Tunable continuous-wave laser at quasi-three-level with a disordered Nd:LGS crystal

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A diode-pumped tunable CW Nd^{3+}:LGS laser at quasi-three-level has been demonstrated. The output power up to 403 mW at the central wavelength of 904 nm was obtained, corresponding to a slope efficiency of 29.7%. Taking advantage of the broad emission spectrum of the disordered crystal Nd:LGS, we tuned the laser wavelength within the spectral range of 899.8 to 906.6 nm with an etalon inserted into the V-type cavity. To the best of our knowledge, it is the first time to obtain a tunable laser based on the $^4F_{3/2}$-$^4I_{9/2}$ transition of Nd^{3+}-doped crystals.

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Disordered crystals doped with Nd^{3+} ions attract more and more interest in recent years, for they possess the advantages of Nd^{3+}-doped glass with respect to its spectral characteristics and ordered crystals with respect to its thermal properties [1,2]. Trigonal disordered multifunctional crystal $La_3Ga_5SiO_{14}$ (LGS) doped with Nd^{3+} is a representative crystal. The Nd:LGS exhibits ordered phases with separate tetrahedral Ga^{3+} cations and disordered phases where Ga^{3+} and Si^{4+} cations are randomly distributed over the same cationic sublattice. This structural disorder generates large inhomogeneous broadening in its spectrum [3,4]. Recently, the laser operation of disordered Nd:LGS around 1.06 μm has been studied [4–6], which demonstrated that LGS is an excellent laser host for Nd^{3+} ions. However, so far, a quasi-three-level Nd:LGS laser has not been reported. Laser running at quasi-three-level and its second harmonic generation in the blue region have significant applications. Generally speaking, the tuning range is very narrow when Nd^{3+}-doped crystals operated at quasi-three-level transition [7–10] as a result of narrow emission spectrum. Fortunately, disordered Nd^{3+}-doped crystals have much wider emission spectrum [4,11–15]; for instance, Nd:CNGG has an emission spectrum of 10 nm (FWHM) at 0.93 μm [13]. Taking advantage of the wide spectrum characters of Nd:LGS, in this Letter we realized a diode-pumped tunable CW laser around 900 nm based on the $^4F_{3/2}$-$^4I_{9/2}$ transition in this crystal. Pumping the crystal with an absorbed power of 2.5 W, we obtained 403 mW maximum output power at the central wavelength of 904 nm, corresponding to a slope efficiency of 29.7%. Further, we realized the laser tuning from 899.8 to 906.6 nm with an etalon. To the best of our knowledge, this is the first time to achieve tunable quasi-three-level laser in the Nd^{3+}-doped crystals.

The Nd:LGS single crystal employed in the experiment was grown by the Czochralski method, and cut along its optical *Z* axis. The disordered structure of Nd:LGS not only leads to a broad fluorescence and absorption spectrum, but also broadens the stimulated emission spectrum [4,11]. Figure 1 presents the spectrum of absorption and emission from $^4F_{3/2}$ to $^4I_{9/2}$ (under the excitation of 808 nm) measured at room temperature. It shows that Nd:LGS has a broad emission spectrum with a 16 nm bandwidth at the peak of 904 nm. However, for a quasi-three-level system, the lower laser level is strongly thermally populated, which induces strong reabsorption and a high laser threshold. Hence, in order to reduce the reabsorption losses, different from the laser operation at 1.06 μm in Nd:LGS crystal (1 at.%) by Yu *et al.* [4], we chose a lower dopant concentration (0.15 at.%) crystal for experiments.

The experimental setup for CW operation is shown in Fig. 2(a). A simple plano-concave cavity was employed. The pump source is a commercial fiber-coupled diode laser (LIMO GmbH, Germany) with a core diameter of 200 μm and a numerical aperture of 0.22. It emits radiation with a wavelength of 809 nm at 29 °C. The spot of the diode laser was focused into the crystal using a refocus module with a magnification of 1. The input mirror M1 was antireflection coated at 808 nm on the both faces and high-reflection coated from 890 to 920 nm. The Nd:LGS single crystal employed in the experiment has

