Hindawi
International Journal of Optics
Volume 2022, Article ID 8480676, 10 pages
https://doi.org/10.1155/2022/8480676

Research Article

Rod-Type Ce/Cr/Nd : YAG Ceramic Lasers with White-Light Pump Source

T. Saiki,[1] T. Iwashita,[1] J. Sakamoto,[1] T. Hayashi,[1] T. Nakamachi,[1] Y. Fujimoto,[2] Y. Iida,[1] and M. Nakatsuka[3]

[1]*Department of Electrical, Electronic and Information Engineering, Faculty of Engineering Science, Kansai University, Suita, Japan*
[2]*Chiba Institute of Technology, Narashino, Japan*
[3]*Institute for Laser Technology, Osaka, Japan*

Correspondence should be addressed to T. Saiki; tsaiki@kansai-u.ac.jp

Received 14 June 2022; Revised 9 August 2022; Accepted 11 August 2022; Published 19 September 2022

Academic Editor: Sulaiman W. Harun

Ceramic is promising for use as a solid-laser material pumped with solar or lamp light. We developed a Cr^{3+} ion doped Nd : YAG ceramic laser that converts white light into near-infrared laser light more efficiently. Investigation of its optical properties has revealed that large gain can be realized with excitation power that is one order of magnitude less than that in the case of Nd : YAG. Ce^{3+} ion doping also makes it possible to utilize the excitation light components with wavelengths of 350 nm or less, preventing generation of color centers. A rod-type Ce^{3+}/Cr^{3+}/Nd : YAG ceramic pumped by white light such as solar light or flash lamp light was developed. Fluorescence lifetime of ceramic was measured. Laser oscillations at free running mode were observed. Also, numerical calculation for output laser power and gain at lasing threshold was performed. Fluorescence lifetime increased as temperature rose, which was observed in Cr/Nd : YAG ceramic. This increase suggests the existence of a cross-relaxation effect. Maximum output laser energy of 73 mJ with the peak power of 330 W was obtained. Obtained output laser energy was around twice more than that in case of Cr^{3+}/Nd : YAG ceramic with the same Nd and Cr ion concentration.

1. Introduction

Solar power can be directly transformed into laser light with high efficiency, and many lasers pumped by solar light or lamp light have been researched in the United States, Germany, Russia, and Israel [1–5].

Examples of applications are in space solar power systems (SSPS) [6–8]. Research on space solar power stations (SSPSs) has been performed to develop the use of solar energy in space. Laser light can be transmitted over a long distance and converted into electrical energy with high efficiency by a photo-electric conversion element [7–9].

We have also proposed an energy cycle using solar-pumped lasers and metals [10–12]. We are conducting research on how to convert solar light into coherent pulsed laser light to produce metal nanoparticles [13, 14]. Renewable energy can be produced using the difference in chemical potential energy between metal and metal oxide. In the production of renewable energy, metal nanoparticles are efficiently produced at a low cost and in less time by using a highly repetitive kHz pulse laser light generated using solar power [12, 15].

Metal nanoparticles are components of nano-inks and nano-pastes for printed electronics that are used to produce electrical and electronic circuits at low temperature, low cost, and in a short time, and they are currently receiving attention [16]. Metal nanoparticles can also be applied to a special metal body with nano-structure. Metal nanoparticles have a wide variety of applications.

Lasers employing a lamp light source have been used in industrial products [17–19]. A high peak power and a high energy of lamp light can be generated easily and can be used for pumping laser materials. Currently, Nd^{3+}/Cr^{3+} : YAG ceramics are promising as laser materials for lamp light or

solar light pumping [13, 19, 20]. Nd/Cr : YAG ceramic lasers that have pure Cr^{3+} ions were developed at the first time [19]. Many optical properties of Nd/Cr : YAG ceramic laser were investigated [13, 19–37]. Subsequently, many laser systems with Nd/Cr : YAG ceramics pumped by lamp light and solar light were reported [4, 13, 20, 29, 32, 33, 35, 37, 38]. We have also proposed a solar-pumped laser system with active-mirror amplifiers for SSPSs. CW 1-kW-output lasers for a Nd/Cr^{3+} : YAG ceramic multi-amplifier system using multistage active-mirror amplifiers with high optical-optical conversion efficiency of over 50% will be achieved by solar light pumping when the temperature of a ceramic disk is over 100°C [38].

On the other hand, Ce-doped Nd : YAG lasers have been developed [39–45]. Laser oscillation with end-side solar pumping has been performed. A multi-mode 40 W laser output has already been obtained for near 1 m^2 area of the solar irradiation. An improvement on conversion efficiency compared to Nd/Cr : YAG was confirmed [43]. Side-pumping using *A* light guide with solar light pumping improves the uniformity of the absorption [42]. The most efficient conversion efficiency from solar light to laser (conversion efficiency of 4.64%, collection efficiency of 41.25 W/m^2) by using Ce/Nd : YAG has been reported [44]. Also, a slope efficiency of 7.64% for using multi-Ce/Nd : YAG rod and 4.5% for using a single Ce/Nd : YAG rod has been achieved [45].

$Ce^{3+}/Cr^{3+}/Nd^{3+}$: YAG ceramic laser material was developed recently [46–48]; the solar light components with wavelengths of 350 nm or less could not be effectively used by Cr ion doping [46]. Co-doping Ce ion is expected to prevent color center generation and improve conversion efficiency for ultraviolet components.

In this paper, the temperature dependence of the fluorescence lifetimes of the Nd ions in a Ce/Cr/Nd : YAG ceramic was newly investigated. Also, the oscillation property of a Ce/Cr/Nd : YAG ceramic laser under white light pumping was investigated. Numerical calculation for output laser power and gain at lasing threshold was performed.

2. Ce/Cr/Nd : YAG Ceramic Laser

Nd/Cr : YAG crystals were developed in 1964 [2], but the crystals were not perfectly grown with low uniformity of Cr^{3+} and had an optical loss. In 1995, Ikesue et al. reported the first fabrication of Nd/Cr : YAG ceramic. An improved lifetime of the Nd-upper level for Nd/Cr : YAG powder was reported by Nakatsuka et al. [19]. Excited Cr^{3+} ions strongly enhance the population inversion at the Nd^{3+} upper level.

Nd/Cr : YAG ceramics have many advantages for optical property when compared with Nd : YAG single crystal. Ceramics have a remarkable advantage that Cr^{3+} ions can be doped at a higher level than a single crystal with reducing Cr^{4+} ions.

Some Nd/Cr^{3+} : YAG ceramic lasers adapted for white-light pumping (such as by solar light) have been developed [13, 20, 38]. The laser material can convert white light to laser light with high optical-optical conversion efficiency, and the lasers can work at temperatures over 100°C. Phonons of Cr ions assist with the transfer of energy. A part of the thermal energy in the ceramic converts the transferred energy to laser light when the cross-relaxation effect occurs owing to the structure of the energy levels of Cr and Nd ions [21, 24, 25, 38]. Additionally, because the spectral bandwidth of fluorescence at 1064 nm is wider than that of Nd : YAG, a decrease in laser gain due to the spectral peak shift barely occurs [24]. The energy transfer between Cr ions and Nd ions has been described in detail [21, 26, 29, 32, 33, 38]. The enhancement of the laser gain and the effective fluorescence lifetime at increased temperatures owing to the excitation of two Nd ions and re-absorption by Nd ions have already been observed [21, 25].

