

Diode-pumped quasi-three-level CW Nd:CLNGG and Nd:CNGG lasers

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Abstract: We have demonstrated what is to our knowledge the first quasi-three-level CW Nd:CLNGG laser with simple linear resonator. When the pump power was 18.2 W, a maximum output power of 1.63 W was obtained at the dual-wavelength of 935 nm and 928 nm. The optical-to-optical conversion efficiency was 9.0% and the slope efficiency was 11.5%. Lasing characteristics of a quasi-three-level CW Nd:CNGG laser were also investigated. A maximum output power of 1.87 W was obtained at the single-wavelength of 935 nm with 15.2 W pump power, corresponding to an optical-to-optical conversion efficiency of 12.3% and a slope efficiency of 15.6%.

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OCIS codes: (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (160.3380) Laser materials.

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1. Introduction

Calcium niobium gallium garnet (CNGG) is a typical disordered crystal, which has a disordering structure due to the random distribution of enormous variety of different types of ions and vacancies in its host lattices. Stoichiometric composition of CNGG was shown to be $\text{Ca}_3\text{Nb}_{1.5}\text{Ga}_{3.5}\text{O}_{12}$ [1]. Single crystals of CNGG were first grown from melt in 1985 [1], but high vacancy concentration in CNGG caused the formation of its nonstoichiometric structure, which could be a major drawback as a crystal. Introduction of Li^+ ions into CNGG can reduce its vacancy concentration and partly overcome its nonstoichiometric structure property [2], at the same time, by introducing Li^+ ions into CNGG a new crystal denoted as calcium lithium niobium gallium garnet (CLNGG) was generated.

In the past two decades, extensive investigations have been made into Nd:CNGG and Nd:CLNGG crystals owing to their unique properties, such as broad absorption and emission bands [1,3,4], lower melting temperature ($\sim 1460^\circ\text{C}$) [5] and large segregation coefficient for Nd^{3+} (0.55) [4]. Their lasing characteristics in different regimes (free running [2], Q-switch [6], ultra short pulse [7]) were different considerably due to their different crystal structures. Most previous investigations were devoted to the four-level laser transition, only few relevant to the quasi-three-level transition.

The quasi-three-level laser transition around 900 nm has many applications. For example, the lasers at 935 nm and 942 nm can be used as the sources for the differential absorption lidar (DIAL) in water vapor detection since these wavelengths overlap the absorption peaks of water vapor [8]. The determination of the spatial distribution of the water vapor in the atmosphere is important for meteorological and climatological studies. Water vapor absorption wavelengths had been directly generated by diode pumped Nd:GSAG (942 nm) and Nd:YGG crystals (935 nm) [9].

However, the quasi-three-level laser transition around 900 nm is difficult to obtain on account of serious re-absorption loss and very small stimulated emission cross section compared with that of the four-level transition [10]. Recently, Li et al. realized the continuous-wave (CW) Nd:CNGG laser at 935 nm for the first time [11]. However, there has no report on the operation of a quasi-three-level Nd:CLNGG laser. In this paper, we successfully realized the CW operation of a Nd:CLNGG laser under the quasi-three-level transition. In addition, lasing characteristics of a quasi-three-level CW Nd:CNGG laser were also investigated.

2. Experimental setup

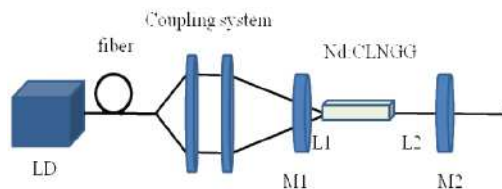


Fig. 1. Experimental setup of the CW quasi-three-level Nd:CLNGG laser.

The schematic of the experimental setup is shown in Fig. 1. We designed a linear resonator to make the system simple and compact. The pump source was a high-brightness fiber-coupled CW laser diode with a center wavelength of 808 nm and spectrum width of 3.5 nm (FWHM). The diameter of the fiber core was 200 μm and the numerical aperture was 0.22. A 1:1 coupling system was used to inject the pump beam into the laser crystal. We measured the absorption spectrum in the 800 nm region and the fluorescence spectrum of the Nd:CLNGG crystal with Nd^{3+} concentration of 0.5 at.% from 900 to 1370 nm, as shown in Fig. 2.