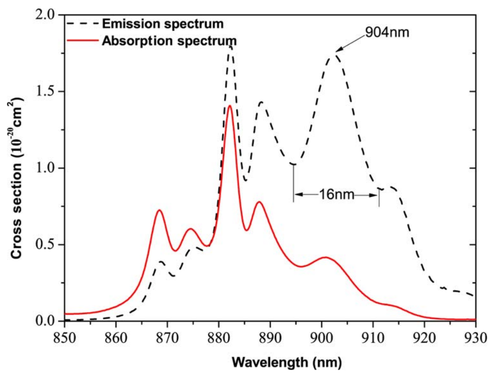

Fig. 1. (Color online) Spectrum of Nd:LGS, centered on the $^4F_{3/2}$-$^4I_{9/2}$ transition.

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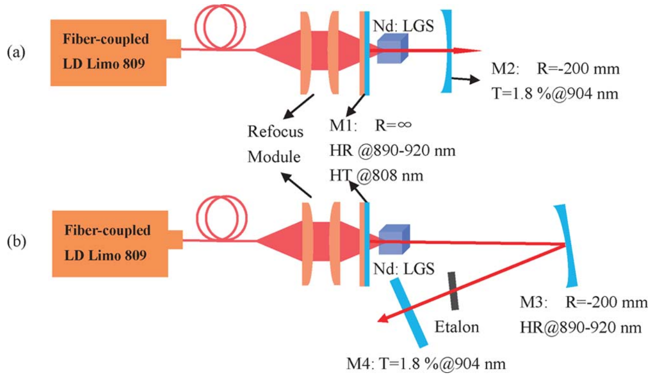

Fig. 2. (Color online) Schematic diagram of the experimental setup: (a) single-wavelength and (b) tunable-wavelength laser. The distances of M1–M2, M1–M3, and M3–M4 were 22, 106, and 100 mm, respectively. LD, laser diode; HR, high reflection; HT, high transmission.

dimensions of $3\,\mathrm{mm} \times 3\,\mathrm{mm} \times 4\,\mathrm{mm}$ $(X \times Y \times Z)$ and Nd^{3+} doping concentration of 0.15 at.%. Both facets of the crystal had been polished and antireflection coated at 808 nm ($R \approx 1\%$), from 880 to 920 nm ($R \approx 0.2\%$), and around 1060 nm ($R \approx 2\%$). The crystal was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink, and the water temperature was maintained at 7 °C during the experiment. The output coupler M2 had a transmission of 1.8% at 904 nm with a curvature radius of 200 mm.

The whole cavity length was 22 mm. The laser output power was measured by a power meter (PM30, Coherent, Inc.). Figure 3 presents the output power of the Nd:LGS laser versus the incident absorbed pump power. The slope efficiency was measured to be 29.7%. The inset of Fig. 3 is the spectrum of the output laser measured by a optical spectrum analyzer with a resolution of 0.05 nm (AQ6315A, Ando, Inc.), from which we can find that the FWHM value is over 1 nm at the central wavelength of 904 nm. Under the 2.5 W absorbed pump power, we obtained the maximum output power of 403 mW, corresponding optical-to-optical efficiency of 16.1%. Under the maximum output power, the beam quality factor M^2 was measured by a laser beam propagation analyzer (M^2-200s-FW, Ophir-Spiricon, Inc.). A typical CCD photograph of the transverse mode at its waist is shown in Fig. 4. Figure 5 shows the measurements of beam radius

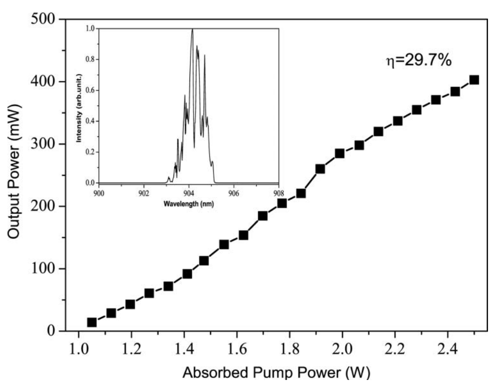

Fig. 3. Output power versus the absorbed pump power. The inset is the laser emission spectrum.