The energy diagram of $Ce^{3+}/Cr^{3+}/Nd^{3+}$: YAG ceramic laser is shown in Figure 1. In the mechanism of absorption and emission from the Cr^{3+} : YAG crystal, the interaction between the energy levels of excited Cr ions and phonons in the YAG lattices (which is called electron-phonon coupling) is very important and results in the broadening of the energy level. Cr ions at the two vibronic states excite the Nd ions at the ground level.

Two processes exist in the cross-relaxation for the Cr/Nd : YAG ceramic. The first process is independent of the temperature of the laser medium. In the transition from the $^4P_{1/2}$ and $4I_{9/2}$ states to the $^4F_{3/2}$ state, cross-relaxation occurs. The second process is important and dependent on the temperature of the laser medium. Additionally, in the transition from the $^4G_{3/2}$ and $^4I_{11/2}$ states to the $^4F_{3/2}$ state, cross-relaxation occurs [21]. It is remarkable that cross-relaxation occurs around the temperature at which the laser system changes because a single photon of absorbed solar light is converted to two output photons. Here, endothermic reaction should be occurred in the Cr/Nd : YAG ceramic because thermal energy to excite is converted to photon energy [21].

$Ce^{3+}/Cr^{3+}/Nd^{3+}$: YAG ceramic laser material and its optical properties were reported by Fujioka et al. [46]. The sensitizing effect of Ce/Cr/Nd : YAG was four times more than that of Cr/Nd : YAG. Optimized sensitizing effect of Ce/Cr/Nd : YAG material for solar-pumped solid-state lasers using the sol-gel synthetic YAG powder method was investigated [46, 48]. It was found that the most efficient composition of Ce/Cr/Nd : YAG is where Ce^{3+} and Cr^{3+} were 0.9 and 8.0 mol% under solar light pumping, respectively, when the Nd^{3+} concentration was 1.0 mol%. Ce^{3+} ion can transfer efficiently to Nd^{3+} in Ce/Cr/Nd : YAG ceramics.

3. Theory for Laser Oscillation

Here, we describe the calculation method for output laser power and gain at lasing threshold of Ce/Cr/Nd : YAG ceramic laser and Cr/Nd : YAG ceramic laser.

The gain G, small signal gain coefficient $g_0 l$, and inversion population of the laser medium N_{inv} are calculated as

$$G = \exp(g_0 l) = \exp(\sigma_L N_{\text{inv}}), \tag{1}$$

and

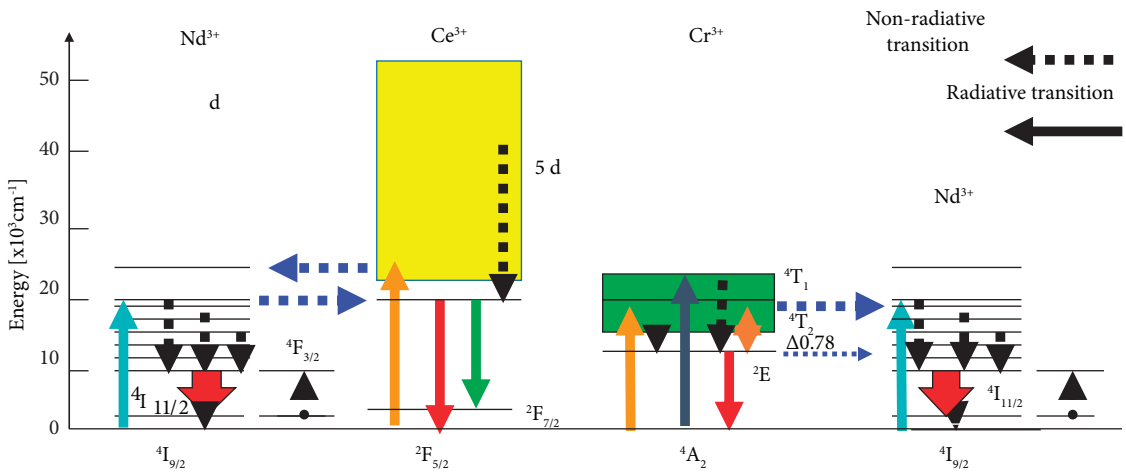

Figure 1: Energy diagram of Ce/Cr/Nd : YAG ceramic laser.

$$N_{\text{inv}} = \Delta N \cdot \tau_R, \tag{2}$$

where l is the length of the rod, ΔN is the pump rate per unit volume, and τ_R is the fluorescence lifetime of the laser medium. The population inversion density at the lower level of Nd ion is omitted. The ΔN is calculated as

$$\Delta N = \frac{\eta_{\text{qd}} \cdot \eta_e \cdot \eta_a \cdot P_{\text{in}}}{A_s \cdot h(C/\lambda_L)}, \tag{3}$$

where η_{qd} is the quantum defect between excitation wavelength and lasing wavelength. η_e is the emission efficiency of Nd ion. η_a is the absorption ratio of the excitation lamp light. P_{in} is the power of the excitation lamp light. A_s is the effective excitation cross section. λ_L is the lasing wavelength.

Equation (4) gives the condition for laser oscillation:

$$G_t^{\,2} R_2 \gamma A = 1, \tag{4}$$

where G_t is the gain at lasing threshold; R_2 is the reflectivity of the output mirror; γ is the cavity efficiency with considering diffraction loss. A is the ratio of area for spontaneous emission component on optical axis. It calculated by using the following equation:

$$A = \frac{d^2}{(2n \cdot \tan\theta \cdot L_{\text{cav}})^2}, \qquad \tan\theta = \frac{d}{2l}. \tag{5}$$

Here, d is the cross-sectional width of the rod, and L_{cav} is the length of the resonator. θ is the fluorescence divergence solid angle. The gain (including ASE) of the laser rod at the oscillation threshold can be calculated by using the following equations:

$$G_t = \exp(g_0 l). \tag{6}$$

$$g_0 = \sigma_s' \varepsilon \Delta N, \qquad \varepsilon = \frac{\varepsilon_0}{1 + (g_0/\alpha)}. \tag{7}$$

σ_s' is the effective stimulated emission cross section of YAG ceramic, and α is the damping coefficient by ASE. ε is the energy storage rate considered from the fluorescence lifetime and temporal duration of excitation light.

The CW output laser power for a microchip laser is calculated as given by equation (8) [49].

$$P_{\text{out}} = \left[\frac{g_0}{L} - \beta\right] \cdot T \cdot I_{\text{sat}} \cdot A_s, \tag{8}$$

where A_s is the effective pumping cross section, L is the loss of light in the laser cavity, T is $1-R_2$, where R_2 is the reflectivity of the output mirror, I_{sat} is the total fluorescence power in the laser cavity, and A is the coupling ratio of the initial fluorescence to the cavity.

β is a variable related to lasing threshold. In the case of the laser oscillation by CW excitation, β is set to be 1. The reason for setting β is that the excitation time in this experiment is remarkably shorter and the number of the population inversion is lower than that of CW excitation.

