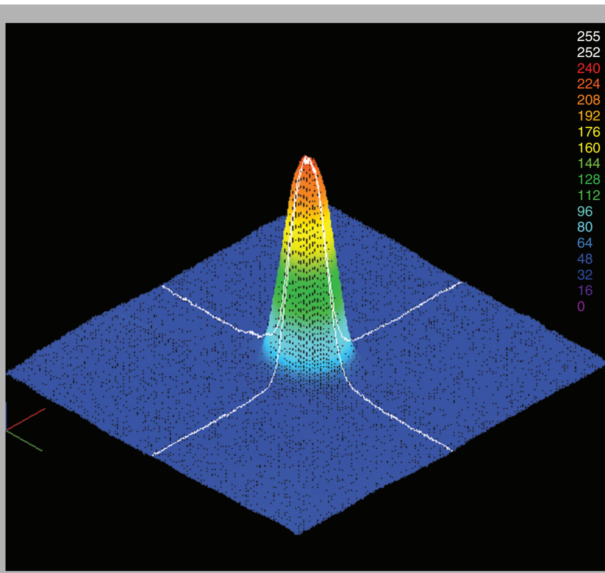
Abstract: The operating characteristics of a Nd:GYSGG laser in the 1.3 μm wavelength band based on the transition $^4F_{3/2} \rightarrow {}^4I_{13/2}$ is demonstrated. Using two different output couplers, single wavelengths operation at 1336 nm and dual-wavelength operation at 1321/1336 nm are obtained. The 1329 nm laser spectrum is also found when the pump level is relatively weak. The stimulated emission cross section of the 1336 nm laser line is estimated to be 1.12 time of that of the 1321 nm laser line. The output power of 1.98 W at 1336 nm is achieved with the pump power of 13.5 W, corresponding to the conversion efficiency of 14.7%. This is the first report on a 1.3-μm Nd:GYSGG laser to our knowledge.



Beam profile of the 1.3 μm Nd:GYSGG laser

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Continuous-wave Nd:GYSGG laser around 1.3 μm

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1. Introduction

The trivalent neodymium ion (Nd^{3+}) doped crystals, such as Nd:YAG, Nd:YVO_4, Nd:$GdVO_4$, Nd:YLF, Nd:YAG, et al. are important laser materials for 1.3 μm lasers, which has wide applications covering the areas of spectroscopy, medicine, fiber optics, laser machining, military, and frequency-doubled red lasers and so on. Much attention has been paid on such lasers in recent years and great development has been achieved. The output powers have reached over 120 W using the diode-side-pumped scheme in Nd:YAG and Nd:YAP [1–4]. For diode-end-pumped schemes, R. Zhou et al. has realized the output power of nearly 28 W in a 1342 nm Nd:$GdVO_4$ laser [5]. Based on frequency doubling, H.B. Peng et al. reported a red laser at 659.5 nm with its power up to 28 W under the Q-switched mode [6], and R. Zhou et al. has achieved continuous-wave 671 nm Nd:$GdVO_4$/LBO red laser with the power of

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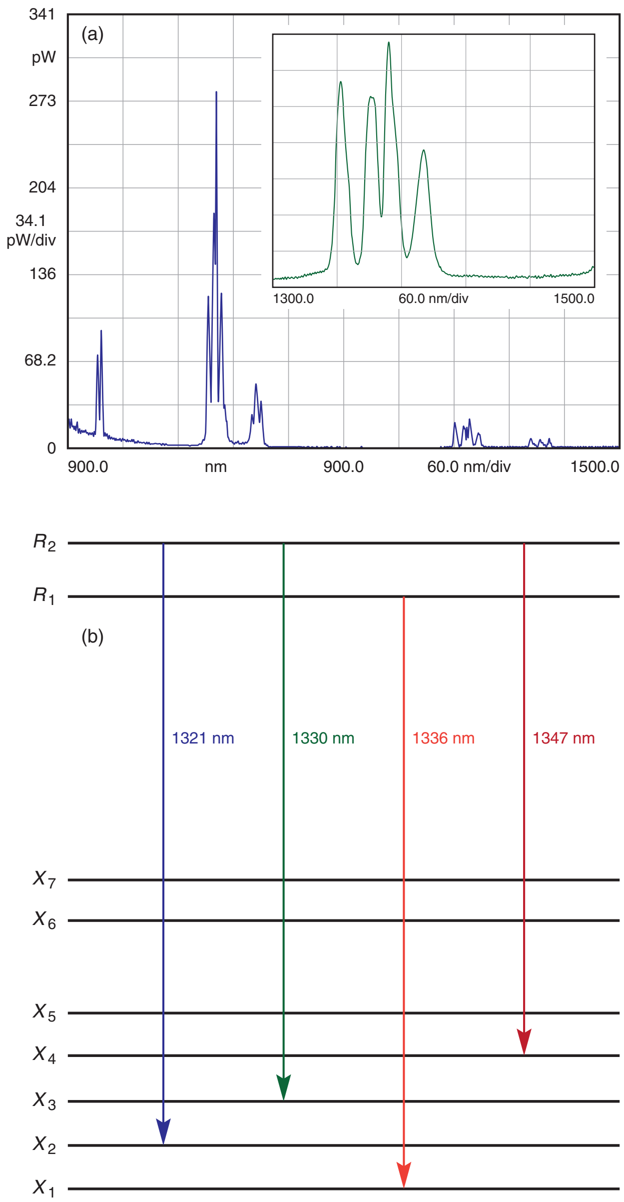