Comparing the absorption spectrum and the fluorescence spectrum with that of the Nd:CNGG crystal in reference [12], we can find that both of them have broad absorption spectra in the 800 nm region and broad fluorescence spectra around 935 nm. From Fig. 2(a) we can see that the peak absorption coefficient of 0.5 at.% Nd-doped Nd:CLNGG crystal at 807 nm was 2.86 cm^{-1} . Three 0.5 at.% Nd-doped Nd:CLNGG crystals with dimensions of $3 \times 3 \times 4 \text{ mm}^3$, $3 \times 3 \times 6 \text{ mm}^3$ and $3 \times 3 \times 10 \text{ mm}^3$ were respectively used in our experiment. To decrease the intracavity loss and prevent the parasitic oscillations in the Nd:CLNGG crystals, both sides of the Nd:CLNGG crystals were coated for antireflection (AR) at 808 nm, 935 nm, 1061 nm and 1342 nm. In addition, a Nd:CNGG crystal with dimensions of $3 \times 3 \times 10 \text{ mm}^3$ and same coating as that of the three Nd:CLNGG crystals was used. To decrease the influence of the thermal lens effect and make the laser operation stable and efficient, the laser crystals were all wrapped within indium foils and mounted in water-cooled copper blocks with a temperature of 5°C . Flat mirror M1 served as an input coupler, which has high reflection (HR) coating at 935 nm and high transmission (HT) coating at 808 nm, 1061 nm and 1342 nm. M2 was a concave mirror with different radii of curvature (ROC) and a transmission of 3.4% at 935 nm.

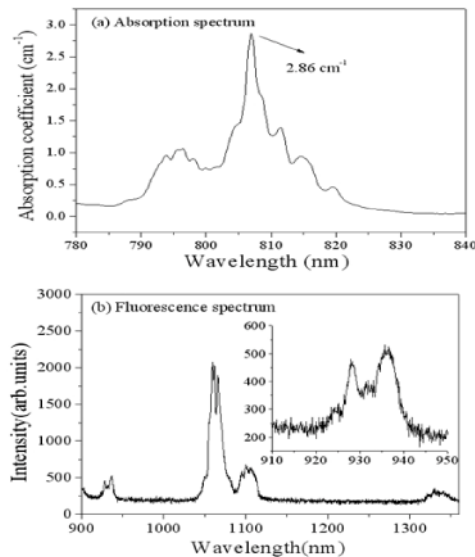


Fig. 2. Absorption spectrum (a) and fluorescence spectrum (b) of Nd:CLNGG crystal.

In Fig. 1, L1 and L2 were the distances from M1 to the left surface of the Nd:CLNGG crystal and M2 to the right surface respectively. Considering mode matching and thermal lens effect of the laser crystal, the values of L1 and L2 were optimized according to ABCD matrix theory with a thin lens in the middle of the laser crystal. Take an example, the focal length of the thermal lens (f) of the 10 mm long Nd:CLNGG crystal was about 18 mm at the pump power of 18 W, which denoted the degree of the thermal lens effect and was measured with the plat-plat method [13] in our experiment. With the f value, we optimized $L1 = 8 \text{ mm}$ and $L2 = 6 \text{ mm}$ for the 10 mm long crystal with ROC of 100 mm. With these optimized values, Fig. 3 gives the U-shape figure depicting spot radii of the 935 nm oscillating laser on the middle of the Nd:CLNGG crystal with the f value changed from 0 to 250 mm. From Fig. 3, we can clearly see that our cavity had a broad stable range (for $f=12$ to 250 mm), which means that our cavity would remain stable even when the thermal lens effect became serious as the pump power increased to 18 W. For different Nd:CLNGG crystals, the proper cavity length were also different. The specific values we selected for different Nd:CLNGG crystals are illustrated in Table 1, which also lists the lasing characteristics of different Nd:CLNGG and Nd:CNGG lasers.

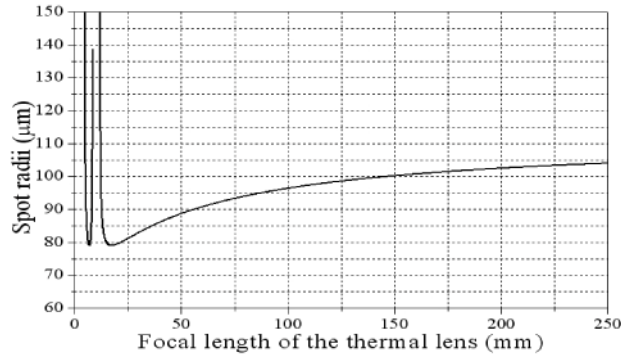


Fig. 3. Spot radii of the oscillating laser on the middle of the 10 mm long Nd:CLNGG crystal with the f value changed from 0 to 250 mm.

