Continuous wave and passively Q-switched laser performance of \( \text{Nd:Lu}_{x}\text{Gd}_{3-x}\text{Ga}_5\text{O}_{12} \) crystal at 1062 nm

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Abstract: Continuous wave (CW) and passively Q-switched (PQS) laser properties at 1062 nm of the Nd:Lu$_x$Gd$_{3-x}$Ga$_5$O$_{12}$ (Nd:LGGG) disordered crystal have been demonstrated. The doping concentrations of Nd$^{3+}$ and Lu$^{3+}$ in the as obtained crystal were measured to be 0.96 and 0.66 at.%, respectively. In the CW regime, the output power of 9.73 W was obtained with an optical-to-optical efficiency as high as 60.7% and slope efficiency of 61.2%. During the passively Q-switched operation, the maximum output power of 1.24 W was achieved under the absorbed pump power of 6.86 W. The maximum peak power of 14.20 kW and single pulse energy of 148 J were obtained with the $T_{oc} = 10\%$ under the absorbed pump power of 6.36 W. The results are much better than those obtained with Nd:LGGG crystal doped with 13.6 at.% Lu$^{3+}$ and 0.53 at.% Nd$^{3+}$ ions.

Continuous wave and passively Q-switched laser performance of Nd:Lu$_x$Gd$_{3-x}$Ga$_5$O$_{12}$ crystal at 1062 nm

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1. Introduction

Nd-lasers have extensive applications in many fields, such as industry, scientific research and medical treatment, due to their high efficiency and high power capability. Recently many efforts have been made to improve the performance of such lasers [1–5]. The Nd:Gd$_3$Ga$_5$O$_{12}$ (Nd:GGG) crystal has been proved to be a good medium for the laser-diode (LD)-pumped solid-state laser at high power application. Compared with Nd:Y$_3$Al$_5$O$_{12}$ (Nd:YAG), Nd:GGG has several advantages, including: easy to get larger size (no core growth), with higher Nd-ions concentration (greater than 4 at.%), and wider phase homogeneity with high pulling rate (up to 5 mm/h) [6].

As a derivative of Nd:GGG crystal, the Nd:LGGG with the Nd$^{3+}$ doping level of 0.53 at.% and the Lu$^{3+}$ concentration of 13.6 at.% has been grown by Czochralski (Cz) method [7]. Compared with Nd single doped Gd$_3$Ga$_5$O$_{12}$ (GGG) crystal, in Nd:LGGG crystal the crystal structure can be more complex and disordered because both Nd and Lu ions have the chance to enter the big dodecahedral and middle-size octahedral sites.

In addition, the random distribution of the Lu and Gd ions neighboring the Nd ions should offer a number of nonequivalent crystal field for Nd ions. Due to Nd$^{3+}$ multi-center distribution and the more complex structure of the host material [8], the Nd-doped Lu$_x$Gd$_{3-x}$Ga$_5$O$_{12}$ (LGGG) crystal possesses wider inhomogeneous broadened spectra. Although the spectra and laser properties of Nd:LGGG crystal with Nd$^{3+}$ doping level of 0.53 at.% and the Lu$^{3+}$ concentration of 13.6 at.% have been studied [7], we believe that the spectral and laser properties could

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be improved through tuning \(\text{Lu}^{3+}\) and \(\text{Nd}^{3+}\) concentration. We think that a higher \(\text{Lu}^{3+}\) doping not only makes it more difficult for crystal growing, but also brings a lot of defects into the crystal. Additionally, higher \(\text{Nd}^{3+}\) doping increases the absorbance of the pump radiation [9]. In this paper, a new Nd:LGGG crystal with lower \(\text{Lu}^{3+}\) and higher \(\text{Nd}^{3+}\) doping has been grown. The doping concentrations were measured to be 0.66 and 0.96 at.% for \(\text{Lu}^{3+}\) and \(\text{Nd}^{3+}\) ions, respectively. As high as 9.73 W continuous wave (CW) output power was obtained with the optical-optical conversion efficiency of 60.7% and the slope efficiency of 61.2%, which were improved a lot in comparison with the former ones [7]. The passively Q-switched (PQS) performance was also investigated with \(\text{Cr}^{4+}:\text{YAG}\) crystal as the saturable absorber and the maximum output power was 1.24 W.