Also, we considered the amount of light entering the rod and the transmittance of light on the surface. The lamp light travels in the 2π direction, but the part actually absorbed by the rod is 1/4 when the solid angle is taken into consideration. The one-sided transmittance of the laser rod was set to 0.9. Quantum deficiency due to the difference between the excitation wavelength and the laser oscillation wavelength is 0.64. The emission efficiency was 1. The absorption rate was set. When the electric input energy to the Xe lamp was calculated as 8.5 J at the maximum. Here, the peak power should be 500 W. Since it is compressed in time, the calculation was performed by doubling the excitation power of the lamp light, the excitation power was set to be 1100 W at the maximum. The electro-optical conversion efficiency of the Xe flash lamp was 16%.

The parameters for calculation are shown in Table 1.

4. Experimental Setup

The solar spectrum and the output of the Xe flash lamp used for excitation are shown in Figure 2.

Table 1: Parameters for calculation.

Lasing wavelength	$\lambda_L = 1064$ nm
Transmittance@ 1064 nm	$T_{rod} = 99\%$
Rod length	$l = 3$ cm
Effective saturation power [21]	$I_s = 98$ W/cm^2
Effective stimulated emission cross section [21]	$\sigma_s' = 2.0 \times 10^{-18}$ cm^2
Absorption efficiency of lamp light	
Ce, Cr, and Nd doping	0.65
Ce, Cr, and Nd doping	0.42
Refractive index	1.83
Cavity length	10 cm
Diffraction efficiency	$\gamma = 0.9$
Emission efficiency	$\eta_e = 1$
Quantum defect	$\eta_{qd} = 0.64$
Cross-sectional width of ceramic rod	$d = 5$ mm

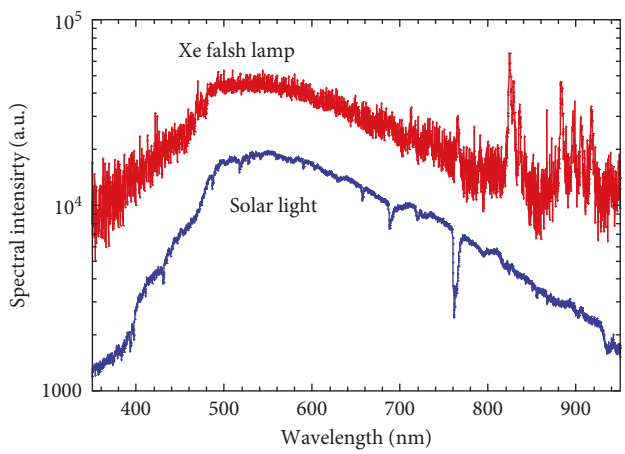

Figure 2: Spectrum of solar light and Xe flash lamp light.

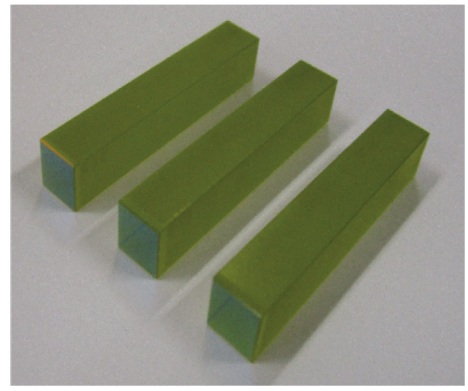

Figure 3: Rod-type Ce/Cr/Nd : YAG ceramic.

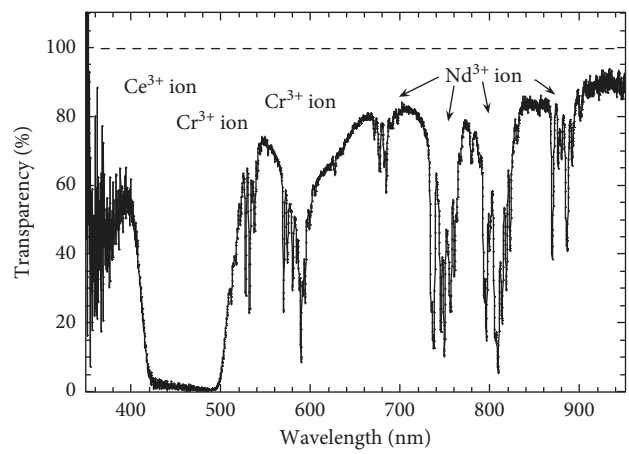

Figure 4: Transparency of Ce/Cr/Nd : YAG ceramic. The thickness is 5 mm.

It was found that the color temperature of the output spectrum of the solar light and the Xe flash lamp used for excitation is about the same as 6000 K. Each peak wavelength is around 500 nm. A photograph of the rod-type Ce/Cr/Nd : YAG ceramic (Kounoshima Co. Ltd., Japan) are shown in Figure 3. The spectrums were measured using a spectrometer (USB4000: Ocean Photonics). When Cr ion is doped in YAG, the color is light green. The color changed to be green mixed with yellow. The color of YAG turns into yellow when Ce is doped. The transmittance of the Ce/Cr/Nd : YAG ceramic (Kounoshima Co. Ltd., Japan) for wavelength is shown in Figure 4. The transparency of the YAG ceramic was also measured using a spectrometer (USB4000: Ocean Photonics).

The absorption band of Ce ion and the absorption band created by Cr ion overlap at around 500 nm. The spectral peak of both the solar and the flash lamp light is 500 nm. The spectral matching makes it possible to absorb excitation light just efficiently.

Fluorescence lifetime of the ceramic was measured by using a high-resolution fluorescence spectroscopy instrument (JASCO, SS-25, Japan).

The temperature dependence of the fluorescence lifetime of Nd ions in Ce/Cr/Nd : YAG ceramic was measured. We measured the fluorescence intensity time variation of Nd ions in the excitation light of 350, 470, 590, 750, and 810 nm. These five excitation wavelengths were chosen because the absorption ratios of the solar light are high.

Furthermore, at the fixed excitation light of 590 nm, the temperature dependence of the Nd ion fluorescence lifetime on the Ce/Cr/Nd : YAG ceramic was measured. A ceramic heater was attached to the ceramic laser medium to measure the temperature dependence of the fluorescence lifetime and raise the medium temperature from 25°C to 95°C in 10°C steps.

The setup of the experiment for laser oscillation is shown in Figure 5. The rod-type Ce/Cr/Nd : YAG ceramic (shown in Figure 3) was used in this experiment. The size of the used ceramic rod was 5 mm × 5 mm × 49 mm length. HR coating and AR coating at the laser wavelength of 1064 nm were done on both surfaces of the ceramic rod. We used a Xe flash lamp as the pumping source. The electrical input energy of this lamp, which is stored in a capacitor as electrical energy, was 8.5 J, and the color temperature was 6000 K. The concentrations of Nd, Cr, and Ce ions were 1, 0.1, and 0.2 atm.%, respectively.