Table 1. Lasing characteristics of different Nd:CLNGG and Nd:CNGG crystals

Crystal	Curvature radius	Cavity length	Laser threshold	Maximum output power	Optical-Optical efficiency	Slope efficiency
Nd:CLNGG (4 mm)	50 mm	29 mm	4 W	778 mW	5.6%	7.9%
Nd:CLNGG (4 mm)	100 mm	26 mm	4 W	868 mW	6.0%	8.3%
Nd:CLNGG (6 mm)	100 mm	25 mm	4 W	1.13 W	7.4%	10%
Nd:CLNGG(10mm)	100 mm	24 mm	4 W	1.63 W	9.0%	11.5%
Nd:CNGG (10mm)	100 mm	24 mm	3.2 W	1.87 W	12.3%	15.6%

3. Experiment results and discussion

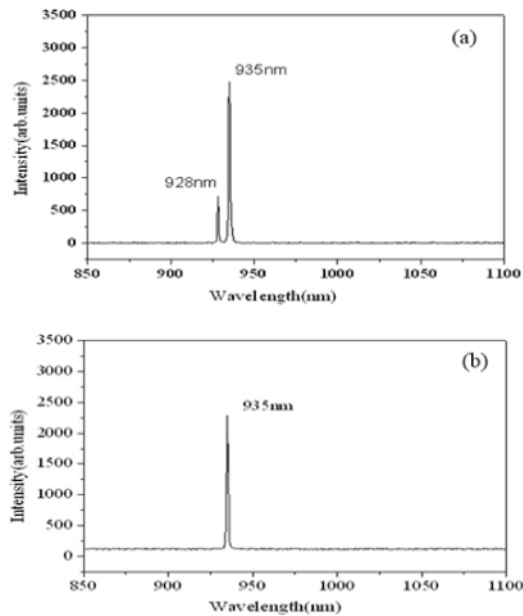


Fig. 4. Laser spectra of the Nd:CLNGG (a) and Nd:CNGG (b) lasers operating on the quasi-three-level transition.

Firstly, the laser emission spectra of the Nd:CLNGG and Nd:CNGG lasers were measured and the typical results were illustrated in Fig. 4(a) and Fig. 4(b). The laser emission spectra were different despite of their similar broad fluorescence spectrum around 935 nm. From Fig.

4, we can see that for the Nd:CLNGG laser the output laser has dual wavelengths at 935 nm and 928 nm, while for the Nd:CNGG laser there was only the 935 nm wavelength left. Namely, different numbers of laser lines were emitted by the Nd:CNGG and Nd:CLNGG lasers under the quasi-three-level transition. Similar phenomenon was obtained by Yu. K. Voronko et al. under the four-level laser transition of the Nd:CLNGG and Nd:CNGG lasers at around 1060 nm [1]. They obtained three wavelengths at 1059.3 nm, 1061.5 nm and 1066 nm for the Nd:CNGG laser, yet for the Nd:CLNGG laser the 1059.3 nm was much weakened as well as the 1061.5 nm and 1066 nm were retained. The difference should attribute to different characters of the Nd^{3+} activator centers in their matrices. According to the investigations of spectroscopic characteristics in the Nd:CLNGG and Nd:CNGG crystals, there exist at least five different types of Nd^{3+} activator centers in any of them due to the random distribution of ions and vacancies in their lattices [1,14]. Different types of Nd^{3+} activator centers can be selectively excited. Every individual Nd^{3+} activator center has its own fluorescence spectrum with different peak position and intensity, and the superposition of them result in the broad fluorescence spectrum of the Nd:CLNGG and Nd:CNGG crystals. Thus, we conclude the reasons as following: firstly, the concentration of the Nd^{3+} activator center that emitting at 928 nm wavelength was very low in the Nd:CNGG crystal; secondly, very little Nd^{3+} activator centers emitting at 928 nm wavelength was excited with the increase of the incident pump power for the Nd:CNGG in our experiment.

In fact, the output laser of any Nd:CLNGG sample at the laser threshold was only at 935 nm, but with the increase of the pump power, the 928 nm soon appeared near the threshold. The two wavelengths occurred almost simultaneously. The output powers of the Nd:CLNGG lasers were all stable even at high pump power while operated at dual-wavelength. These phenomena we observed were accordance with the Nd:CNGG laser operating on the four-level transition [15]. Furthermore, we found that the intensity instability of all the dual-wavelength Nd:CLNGG lasers at the maximum output power was less than 30% within 15 min observing through the spectrometer.