Figure 1 (online color at www.lasphys.com) The fluorescence spectrum excited at 808 nm and energy level transition of $^4F_{3/2} \rightarrow {}^4I_{13/2}$ for Nd:GYSGG

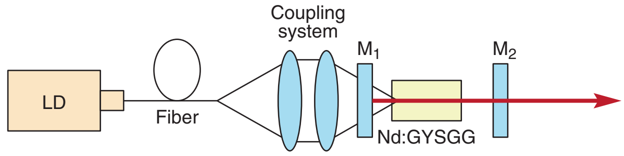

Figure 2 (online color at www.lasphys.com) Experimental setup of the 1.3 μm Nd:GYSGG laser

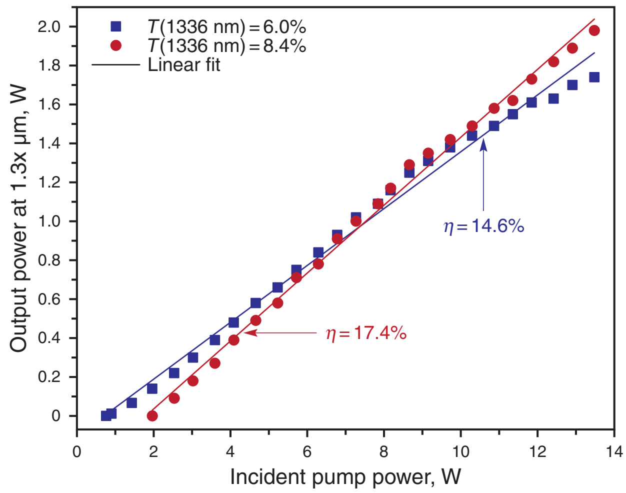

Figure 3 (online color at www.lasphys.com) Output characteristics of the 1.3 μm Nd:GYSGG laser

nearly 4 W [7]. The Frequency tripled blue laser from the Nd:YAG line at 1319 nm is also researched and the maximum output power reported up to now is over 7 W [8]. Besides single-wave operating, multi-wavelength 1.3 μm lasers have also attracted broad attention among the applications of precision laser spectroscopy, lidar, nonlinear optical frequency conversion, and so on. A lot of works have been reported concerning the compact and efficient simultaneous dual-wavelength laser emission at 1319 and 1338 nm in Nd:YAG for difference frequency generation to the terahertz wavelength range [9–11].

A new Nd^{3+} doped garnet laser crystal – Nd:GYSGG, has been grown by replacing part of the Y^{3+} ions with Gd^{3+} in Nd:YSGG recently, and its excellent continuous and AO Q-switched laser performance around 1.06 μm has been reported in our previous work [12]. B.Y. Zhang et al. also studied its passively Q-switched and mode-locked operation recently [13]. Similar to the other Nd^{3+} doped garnet crystals, the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition can also be used for the generation of 1.3 μm lasers. However, the emission cross section of Nd:GYSGG in this range is quite small with the fluorescence branching ratio of about 10%, only 1/5 of that for $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition [14]. The fluorescence spectrum of Nd:GYSGG excited at 808 nm is shown in Fig. 1a, measured by an Agilent 86142B spectrum analyzer. There are four distinct peaks in the 1.3 μm range at the wavelengths of 1321, 1330, 1336, and 1347 nm, in which the third one is the strongest. The diagram of the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ energy level transition is shown in Fig. 1b. The 1336 nm laser transition is $R_1 \rightarrow X_1$, while the other three have the same upper Stark level R_2. According to [15], if an optimized reflectivity ratio between two wavelengths determined by their stimulated emission cross sections and fluorescence branching ratios is used in a laser