We set up a rate equation for a Ce ion, Cr ion, and Nd ion, did a computer simulation, and estimated the ceramic level density on the laser Nd ion, fluorescence lifetime of Nd

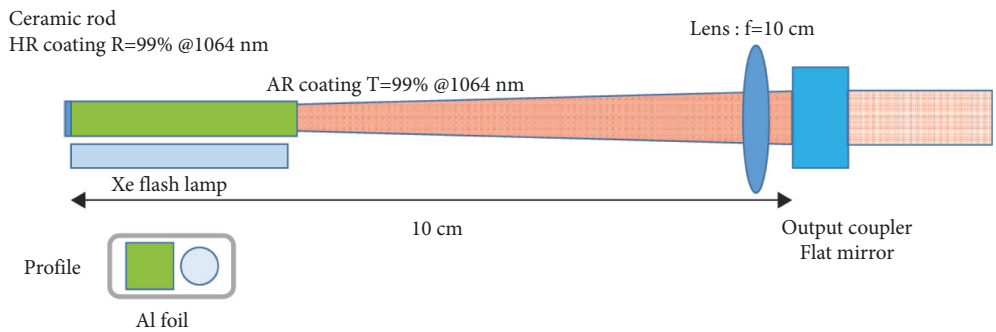

Figure 5: Experimental setup for laser oscillation.

ion, and amplifying characteristics [48]. In the results of the calculation, by comparing the cases in which Ce was not added and 0.1% Ce was added, 0.1% Ce was found to double the laser output laser power. The concentrations of Nd, Cr, and Ce were 1, 0.1, and 0.2 atm.%, respectively. In the experiment, the Ce/Cr/Nd : YAG ceramic rod was pumped at a room temperature of 25°C.

The cavity length was chosen to be 10 cm. The pulse duration of the pumping Xe flash lamp light was 550 μs. The reflectivities of the output couplers were 80%, 90%, and 95%.

5. Results

Measured fluorescence decays of Nd ion by an PIN diode and an oscilloscope as the excitation wavelength of Ce/Cr/Nd : YAG ceramic laser media increases are shown in Figure 6. Fluorescence decays were observed with the excitation wavelength is fixed to be 590 nm. The fluorescence lifetime was observed to be longer than that of the Nd : YAG laser materials. The evaluated fluorescence lifetime of the Ce/Cr/Nd : YAG ceramic laser media was over 800 μs due to the excited Cr ion. When the excitation light is absorbed by Ce ion, it has three decay components for fluorescence emitted from Nd ion. Here, we analyzed and evaluated the longest component, which is especially related to the population inversion. The fluorescence was observed at different excitation wavelengths by exciting Ce or Cr ion. When comparing the fluorescence lifetime of Ce/Cr/Nd : YAG ceramic and Cr/Nd : YAG ceramic, the longer fluorescence lifetime is due to the absorption band of Ce and Cr ions, as mentioned above. They overlap around 500 nm. Thus, two paths for energy transfer exits. One is the energy transition from Cr ion to the Nd ion and another is the energy transition from the Ce ion to the Nd ion. The energy transition time from Ce ion to Nd ion is very fast, but the energy transition time from Ce ion to Nd ion is slow and 0.5 ms [19].

The measurement results of the temperature dependence on the fluorescence lifetime of the Nd ion for a Ce/Cr/Nd : YAG ceramic laser media are shown in Figure 7. For comparison, we also show measurement results of that for a Cr/Nd : YAG ceramic laser media. The evaluated fluorescence lifetime increased as temperature rose, which is the same as with Cr/Nd : YAG ceramic. In both ceramic, the fluorescence lifetime increases at the temperatures of over 65°C.

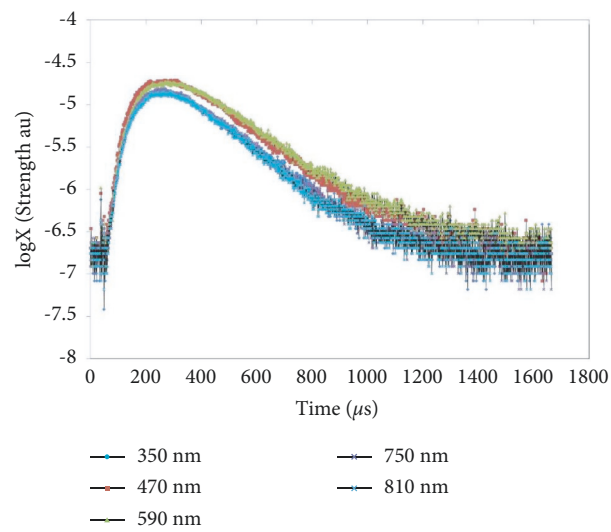

Figure 6: Measured fluorescence decay.

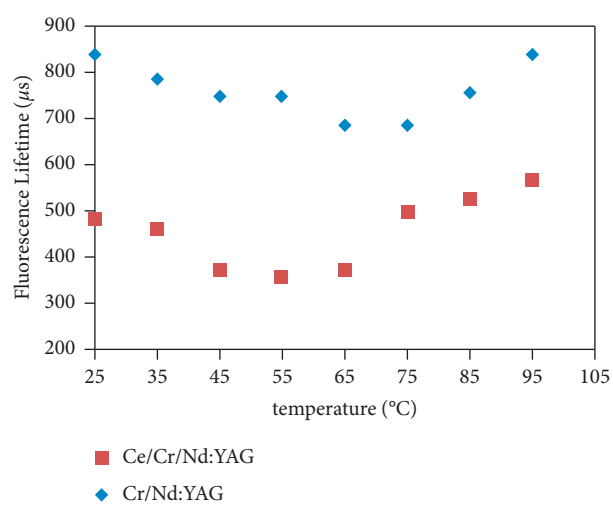

Figure 7: Dependence of temperature on fluorescence lifetime.

This increase of the fluorescence lifetime suggests the existence of a cross-relaxation effect [21, 25, 38]. The increase occurs by the reabsorption of the Nd ions in the lower level and exciting them to the upper level [25].

The temporal waveform of the Xe flash lamp light and the output laser pulse are shown in Figure 8. The lasing

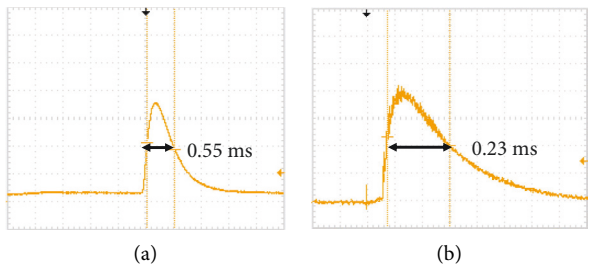

Figure 8: Temporal waveform. (a) Xe flash lamp light. Pulse duration: FWHM 0.55 ms. (b) Output laser pulse. Pulse duration: FWHM 0.23 ms.

wavelength was 1064.1 nm. The temporal duration of the Xe flash lamp light was 0.56 ms, and the temporal duration of the laser pulse was 0.23 ms as shown Figure 8(a). The obtained temporal duration was the same in the case of the Cr/Nd : YAG ceramic laser.

Measured output laser energy of the rod-type Ce/Cr/Nd : YAG ceramic laser by single shot is shown in Figure 9.

The obtained maximum output laser energy of the Ce/Cr/Nd : YAG ceramic laser was 74 mJ when the reflectivity of the output coupler was 90%.

The lasing thresholds of the electrical input energies were 2.2, 2.4, and 3 J when the reflectivities of the output couplers were 95, 90, and 80%, respectively. The obtained maximum output laser energy of the Cr/Nd : YAG ceramic laser was 40 mJ when the reflectivity of the output coupler was 90%. Thresholds for lasing of the electrical input energies were 3.3, 3.7, and 4 J when the reflectivities of the output couplers were 95, 90, and 80%, respectively.

