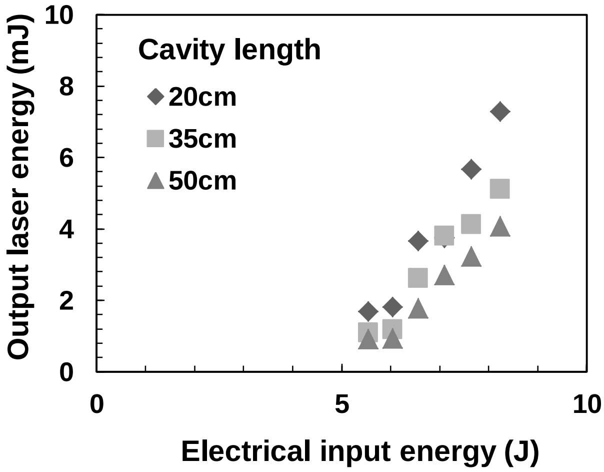


(c)

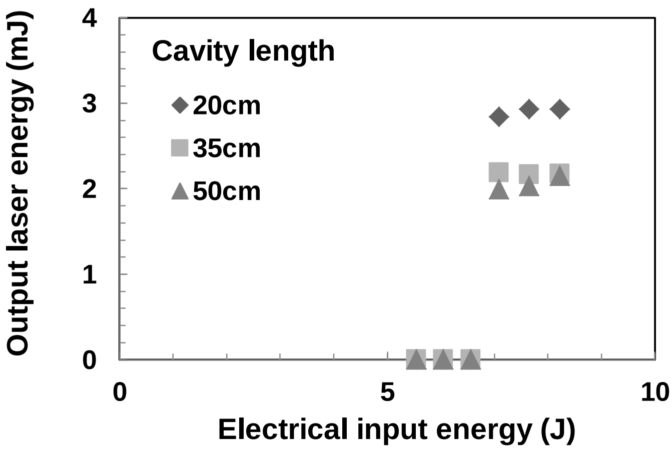
Fig.3. Output laser energy (SESEM, R=97%) (a) Cr^{4+}:YAG T=90%, (b) Cr^{4+}:YAG T=80%, (c) Cr^{4+}:YAG T=70%


Cavity length
20cm
35cm
50cm
Output laser energy (mJ)
Electrical input energy (J)
0
2
4
6
8
10
12
0
5
10

(a)


Cavity length
20cm
35cm
50cm
Output laser energy (mJ)
Electrical input energy (J)
0
2
4
6
8
10
0
5
10

(b)


Cavity length
20cm
35cm
50cm
Output laser energy (mJ)
Electrical input energy (J)
0
1
2
3
4
0
5
10

(c)

Fig.4. Output laser energy (SESEM, R=86%) (a)Cr^{4+}:YAG T=90%, (b) Cr^{4+}:YAG T=80%, (c) Cr^{4+}:YAG T=70%

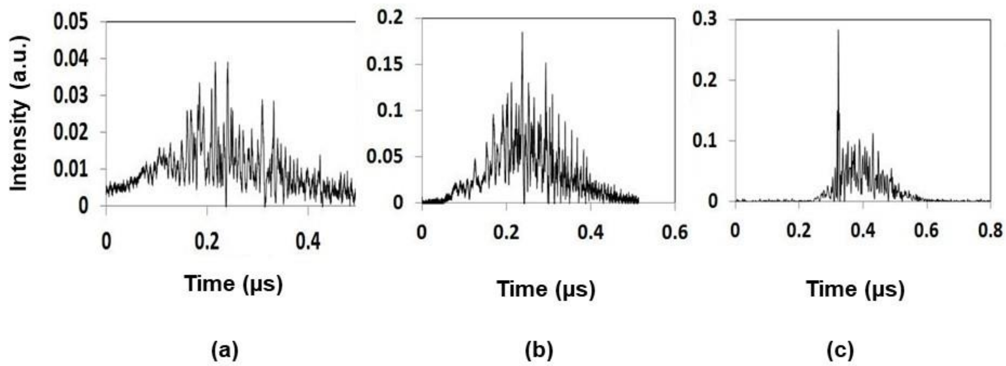


Fig.5. Q-switched and Mode-locked pulses.