2. Experiment setup

The Nd:LGGG samples used for spectral examination were cut with dimensions of \(7 \times 7 \times 2 \text{ mm}^3\), and the two polished faces \((7 \times 7 \text{ mm}^2)\) were perpendicular to the \(\langle 111 \rangle\) direction. The absorption spectrum was measured by using a U-3500 spectrophotometer and the fluorescence spectrum excited by an 808 nm laser diode (LD) was measured by a FLS920 spectrophotometer at room temperature. The laser experimental setup is shown schematically in Fig. 1. The sample used in laser experiments was cut along the \(\langle 111 \rangle\) direction with dimensions of \(3 \times 3 \times 6.1 \text{ mm}^3\), and was uncoated. It was wrapped with indium foil and held in water cooling aluminum block to maintain a temperature of 20 °C. The input concave mirror M1 with the curvature radius of 200 mm was anti-reflection (AR) coated at 808 nm \((R < 0.5\%)\) on the flat face and high-reflection coated at 1.06 \(\mu\text{m}\) \((R > 99.8\%)\) and high-transmission coated at 808 nm on the concave face. M2 was a flat mirror with different transmissions of 5%, 10%, and 27% at 1062 nm. The pump source was a fiber coupled diode laser emitting at 805 nm. The fiber bundle was with a diameter of 600 \(\mu\text{m}\) and a numerical aperture of 0.22. Its radiation was coupled into the laser crystal by a focusing optical system with a focal length of 15 mm. The beam-waist radius in the Nd:LGGG crystal was estimated to be 170 \(\mu\text{m}\). The laser pulse signal was recorded by a Tektronix DPL7104 digital oscilloscope (1 G bandwidth, 5 Gs/s sampling rate) and a photo detector (New Focus, model 1623, rise time \(\leq 1 \text{ ns}\)). The average output power was measured by a laser power meter (Fieldmax II, Coherent).

3. Results and discussions

The absorption cross-section of Nd:LGGG in the wavelength ranging from 400 to 1000 nm is shown in Fig. 2. There are five strong-absorption bands around 530, 588, 736, 805, and 873 nm, which are assigned to spin-and electric-dipole-allowed transitions from the ground
state \( (^2I_9/2) \) to \( ^2K_{13/2} + ^4G_{7/2} + ^4G_{9/2}, ^4G_{5/2} + ^2G_{7/2},
^4F_{7/2} + ^4S_{3/2}, ^4F_{3/2} + ^2H_{9/2}, \) and \( ^4F_{3/2} \) energy levels, respectively [10]. Among all absorption peaks, the strongest one located at 805 nm with a full-width at half-maximum (FWHM) of 8.6 nm, which is much larger than that of Nd:YAG (FWHM = 0.9 – 2.1 nm) [11]. This large absorption bandwidth indicates that the Nd:LGGG is suitable for diode pumping. Room-temperature fluorescence spectrum upon excitation at 806 nm is shown in Fig. 3. There are three main emission bands with the central wavelength located at 937, 1062, and 1331 nm, respectively. The strongest emission located at 1062 nm is associated with the \( ^4I_{11/2} \) transition of Nd\(^{3+} \) ions. The excited state fluorescence lifetime was measured to be 220.35 \( \mu \)s (Fig. 4).

### 3.1. Continuous-wave laser operation

The CW operation of Nd:LGGG laser was performed by optimizing the cavity length to be 17 mm. The absorption coefficient was measured to be 86.2\%. Fig. 5 shows the CW output power versus the absorbed pump power of the laser at the 1062 nm with the output coupler of 5\%, 10\%, and 27\%, respectively. As can be seen from Fig. 5, the

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**Figure 4** (online color at www.lasphys.com) Excited state fluorescence lifetime of Nd:LGGG (\( \lambda_{exc} = 806 \) nm and \( \lambda_{em} = 1062 \) nm)

**Figure 5** (online color at www.lasphys.com) The output power versus the absorbed pump power at the cavity length of 17 mm

**Figure 6** (online color at www.lasphys.com) The Q-switched output power versus the absorbed pump power at the cavity of 30 mm

**Figure 7** (online color at www.lasphys.com) The variation of the pulse width and the repetition rate versus the absorbed pump power
threshold pump power \( (P_{th}) \) were 0.33, 0.54 and 1.64 W with the output coupler of 5%, 10%, and 27%, respectively. Based on the CW model developed by Mermilliod et al. [12], the \( P_{th} \) for the CW laser can be calculated by

\[
P_{th} = \frac{\hbar \nu p (\omega_p^2 + \omega_c^2) (T_{oc} + L)}{4 \eta p \sigma \tau},
\]