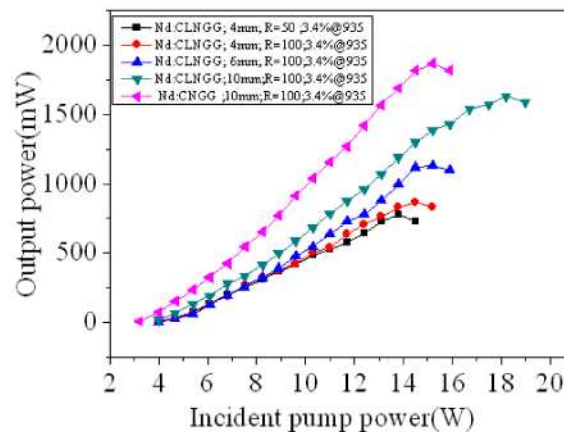


Fig. 5. Dependence of the output powers on the pump power with three Nd:CLNGG crystals and a Nd:CNGG crystal.

Secondly, the input-output characteristics of all the laser crystals (4 mm, 6 mm, 10 mm long Nd:CLNGG crystals and 10 mm long Nd:CNGG crystal) were measured and illustrated in Fig. 5. From Fig. 5, we can see that better result was achieved with the 10 mm long Nd:CLNGG crystal compared with that of the 4 mm and 6 mm in lengths by using the output mirror with transmission of 3.4% at 935 nm and ROC of 100 mm. The laser threshold of the 10 mm long Nd:CLNGG crystal was about 4 W. When the pump power was 18.2 W, the maximum output power of 1.63 W was obtained, corresponding to an optical-to-optical conversion efficiency of 9.0% and a slope efficiency of 11.5%. For the 10 mm long Nd:CNGG crystal, the laser threshold was about 3.2 W. When the pump power was 15.2 W,

the highest output power of 1.87 W was accessed. The corresponding optical-to-optical conversion efficiency and slope efficiency were 12.3% and 15.6%, respectively. When the pump power exceeded 15.2 W, the output power also began to decline due to severe thermal lens effects. As far as we know, 1.87 W is also the maximum output power that obtained with Nd:CNGG lasers operating on the quasi-three-level transition. Seeing from the results in Fig. 5 and the comparison results in Table 1 we can conclude that the Nd:CLNGG and Nd:CNGG lasers displayed comparable performance under the same experiment conditions. Moreover, both of the lasers emitted at 935 nm wavelength, which could be used for the light source of the water vapor differential absorption lidar (DIAL) detection system [8].

When the output power was 1.4 W, we also measured its beam spatial profile of the 10 mm long Nd:CNGG using a laser beam analyzer (OPHIR) and the result was illustrated in Fig. 6, which shows that the transverse mode present a perfectly Gaussian profile of intensity.

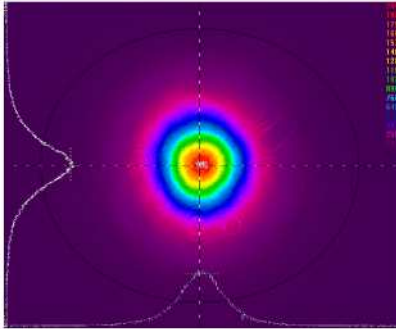


Fig. 6. Beam spatial profile of the 10 mm long Nd:CNGG laser under the output power of 1.4 W.

4. Conclusion

In conclusion, we realized the CW operation of a Nd:CLNGG laser on the $^4F_{3/2}$ to $^4I_{9/2}$ transition for the first time. Lasing characteristics of the 4 mm, 6 mm and 10 mm long Nd:CLNGG crystals with doping concentration of 0.5 at.% were investigated. The maximum output power of 1.63 W was obtained with the 10 mm long Nd:CLNGG crystal when the pump power was 18.2 W at dual-wavelength of 935 nm and 928 nm. The optical-to-optical conversion efficiency was 9.0% and the slope efficiency was 11.5%. We also investigated the lasing characteristics of the 10 mm long Nd:CNGG crystal. By using the 10 mm long Nd:CNGG crystal, the highest output power of 1.87 W was obtained at the pump power of 15.2 W, corresponding to an optical-to-optical conversion efficiency of 12.3% and a slope efficiency of 15.6%. 1.87 W is also the maximum output power ever obtained with Nd:CNGG laser operating on the quasi-three-level transition.

Acknowledgements

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