(Cavity length 20cm, SESAM R=97%)

(a) Cr^{4+}:YAG T=90%, (b) Cr^{4+}:YAG T=80%, (c) Cr^{4+}:YAG T=70%

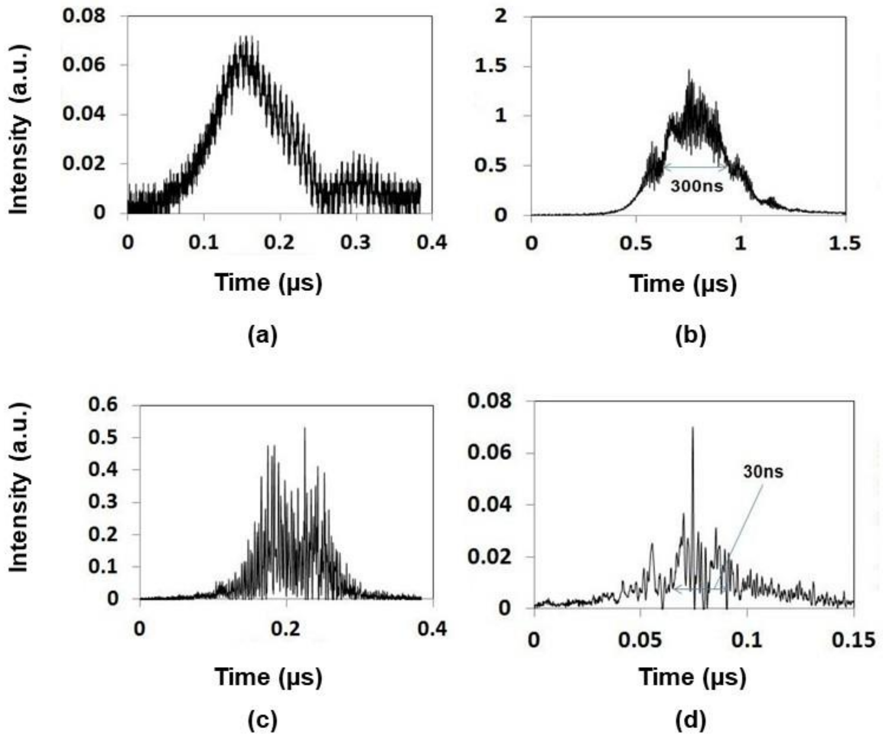


Fig.6. Q-switched and Mode-locked pulses

(Cavity length 20cm, 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%

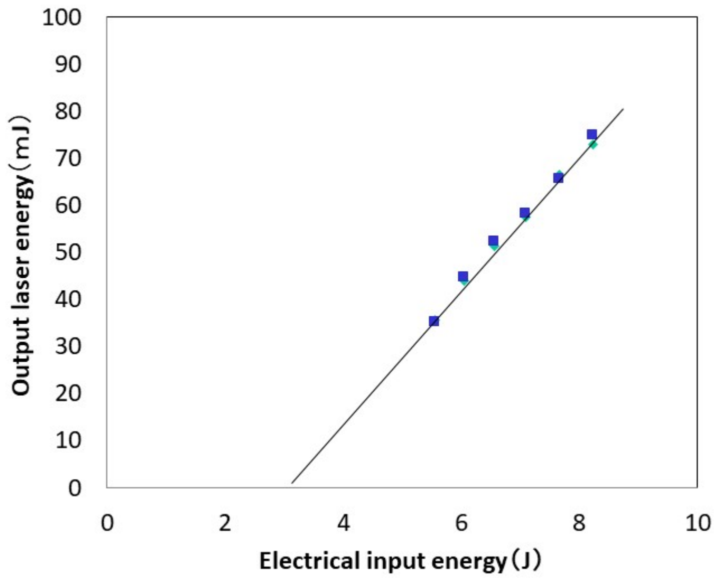
3.2 Using Cr^{4+}: YAG crystal

The experimental results of the measured output laser energy for the Q-switched and self-mode-locked laser oscillation are shown in Fig. 7. The obtained maximum output laser energies in free-running mode were 75 mJ when the electrical input energy was 8 J as shown in Fig. 7(a).

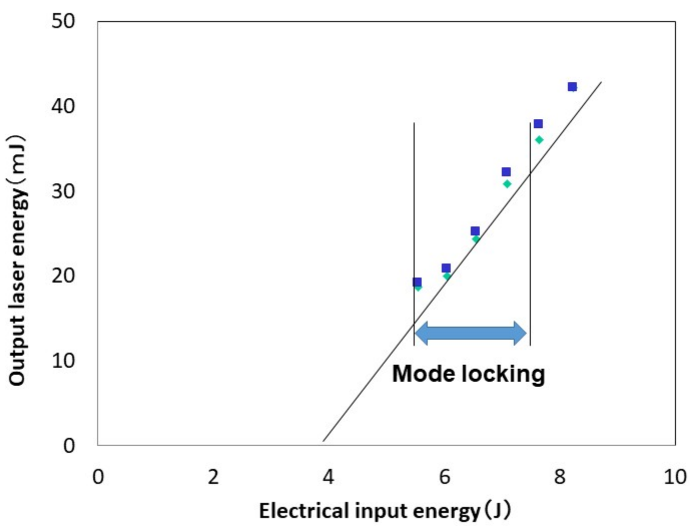
When the initial transmittances of Cr^{4+}: YAG were 90% and 95%, the obtained maximum output laser energies were 40 mJ and 43 mJ when the electrical input energy was 8 J as shown in Figs. 7(b) and (c). Also, local increments in the output laser energy for the electrical input energies were observed owing to the cross-relaxation effect of the doped Nd ions [16-18], as shown in Figs. 7(b) and (c).