The lasing threshold of Ce/Cr/Nd : YAG ceramic laser was improved by doped Ce ion. Regarding the laser output, when R was 90% and the electrical excitation energy was 7.5 J–8.2 J, an increase in laser output energy due to cross-relaxation effect was observed.

Large gain was evaluated by using the lasing threshold. The calculation was performed using equations (4)–(7). The analysis results are shown in Figure 10. The solid line is the calculated large gain with considering ASE loss, and the dotted line is the calculated large gain without considering ASE loss. The reason why the laser oscillation threshold is large is that the laser gain is suppressed to a low level by ASE loss.

For Ce/Cr/Nd : YAG ceramic laser, when R were 95%, 90%, and 80%, the laser gain was evaluated to be 16, 17, and 18 for the excitation electrical input energy of 2.2, 2.4, and 3 J. For Cr/Nd : YAG ceramic laser, when R were 95%, 90%, and 80%, the large laser gain was evaluated to be 16, 17, and 18 for the excitation electrical input energy of 3.3, 3.7, and 4 J.

Laser oscillations of the Nd : YAG lasers could not be obtained because of the low laser gain at these pumping energy levels.

In order to evaluate whether the peak power value obtained from the experiment at the time of laser oscillation is appropriate, a computer analysis of the peak intensity was performed. The results are shown in Figure 11. The calculation was performed using equations (1)–(3) and (8). β was set to be 115, 60, and 45 for each of $R = 95\%$, 90%, and 80% when Ce/Cr/Nd : YAG ceramic was used.

β was set to be 120, 60, and 30 for each of $R = 95\%$, 90%, and 80% when Cr/Nd : YAG ceramic was used. The output laser peak power obtained by the experiment and computer analysis were in good agreement.

A comparison of the laser output peak power by experiment for the reflectivity of output coupler and the calculated results is shown in Figure 12. The optimum reflectance for both ceramic laser was 90%. The peak power is higher than the calculated value, which is due to the above-mentioned cross-relaxation effect. The effect is not included in calculation. It was considered that the number of population inversion in the case of the Ce/Cr/Nd : YAG ceramic laser increased 1.4 times compared to the case without cross-relaxation. Also, the number of population inversion increased 1.3 times compared to the case without cross-relaxation in the case of Ce/Cr/Nd : YAG ceramic.

6. Discussion

We obtained laser oscillation of a rod-type Ce/Cr/Nd : YAG ceramic laser. When the reflectivity of the output coupler was 90%, the measured maximum output laser energy was 73 mJ and averaged laser power was 330 W. In an experiment on rod-type laser oscillation, it was possible to reach laser oscillation with the same low excitation power as that needed to reach it with a Cr/Nd : YAG ceramic laser. Scattering at the laser oscillation wavelength for Ce/Cr/Nd : YAG ceramic was small, and the transmittance was very high.

The calculated laser small signal gain at lasing threshold is to 20 times, which is sufficiently high. A color center due to ultraviolet irradiation of Ce/Cr/Nd : YAG ceramic was not found after the laser oscillation experiment. The maximum conversion efficiency from the excitation light to laser was estimated to be 30%.

Here, the problems of the laser oscillator are mentioned below. It has been considered that optimization of the doped Ce ion is still inappropriate. Because Ce ion has a high absorption coefficient compared to other materials, the doped density is still too large. The doped density should to be below 0.1 atm.% to reduce the thermal load. Absorption should deviate to the surface and it will cause thermal problems. In this experiment, the laser oscillation is basically a single shot, there are no thermal problems such as the thermal lens effect. Thermal problems should occur when CW excitation or repeated excitation is performed. Absorption of the lamp light for Cr/Nd : YAG ceramic is not

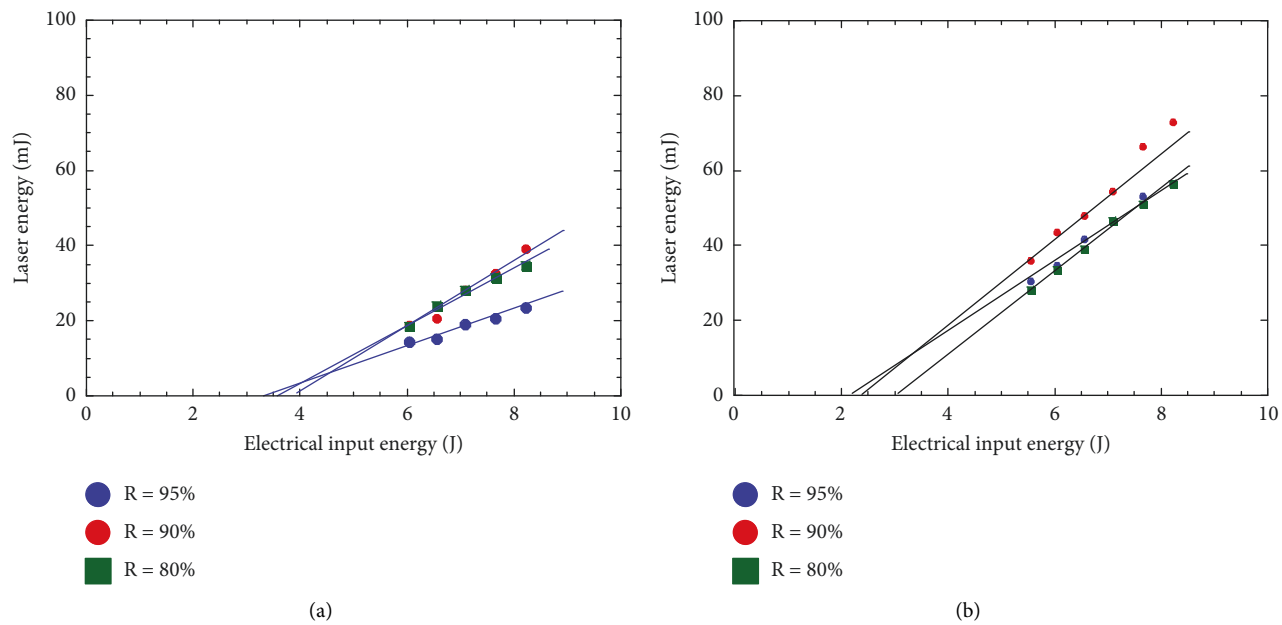

Figure 9: Measured output laser energy. (a) Cr/Nd : YAG ceramic laser. (b) Ce/Cr/Nd : YAG ceramic laser.

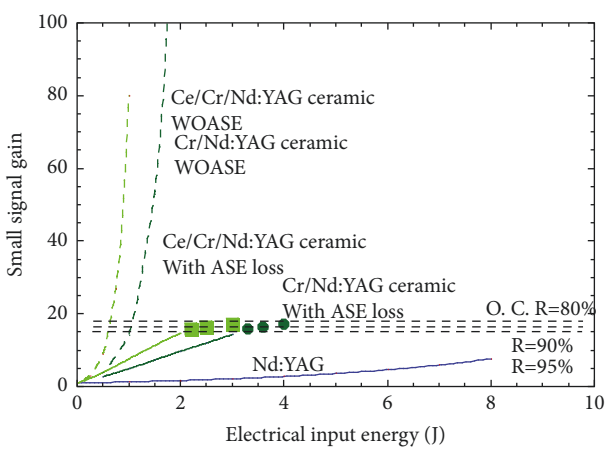

Figure 10: Calculated laser gain at lasing threshold.

enough due to the thin thickness. If the thickness of Cr/Nd : YAG ceramic should be increased to 1 cm, the absorption rate increases and the conversion efficiency should be good. In that sense, the active-mirror-type laser seems to be the most suitable. This laser material is a special because it can operate with high efficiency even at nearly 200°C. The optical conversion efficiency from lamp light ot laser for Ce/Cr/Nd : YAG ceramic is estimated to be up to 26%. Also, the optical conversion efficiency from lamp light of laser for Cr/Nd : YAG ceramic is estimated to be up to 14%.