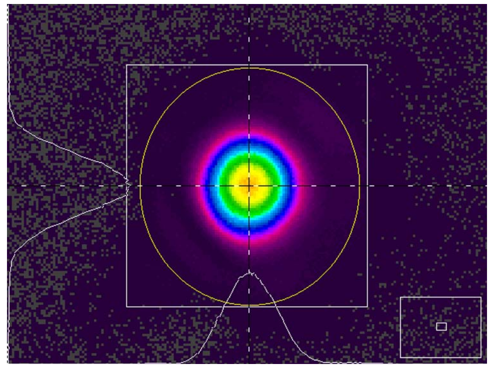

Fig. 4. (Color online) Typical CCD photo of the transverse mode corresponding to an output power of 403 mW.

versus position of the CCD, which corresponds to a beam quality factor M^2 of 1.21 and 1.22 for tangential direction and sagittal direction, respectively.

In the CW experiment, we observed the self-frequency tuning from 902.7 to 905.0 nm when the crystal was rotated in its own plane, which is perpendicular to its z axis. A similar phenomenon was also obtained at 1.06 μm by Aramburu *et al.* [5]. The tuning range was not very wide, so we decided to perform the wavelength tuning using a Fabry–Perot etalon. The experimental setup for tunable laser is shown in Fig. 2(b). A 100 μm etalon was inserted into the V-type cavity for the wavelength tuning. As shown in the Fig. 6, under the 2.5 W absorbed pump power, the central wavelength was tuned from 899.8 to 906.6 nm by delicately adjusting the inclined angle of the etalon with respect to the propagation direction of the laser beam. The FWHM of the tunable emission spectrum is less than 0.2 nm for the effect of the Fabry–Perot etalon.

In conclusion, we demonstrated a simple and compact diode-pumped tunable CW laser with the disordered crystal Nd:LGS as a gain medium based on the ${}^4F_{3/2}$-${}^4I_{9/2}$ transition. Up to 403 mW maximum output was obtained with an absorbed power of 2.5 W, corresponding to the slope and optical to optical efficiencies of 29.7% and 16.1%. With a 100 μm etalon inserted into the V-type

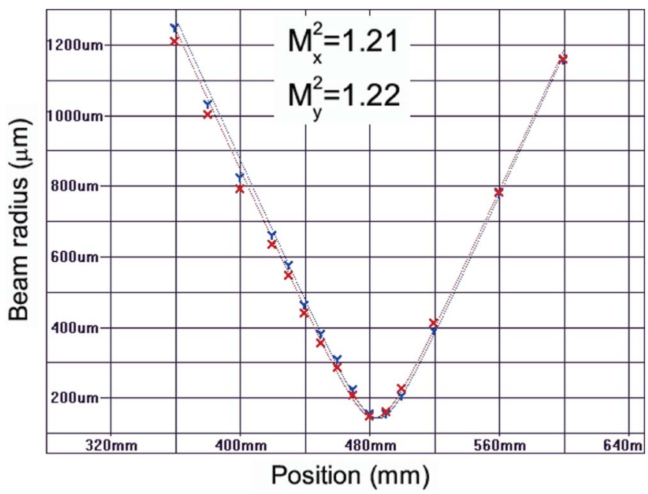

Fig. 5. (Color online) Measured beam quality factor (M^2) of Nd:LGS laser by the laser beam propagation analyzer M^2-200s-FW.

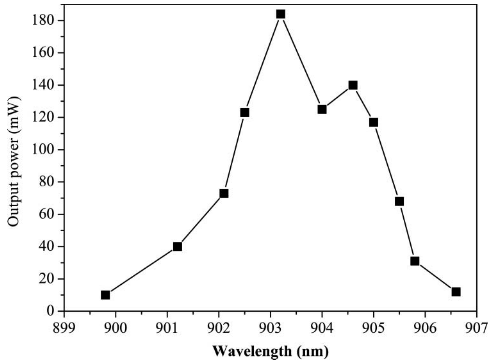

Fig. 6. Nd:LGS laser output power as a function of the laser wavelength at 2.5 W absorbed pump power.

cavity, we tuned the laser wavelength from 899.8 to 906.6 nm. We believe that, if we could choose a proper length of the crystal and dopant concentration, improve the coating of the mirrors, and raise the pump power density, we may get better results, and it will be our future works.

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