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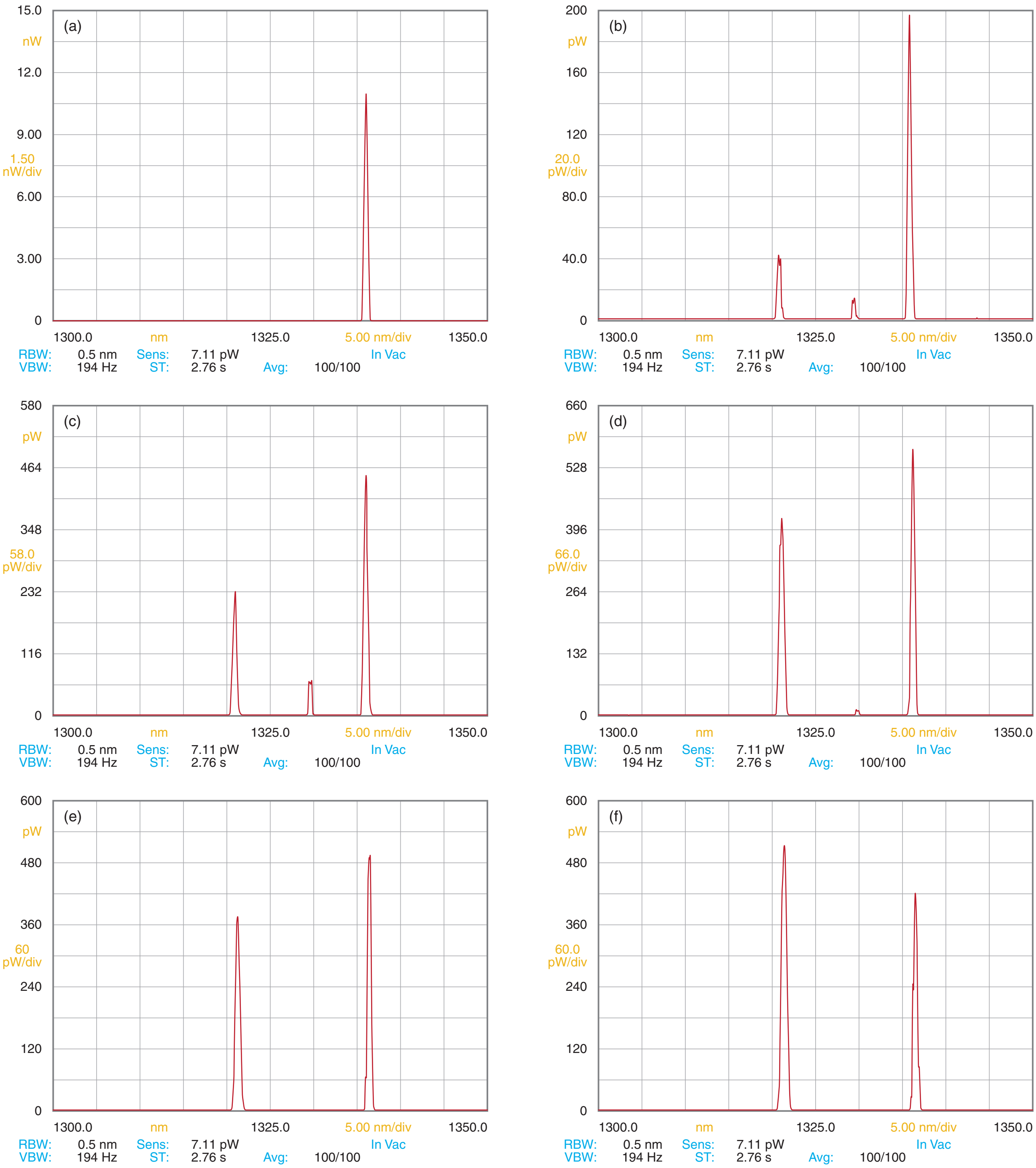

Figure 4 (online color at www.lasphys.com) Output spectra of the Nd:GYSGG laser with OC1 (a) and OC2 when the incident pump powers are around 1.0 W (b), 3.0 W (c), 5.7 W (d), 8.2 W (e), and above 10 W (f)

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cavity, a dual-wavelength laser with the same threshold can be achieved. Therefore, it can be concluded that if output couplers with suitable reflectivities for the laser transitions in Fig. 1b are chosen, the Nd:GYSGG laser can operate at dual-wavelength even multi-wavelength mode at the 1.3 μm band.