At present, a problem exists in the configuration of the laser oscillator. Especially for the excitation method, the laser rod is pumped from the side surface. However, the surface is a scratched surface to prevent the parasitic oscillation. Furthermore, because the flash lamp is set close to the rod, the lamp light is absorbed with spreading, and the excitation light pass through from the side surface of the rod, and the absorption of the lamp light degrade.

The pulse duration of the lamp light for excitation is shorter than the lifetime of Nd ion. A long pulse with a temporal duration of 5 ms or more should be used to excite the laser rod in order to improve the lasing threshold. In the case of CW excitation using such as solar light, laser oscillation should be obtained sufficiently with an excitation power of below 100 W.

It has been found that the cross-relaxation occurs because the temperature of the material reaches a high temperature instantaneously due to the excitation of the Xe flash lamp in a very short time. This phenomenon seems to be difficult to consider in computer simulations because the instantaneous temperature is unknown.

Here, we consider the advantages and disadvantages between Ce/Cr/Nd : YAG ceramics and Ce/Nd : YAG.

(1) The difference for absorption of excitation light. Ce has absorption of 400–500 nm. Cr has an absorption band at 500–700 nm. The laser materials have different defects that they cannot absorb specific wavelengths.

(2) The fluorescence life time and effective stimulated emission cross-section: the increase in fluorescence lifetime does not occur with the addition of Ce and is the same as Nd : YAG. Same sensitization as Cr/Nd : GSGG. The effective fluorescence lifetime increases only when excited Cr ion is excited. And, increment in effective stimulated emission cross-section. They introduce the improvement on the laser gain and the oscillation threshold.

(3) Ce doping does not cause cross-relaxation. Conversion efficiency is reduced. Only conversion efficiency of less than 40% can be achieved.

In the experimental results by solar light pumping, the conversion efficiency of Ce/Nd : YAG laser is higher than

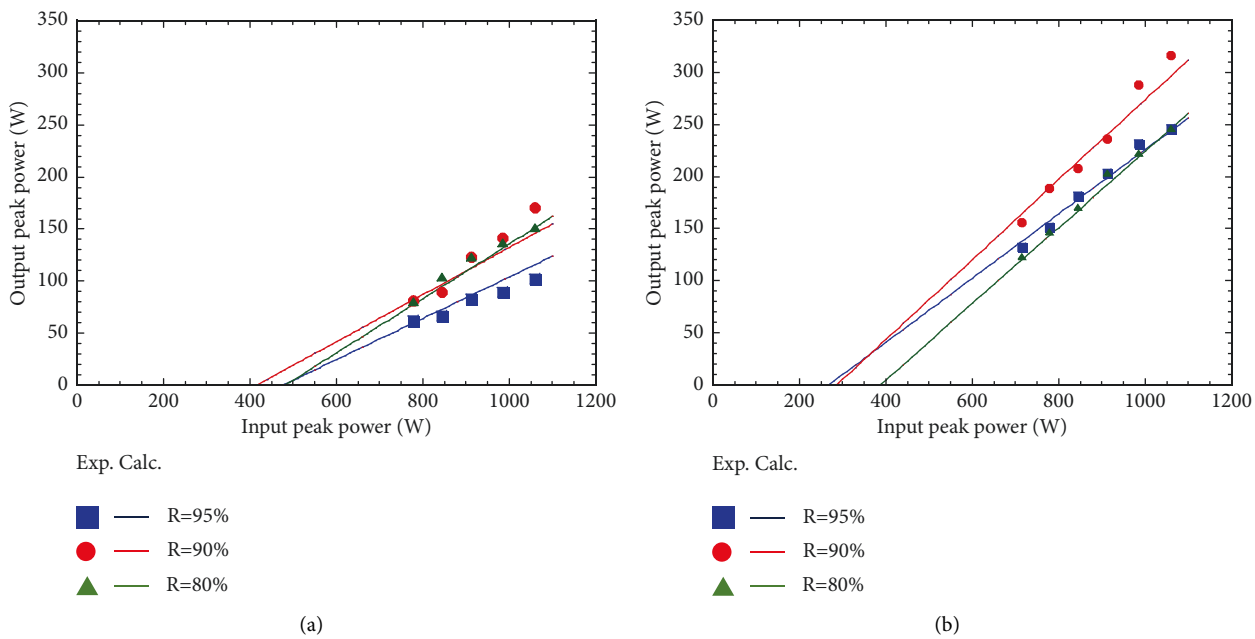

Figure 11: Calculated output laser peak power. (a) Cr/Cr/Nd : YAG ceramic laser. (b) Ce/Nd : YAG ceramic laser.

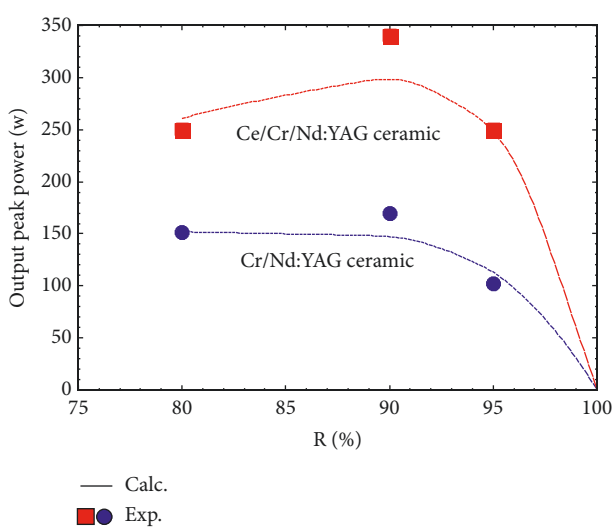

Figure 12: Dependence of mirror reflectivity on output laser peak power.

that of Nd/Cr : YAG laser [35, 38, 44]. The excitation power is considered to be high, the thermal load increases, and the number density of the lower level of Nd ions increases. Thus, the advantage of Cr ion doping should vanish. In other reports, the output laser power of solar-pumped Nd/Cr : YAG composite laser excited at a low solar power of several Watts was improved eight times by increasing the Cr ion doping. The conversion efficiency has been approached to 30% [33].

We compared them, we consider that Cr ion doping in Nd : YAG is superior than Ce doping.