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

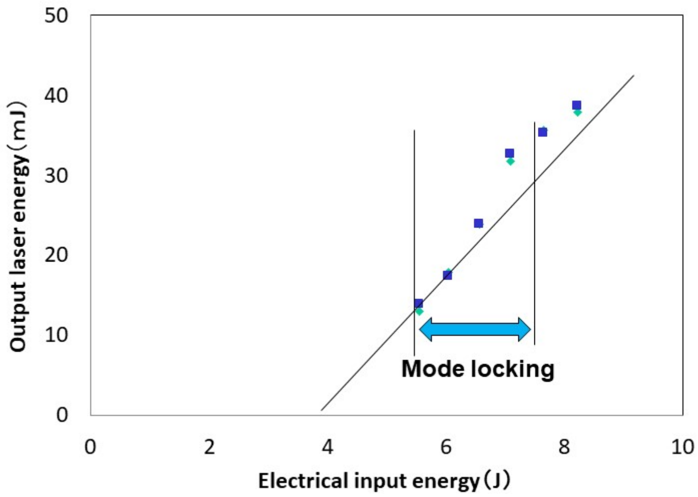
The observed temporal waveforms for the Q-switch and self-mode-locked laser oscillation are shown in Fig. 8. The electrical input energy was 5.6 J in Fig. 8(a), 6.0 J in Fig. 8(b), and 6.4 J in Fig. 8(c). Q-switch and self-mode-locked laser oscillations were only observed below low electrical input energy of 7.4J. Here, the maximum laser peak power was estimated to be 60 kW.



(a)

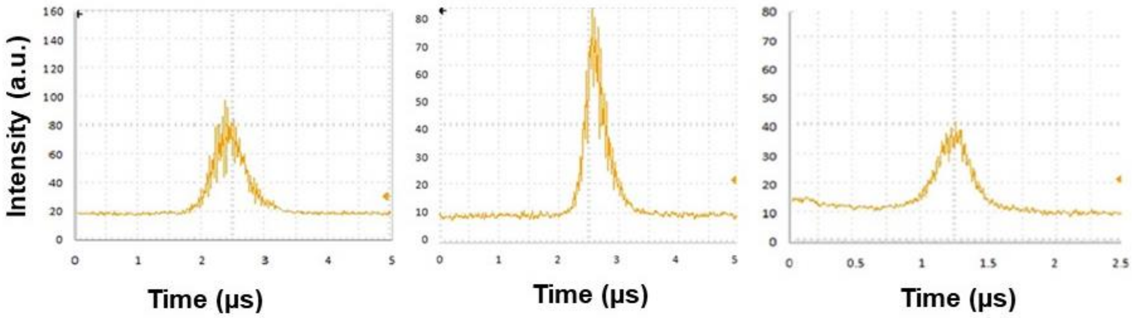


(b)



(c)

Fig. 7. Measured output laser energy. (a) R=90%, Free-running mode. (b) The initial transmittance of Cr^{4+}:YAG crystal is 90%. (c)The initial transmittanc of Cr^{4+}:YAG crystal is 95%.



(a) **(b)** **(c)**

Fig.8. Measured temporal waveform of single laser pulse. The initial transmittance is 90%. Electrical input energy is 5.6J. (b) Electrical input energy is 6.0J. (c) Electrical input energy is 6.4J.

4. Conclusion

We conducted an experiment on a Q-switched and mode-locked Nd/Cr:YAG ceramic laser. The maximum output laser energy was 11 mJ with multiple Q-switched pulses when the electrical input energy was 8 J and the maximum output laser energy was 3 mJ. 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 8J and when using only single Cr^{4+}: YAG crystal, respectively. The output energy of the single laser pulse using only single Cr^{4+}: YAG crystal was three times higher than the case using SESAM. Also, the output energies of laser pulse for the Q-switched and self-mode-locked laser oscillation using only single Cr^{4+}: YAG crystal increased locally for the input electrical energy owing to the cross-relaxation effect of the doped Nd ions.

Acknowledgement

Nd/Cr:YAG ceramics were supplied by Drs. T. Yanagitani and H. Yagi of Kohnoshima Chemical Co., Ltd. We thank M. Nakatsuka, Institute for Laser Technology(ILT) and K. Fujioka, Osaka Univ. for performing this researches.

5.Refernces

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Additional Information

Competing Interests: The authors declare that they have no competing interests.

No data were used to support this study.

The authors received no specific funding for this work.