2. Experimental setup

The experimental setup is shown in Fig. 2. A simple plano-plane cavity is used with the cavity length of 20 mm. A fiber coupled diode laser with the central wavelength of 808 nm at room temperature and the maximum output power of 30 W is used as the pump source. The fiber numerical aperture is 0.22 and its core diameter is 400 μm. The pump wave is focused into the Nd:GYSGG crystal by the coupling system at a spot radius of about 160 μm. The Nd:GYSGG crystal is 1.1 at.% doped, grown by the Czochralski method and cut along the $\langle 111 \rangle$ direction into small pieces of 3×3×6 mm^3, with its both end faces polished and anti-reflection (AR) coated at 808 nm and 1.3 – 1.4 μm for diode-end-pumping. The laser crystal is wrapped by indium foil, fixed by copper block, and cooled by water at 14°C. The rear mirror M_1 is high-reflection (HR) coated at 1.3 – 1.4 μm (R > 99%) and the output coupler is partly transmission (PT) coated at 1.3 – 1.4 μm. In order to suppress the laser oscillation from transitions $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and $^4F_{3/2} \rightarrow {}^4I_{9/2}$, M_1 mirror also has AR coatings around 0.94 and 1.06 μm.

3. Experimental results and discussions

Two output couplers are used in the experiment. The first one (OC1) has a transmittance of 10% at 1321 nm and 8.4% at 1336 nm, and the second one (OC2) has a transmittance of 5.2% at 1321 nm and 6% at 1336 nm. The output characteristics for both output couplers are shown in Fig. 3. While using OC1 as the output coupler, the 1336 nm laser line begins to oscillate when the incident pump power is 1.8 W. With the increase of pump power, the output power almost linearly increases. However, the output spectrum keeps simplex at 1336 nm, as shown in Fig. 4a. The output power of 1.98 W is obtained when the incident pump power is 13.5 W with the conversion efficiency of 14.7% and the slope efficiency of 17.4%. Considering the absorption efficiency of the Nd:GYSGG crystal is about 85%, the conversion efficiency from the absorbed pump power to output laser should be above 17%. Replacing OC1 with OC2, the oscillating threshold reduces to 0.7 W, and three wavelengths at 1321, 1330, and 1336 nm are generated simultaneously. The output spectra with the related incident pump power of around 1.0, 3.0, 5.7, 8.2, and > 10 W are shown in Fig. 4b – Fig. 4f. The output power is 1.74 W when the incident pump power is 13.5 W.