Cross-relaxation does not occur between Ce ion and Nd ion. It occurs only between Cr ion and Nd ion. The reasons are as follows:

(1) For energy level of Nd ion, only two-level excitation can occur cross-relaxation. There are only two levels, $^4P_{1/2}$ and $^4G_{3/2}$, in order to excite the basis and lower levels of Nd ions by the re-absorption process. Because the Ce ion has electron-phonon coupling energy band at a higher energy position of 23000 cm^{-1} or higher, the above two energy level cannot be excited. In this fluorescence lifetime measurement, we just reconfirmed in this experiment. As proof of this, only a linear increase in output laser energy has been obtained in the flashlamp laser oscillation experiments using a flat resonator and Ce/Nd : YAG as shown in Reference [39]. It is different from the results of output laser energy of the Cr/Nd : YAG ceramic laser in experiments that we have obtained the data in the past.

(2) The temperature property of the fluorescence lifetime in this experiment is shifting to a higher temperature because the temperature that starts to increase is rather deteriorated. This indicates that the population number density at the lower level that are excited by reabsorption excitation is small. If the Ce ion has a mechanism that causes cross-relaxation, the temperature at which the increase starts should be at the same or lower position. The addition of Ce increases the overall fluorescence lifetime. It is considered that this is because the light of 590 nm is divided and absorbed by Ce and Cr. Since the absorbed energy of Ce is transferred to Nd, it is considered that Cr and Nd ions are excited at the same time and the lifetime is extended to nearly 1 ms.

Until now, cross-relaxation effect, such as an increase in the temperature characteristics of the fluorescence lifetime, for the Ce/Nd : YAG laser is not reported in the past.

7. Conclusion

We had obtained laser oscillation of rod-type Ce/Cr/Nd : YAG ceramic laser.

Measured maximum output laser energy was 73 mJ with the peak power of 330 W when the reflectivity of the output coupler was 90%. The output laser energy was improved by doped Ce ion. We obtained 1.8 times high output laser energy for the Ce/Cr/Nd : YAG ceramic laser than that in the case of the Cr/Nd : YAG ceramic laser.

8. Disclosure

Part of this study was performed as joint research with the Institute of Laser Engineering, Osaka University.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors thank Drs. T. Yanagitani and H. Yagi of Konoshima Chemical Co. Ltd., to supply the Ce/Cr/Nd : YAG ceramic and Nd/Cr : YAG ceramic .

References

[1] C. G. Young, "A sun-pumped cw one-watt laser," *Applied Optics*, vol. 5, no. 6, p. 993, 1966.

[2] Z. J. Kiss, H. R. Lewis, and R. C. Duncan, "Sun pumped continuous optical maser," *Applied Physics Letters*, vol. 2, no. 5, pp. 93-94, 1963.

[3] M. Weksler and J. Shwartz, "Solar-pumped solid-state lasers," *IEEE Journal of Quantum Electronics*, vol. 24, no. 6, pp. 1222–1228, 1988.

[4] T. Yabe, T. Ohkubo, S. Uchida et al., "High-efficiency and economical solar-energy-pumped laser with Fresnel lens and chromium codoped laser medium," *Applied Physics Letters*, vol. 90, no. 26, Article ID 261120, 2007.

[5] S. Mizuno, H. Ito, K. Hasegawa, T. Suzuki, and Y. Ohishi, "Laser emission from a solar-pumped fiber," *Optics Express*, vol. 20, no. 6, p. 5891, 2012.

[6] D. G. Rowe, "Solar-powered lasers," *Nature Photonics*, vol. 4, p. 64, 2010.

[7] H. Yugami, H. Naito, and H. Arashi, "Development of solar-pumped lasers and its applicaton to laser power baming in space," *The Review of Laser Engineering*, vol. 24, no. 12, p. 1308, 1995.

[8] R. L. Fork, "High energy lasers may put power in space," *Laser Focus World*, vol. 113, 2001.

[9] *Laying the Foundation for Space Solar Power an Assessment of NASA's Space Solar Power Investment Strategy*, National Research Council National Academy press, Washington D.C, 2001.

[10] P. Charvin, S. Abanades, F. Lemort, and G. Flamant, "Hydrogen production by three-step solar thermochemical cycles using hydroxides and metal oxide systems," *Energy & Fuels*, vol. 21, no. 5, pp. 2919–2928, 2007.

[11] M. S. Mohamed, T. Yabe, C. Baasandash et al., "Laser-induced magnesium production from magnesium oxide using reducing agents," *Journal of Applied Physics*, vol. 104, no. 11, Article ID 113110, 2008.

[12] T. Saiki, S. Taniguchi, K. Nakamura, and Y. Iida, "Development of solar-pumped lasers and its application," *Electrical Engineering in Japan*, vol. 199, no. 2, pp. 3–9, 2017.

[13] T. Saiki, S. Motokoshi, K. Imasaki et al., "Laser pulses amplified by Nd/Cr : YAG ceramic amplifier using lamp and solar light sources," *Optics Communications*, vol. 282, no. 7, pp. 1358–1362, 2009.

[14] A. Henglein, "Physicochemical properties of small metal particles in solution: microelectrode reactions, chemisorption, composite metal particles, and the atom-to-metal transition," *Journal of Physical Chemistry*, vol. 97, no. 21, pp. 5457–5471, 1993.

[15] T. Okada, T. Saiki, S. Taniguchi et al., "ISRN renewable energy 2013," , Article ID 827681, 2013.

[16] J. W. Chung, S. H. Ko, N. R. Bieri, C. P. Grigoropoulos, and D. Poulikakos, "Conductor microstructures by laser curing of printed gold nanoparticle ink," *Applied Physics Letters*, vol. 84, no. 5, pp. 801–803, 2004.

[17] K. H. Kim, D. D. Venable, L. A. Brown, and J. H. Lee, "Thermal effects on cavity stability of chromium- and neodymium-doped gadolinium scandium gallium garnet laser under solar-simulator pumping," *Journal of Applied Physics*, vol. 69, no. 5, pp. 2841–2848, 1991.

[18] J. H. Kelly, D. L. Smith, J. C. Lee et al., "High-repetition-rate Cr: Nd: GSGG active-mirror amplifier," *Optics Letters*, vol. 12, no. 12, p. 996, 1987.

[19] M. Nakatsuka, K. Fujioka, H. Yoshida, and H. Fujita, "Recent topics in engineering for solid-state peak-power lasers in repetitive operation," *Journal of the Korean Physical Society*, vol. 43, p. 607, 2003.

[20] H. Yagi, T. Yanagitani, H. Yoshida, M. Nakatsuka, and K. Ueda, "The optical properties and laser characteristics of Cr^{3+} and Nd^{3+} co-doped $Y_3Al_5O_{12}$ ceramics," *Optics & Laser Technology*, vol. 39, no. 6, pp. 1295–1300, 2007.

[21] T. Saiki, M. Nakatsuka, and K. Imasaki, "Highly efficient lasing action of Nd^{3+}- and Cr^{3+}-doped yttrium aluminum garnet ceramics based on phonon-assisted cross-relaxation using solar light source," *Japanese Journal of Applied Physics*, vol. 49, no. 8, Article ID 082702, 2010.

[22] P. Hong, X. X. Zhang, C. W. Struck, and B. Di Bartolo, "Luminescence of Cr^{3+} and energy transfer between Cr^{3+} and Nd^{3+} ions in yttrium aluminum garnet," *Journal of Applied Physics*, vol. 78, no. 7, pp. 4659–4667, 1995.