where \( \hbar \nu p \) is the pump photon energy; \( \sigma \) is the stimulated emission cross-section; \( \omega_p \) and \( \omega_c \) are the cavity and pump beam waists, respectively, and in our experiments \( \omega_p \) is 300 \( \mu \)m and \( \omega_c \) is calculated to be 100 \( \mu \)m by ABCD theory; \( \eta p \) is the excited quantum efficiency and \( \eta p = 1 \); \( T_{oc} \), \( L \), and \( \tau \) represent the transmission of output coupler, the value of the optical losses and the excited state fluorescence lifetime, respectively. By using the measured thresholds and \( \tau = 220.35 \mu s \) measured by a FLS920 spectrophotometer at room temperature, the emission cross-section of \( \nu x = 1062 \text{ nm} \) is calculated to be \( 2.04 \times 10^{-19} \text{ cm}^2 \) according to Eq. (1). This value is smaller than that of Nd:GGG (about \( 2.46 \times 10^{-19} \text{ cm}^2 \)) [12], which can be attributed to the inhomogeneous broadening of fluorescence line in the mixed Nd:LGGG crystal [6]. However, the value was bigger than Nd:LGGG crystal with higher Lu\(^{3+} \) doping \( (1.1 \times 10^{-19} \text{ cm}^2) \), which can be attributed to the lower Lu\(^{3+} \) doping that makes the crystal narrower inhomogeneous broadened spectra. Under an absorbed pump power of 16.04 W, the highest output power of 9.73 W was obtained with the output coupler of 10%, giving the maximum slope efficiency of 61.2% and the optical conversion efficiency of 60.7%. These results are much better than the previous ones, which were reported to be 4.31 W, 42.2% and 39.2%, respectively [7]. The slope efficiency was comparable but the output power was much higher than that \( (\eta = 61\%, P_{out max} = 230 \text{ mW}) \) of obtaining in [13].

From the above results we can find that this new Nd:LGGG sample has large FWHM in absorption spectra because of the inhomogeneous broadening when doping Lu ions inside. At the same time the CW laser operation has a higher output power and efficiency when comparing with the previous results [7], which should be concluded due to the better crystal quality, since the lower Lu doping will result in lesser defects in the crystal. To our best of knowledge, this is the best result about Nd:LGGG crystal CW.

### 3.2. Passively Q-switched laser operation

The cavity length was extended to 30 mm for passively Q-switched operation. The saturable absorber Cr\(^{4+} \)-YAG which has a dimension of \( 5\times5\times1 \text{ mm}^3 \) and the initial transmission of \( T_0 = 82.38\% \) was inserted into the cavity close to the mirror M2. In order to protect the saturable absorber, the maximum pumping power was limited to be 7 W. The results of the average output power versus the absorbed pumping power are shown in Fig. 6 with the different output coupler of 5%, 10%, and 27%. When the output coupler is \( T_{oc} = 10\% \), we obtained the optimal output power of 1.24 W under the absorbed pump power of 6.86 W.

The pulse width and the repetition rate versus absorbed pump power with the \( T_{oc} = 5\% \) and \( T_{oc} = 10\% \) are shown in Fig. 7. It can be seen that the pulse width decreases while the repetition frequency of the output laser increases with the increasing the power of the pumping laser. This result is coincident with the basic theory of Q-switching [14], and similar experimental results had been shown in [6,15]. The minimum pulse width of 9.95 ns was obtained at the absorbed power of 6.36 W with the \( T_{oc} = 5\% \). The largest single pulse energy and peak power for the passively Q-switched were calculated to be 148 \( \mu \)J and 14.20 kW with the \( T_{oc} = 10\% \) and the output power of 1.11 W under the absorbed pump power of 6.36 W. The corresponding pulse repetition rate and the minimum pulse width were 7.51 kHz and 10.41 ns, respectively. The pulse width was showed in Fig. 8a, and the pulse train was presented in Fig. 8b. It is believed that the better passively Q-switched laser output could be obtained on condition that the proper saturable absorber and output coupler were used.
4. Conclusions

In this paper a Nd:LGGG crystal with doping level of 0.96 at.% Nd\textsuperscript{3+} and 0.66 at.% Lu\textsuperscript{3+} inside, has been grown by Cz method. In the CW laser operation, the maximum output power of 9.73 W was achieved with the optical-to-optical and slope efficiency of 60.7\% and 61.2\%, respectively. While in the Q-switched operation, the output power of 1.24 W, single pulse energy 148 J and maximum peak power 14.20 kW were realized. To our best of knowledge, these are the best results obtained in Nd:LGGG crystals when comparing with the previous works on this kind of laser crystal. Therefore, the Nd:LGGG crystal is a promising laser material for CW and passively Q-switched laser operation. In addition, we believe that the laser performance of the Nd:LGGG crystal could be further improved by tuning the doping concentrations. More detailed works on the series of Nd:LGGG crystals are under study, and their spectral and laser properties will be reported in future.

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