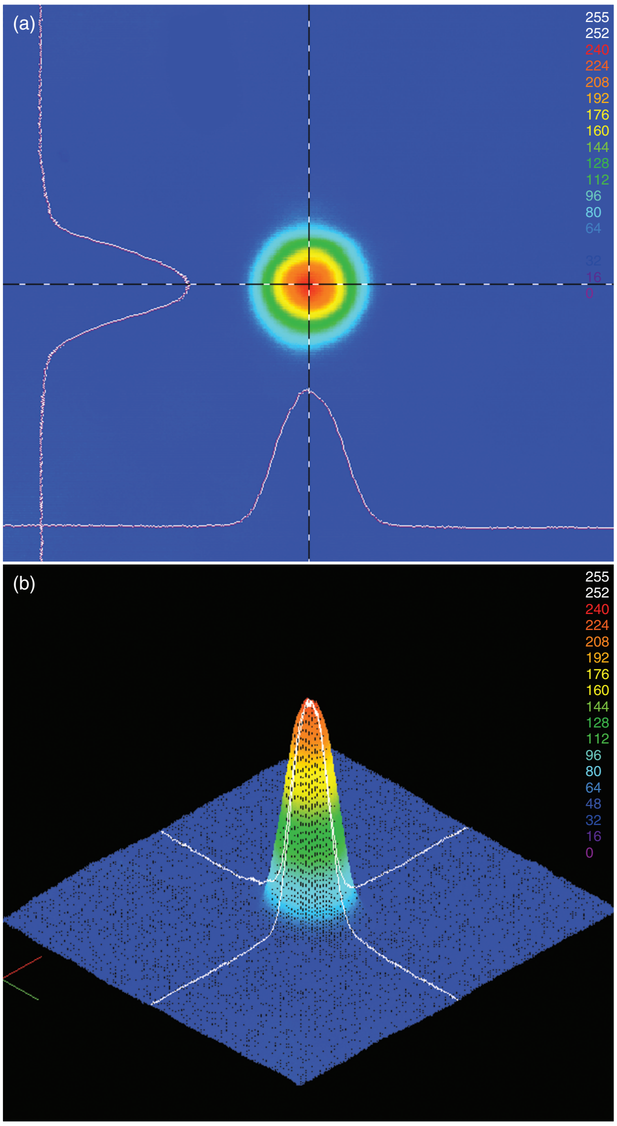

Figure 5 (online color at www.lasphys.com) Beam profile of the 1.3 μm Nd:GYSGG laser

From Fig. 4 we can see a multi-wavelength laser is achieved in which two laser lines at 1321 and 1336 nm can operate stably with comparable output power when the pump intensity is relatively high. For an optimized dual-wavelength laser cavity, the reflectivity relation for both lasing wavelength can be expressed as following [15]

$$\ln\left(\frac{1}{R_2}\right) = \left[\frac{\eta_{Q,2}\sigma_2 \iiint s_2(r,z) r_p(r,z) dv}{\eta_{Q,1}\sigma_1 \iiint s_1(r,z) r_p(r,z) dv}\right]\left[\ln\left(\frac{1}{R_1}\right) + L_1\right] - L_2 \,, \tag{1}$$

where L_i is the round trip cavity excess loss at corresponding transition wavelength, $\eta_{Q,i}$ is the corresponding quantum efficiency, $s_i(r,z)$ is the corresponding normalized

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cavity mode intensity distribution, $r_p(r,z)$ is the normalized pump intensity distribution in the active medium, and R_i is the corresponding reflectivity of the output coupler. It is supposed that the reflectivity of the rear mirror for both wavelengths is 100%. Since the difference between the two lasing wavelength in our experiment is small, we can further assume that $\eta_{Q,i}$, $s_i(r,z)$, and $r_p(r,z)$ can be neglected. Then Eq. (1) is simplified as

$$\ln\left(\frac{1}{R_2}\right) = \frac{\sigma_2}{\sigma_1}\left[\ln\left(\frac{1}{R_1}\right) + L\right] - L\,. \qquad (2)$$

In Eq. (2), the subscript 1 represents the parameters of 1321 nm laser line, and subscript 2 represents that of 1336 nm. For OC2, $R_1 = 94.8\%$ and $R_2 = 94\%$. Since the threshold of 1321 and 1336 nm is almost the same and the internal loss $L = 2.5\%$ is obtained using the Findlay-Clay method [16], the above parameters can be substituted into Eq. (2) and the solution is that the stimulated emission cross section of 1336 nm is about 1.11 times of that of 1321 nm.

Although gain competing exists between the two laser transitions, the stability of the output power is quite good with the root mean square (rms) fluctuation of less than 0.8% in an hour when the output power is about 1.8 W. Besides, we can get a very good beam quality. Fig. 5 shows the transverse beam profile when the output powers of two wavelengths at 1321 and 1336 nm are comparable (the output power is 1.2 W in total) both in two-dimensional and three-dimensional mode with the M^2 factor less than 1.2.

4. Conclusions

In conclusion, we have reported the output characteristics of a Nd:GYSGG laser in the wavelength band of 1.3 μm based on the energy level transition of ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$, for the first time to our knowledge. Using a plane-parallel cavity, single-wavelength operation at 1336 nm, and dual-wavelength operation at 1321/1336 nm with a minor wavelength at 1330 nm can be obtained with variable power proportions according to the pump intensity. The output power of 1.98 W at 1336 nm is achieved with the pump power of 13.5 W, corresponding to the conversion efficiency of 14.7%. The stimulated emission cross section of the 1336 nm laser line is measured to be 1.11 times of that of the 1321 nm laser line.

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