[23] M. Yamaga, Y. Oda, H. Uno, K. Hasegawa, H. Ito, and S. Mizuno, "Formation probability of Cr-Nd pair and energy transfer from Cr to Nd in $Y_3Al_5O_{12}$ ceramics codoped with Nd and Cr," *Journal of Applied Physics*, vol. 112, no. 6, Article ID 063508, 2012.

[24] T. Saiki, M. Nakatsuka, K. Fujioka, S. Motokoshi, and K. Imasaki, "Cross-relaxation and spectral broadening of gain for Nd/Cr : YAG ceramic lasers with white-light pump source under high-temperature operation," *Optics Communications*, vol. 284, no. 12, pp. 2980–2984, 2011.

[25] T. Saiki, M. Nakatsuka, K. Fujioka, S. Motokoshi, K. Imasaki, and Y. Iida, "Increase in effective fluorescence lifetime by cross-relaxation effect depending on temperature of Nd/Cr : YAG ceramic using white-light pump source," *Optics and Photonics Letters*, vol. 6, Article ID 1350003, 2013.

[26] Y. Honda, S. Motokoshi, T. Jitsuno et al., "Temperature dependence of optical properties in Nd/Cr : YAG materials," *Journal of Luminescence*, vol. 148, pp. 342–346, 2014.

[27] V. Lupei, A. Lupei, C. Gheorghe, and A. Ikesue, "Emission sensitization processes involving Nd^{3+} in YAG," *Journal of Luminescence*, vol. 170, pp. 594–601, 2016.

[28] K. Hasegawa, T. Ichikawa, S. Mizuno et al., "Energy transfer efficiency from Cr^{3+} to Nd^{3+} in solar-pumped laser using transparent Nd/Cr: $Y_3Al_5O_{12}$ ceramics," *Optics Express*, vol. 23, no. 11, p. A519, 2015.

[29] T. Kato, H. Ito, K. Hasegawa et al., "Energy transfer efficiency from Cr^{3+} to Nd^{3+} in Cr, Nd YAG ceramics laser media in a solar-pumped laser in operation outdoors," *Optical Materials*, vol. 110, Article ID 110481, 2020.

[30] T. Li, T. Zhou, Y. Cao et al., "Optical properties and energy transfer performances in high quality Cr, Nd : YAG transparent laser ceramics for solar pumped lasers," *Optics Express*, vol. 30, no. 6, pp. 8762–8776, 2022.

[31] V. Lupei, A. Lupei, C. Gheorghe, and A. Ikesue, "Spectroscopic and de-excitation properties of (Cr, Nd): YAG transparent ceramics," *Optical Materials Express*, vol. 6, no. 2, pp. 552–557, 2016.

[32] T. Kato, H. Ito, K. Hasegawa et al., "Effect of Cr content on the output of a solar-pumped laser employing a Cr-doped Nd: YAG ceramic laser medium operating in sunlight," *Japanese Journal of Applied Physics*, vol. 58, no. 6, Article ID 062007, 2019.

[33] Y. Suzuki, H. It, T. Kato et al., "Continuous oscillation of a compact solar-pumped Cr, Nd-doped YAG ceramic rod laser for more than 6.5 h tracking the sun," *Solar Energy*, vol. 177, pp. 440–447, 2019.

[34] H. Zhang, D. Sun, J. Luo et al., "Influence of Cr^{3+} doping on the spectroscopies and laser performance of Cr, Nd : YAG crystal operated at 1.06 μm," *Optical Engineering*, vol. 58, no. 2, 2019.

[35] D. Liang, C. R. Vistas, B. D. Tibúrcio, and J. Almeida, "Solar-pumped Cr: Nd: YAG ceramic laser with 6.7% slope efficiency," *Solar Energy Materials & Solar Cells*, vol. 185, pp. 75–79, 2018.

[36] D. Liang and J. Almeida, "Highly efficient solar-pumped Nd : YAG laser," *Optics Express*, vol. 19, no. 27, Article ID 26399, 2011.

[37] T. Ogawa, S. Wada, and M. Higuchi, "Development of Nd, Cr co-doped laser materials for solar-pumped lasers," *Japanese Journal of Applied Physics*, vol. 53, no. 8S2, Article ID 08MG03, 2014.

[38] T. Saiki, N. Fujiwara, N. Matsuoka, M. Nakatuka, K. Fujioka, and Y. Iiida, "Amplification properties of KW Nd/Cr : YAG ceramic multi-stage active-mirror laser using white-light pump source at high temperatures," *Optics Communications*, vol. 387, pp. 316–321, 2017.

[39] Y. Guo, J. Huang, G. Ke, Y. Ma, J. Quan, and G. Yi, "Growth and optical properties of the Nd, Ce : YAG laser crystal," *Journal of Luminescence*, vol. 236, Article ID 118134, 2021.

[40] C. R. Vistas, D. Liang, J. Almeida et al., "Ce : Nd : YAG side-pumped solar laser," *Journal of Photonics for Energy*, vol. 11, no. 1, Article ID 18001, 2021.

[41] C. R. Vistas, D. Liang, D. Garcia, J. Almeida, B. D. Tibúrcio, and E. Guillot, "Ce : Nd : YAG continuous-wave solar-pumped laser," *Optik*, vol. 207, Article ID 163795, 2020.

[42] J. Almeida, D. Liang, D. Garcia et al., "40 W continuous wave Ce: Nd: YAG solar laser through a fused silica light guide," *Energies*, vol. 15, no. 11, p. 3998, 2022.

[43] C. R. Vistas, D. Liang, D. Garcia et al., "Uniform and non-uniform pumping effect on Ce : Nd : YAG side-pumped solar laser output performance," *Energies*, vol. 15, no. 10, p. 3577, 2022.

[44] D. Garcia, D. Liang, C. R. Vistas et al., "Ce : Nd : YAG solar laser with 4.5% solar-to-laser conversion efficiency," *Energies*, vol. 15, no. 14, p. 5292, 2022.

[45] D. Liang, C. R. Vistas, D. Garcia et al., "Most efficient simultaneous solar laser emissions from three Ce : Nd : YAG rods within a single pump cavity," *Solar Energy Materials and Solar Cells*, vol. 246, Article ID 111921, 2022.

[46] K. Fujioka, T. Saiki, S. Motokoshi, Y. Fujimoto, H. Fujita, and M. Nakatsuka, "Parameter mapping survey on optimized sensitizing effect of Ce/Cr/Nd : YAG material for solar-pumped solid-state lasers," *Journal of Luminescence*, vol. 143, pp. 10–13, 2013.

[47] P. Samuel, G. A. Kumar, T. Yanagitani, H. Yagi, K. Ueda, and S. M. Babu, "Efficient energy transfer between Ce^{3+}/Cr^{3+} and Nd^{3+} ions in transparent Nd/Ce/Cr: YAG ceramics," *Optical Materials*, vol. 34, pp. 303–307, 2011.

[48] T. Hayashi, T. Saiki, K. Fujioka, Y. Iida, and M. Nakatsuka, "Analysis on amplifi cation properties of Ce/Cr/Nd : YAG ceramic lasers by computational calculation," *The Review of Laser Engineering*, vol. 39, no. 11, pp. 854–861, 2011.

[49] A. Yariv and P. Yeh, *Photonics: Optical Electronics in Modern Communication (The Oxford Series in Electrical and Computer Engineering)*, Oxford University Pr on Demand, England, UK, 2007.