Efficient Pumping Scheme by Direct Excitation of Upper Laser Level in Nd:CNGG [*]

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We report an efficient pumping scheme which involves a direct excitation of the upper lasing level of a four-level laser in a Nd-doped $Ca_3(NbGa)_{2-x}Ga_3O_{12}$ (Nd:CNGG) by using a tunable Ti:sapphire, 700–920 nm, cw pump source. The slope efficiency is improved from 10.5% of the traditional band pumping at 808 nm to 21.8% of the direct pumping at 882 nm. The influence of pumping wavelength on lasing is discussed. We present a scheme of double pumping for lasing.

Energy difference between the pumping and lasing photons, the non-unity coupling between the pump band and the upper lasing level and some parasitic effects such as concentration quenching, upconversion and dark sites [1,2] always generate heat in the gain material in the excitation and lasing process in solid-state lasers. Heat generation can affect laser beam quality and thermal stability of the laser cavity. In addition, it limits the average emission power and the slope efficiency. The heat generated during the pumping process, therefore, is a severe limitation to construct high efficiency and high power solid-state lasers. To deal with the thermally induced effects, the direct pumping from the ground state and the thermally excited ground levels to lasing levels, which can reduce the Stokes factor losses between the pump and emission energy quanta and eliminates the loss induced by the nonunity quantum efficiency, has been demonstrated.[3−6] Recently, the efficiency benefits of direct pumping with Nd-doped materials over the traditional 808 nm pump band excitation have been reported.[4−11]

The Nd:CNGG crystal is a typical disordered laser material due to the random distribution of the niobium and gallium ions and of vacancies at octahedral and tetrahedral lattice sites. The crystal has a low melting point of $1460°C$,[12,13] therefore it can be grown in a platinum crucible by the Czochralski method.[14] In addition, most important merit of Nd:CNGG is the relatively broader absorption band[14] and large emission bandwidth originating from the disordered nature of crystal, and then it is a candidate for generating ultra-short pulses and for tunable mode-locked laser.[15] Aside from these merits, the thermal conductivity $(0.047 W/cm°C)$ of

Nd:CNGG is much lower than that of the Nd:YAG crystal $(0.13 W/cm°C)$, resulting in the unfavourable thermal stability of the cavity. This problem can be solved partially by the direct pumping scheme, thus the higher optical-to-optical efficiency and higher power of lasing in the Nd:CNGG crystal can be obtained.
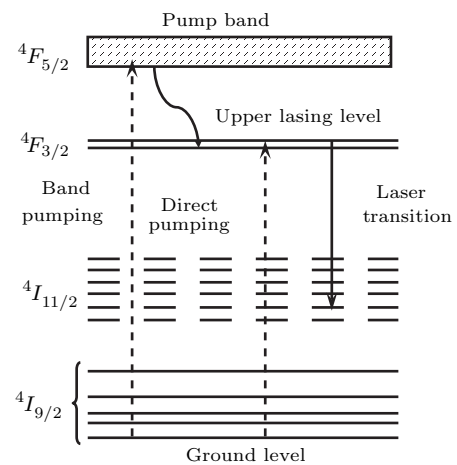

Fig. 1. Transition involved in the traditional band pumping and the direct pumping together with emission at 1061 nm Nd:CNGG laser.

In this Letter we report, for the first time to our best knowledge, the laser emission in Nd:CNGG at the 1061 nm $^4F_{3/2}$ to $^4I_{11/2}$ transition under direct pumping into the $^4F_{3/2}$ upper level. The schematic of the traditional 808 nm band pumping together with the direct pumping to upper lasing level of the Nd^{3+} ion is shown in Fig. 1. We can not obtain the efficient lasing at 1061 nm by direct pumping with a Ti:sapphire laser in a single end-pumping configura-

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tion, mainly due to the lower pump power, the lower concentration of Nd^{3+} ions and the higher threshold for Nd:CNGG crystal. We take the double pumping scheme with a tunable Ti:sapphire, 700–920 nm, cw laser and a diode, 808 nm cw laser. We show experimentally the efficiency benefits from the direct pumping over the traditional band pumping by comparing the performance of the laser pumped directly to the upper lasing level (860–900 nm) with diode pumping at 808 nm. The slope efficiency increases from 10.5% pumping by the traditional diode at 808 nm to 21.8% by the direct pumping at 882 nm. In our experiment, we prove the feasibility of direct pumping and this is the base for our further works.
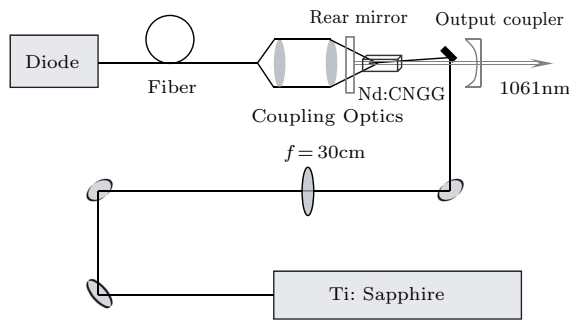

Fig. 2. Schematic diagram of the experimental setup.
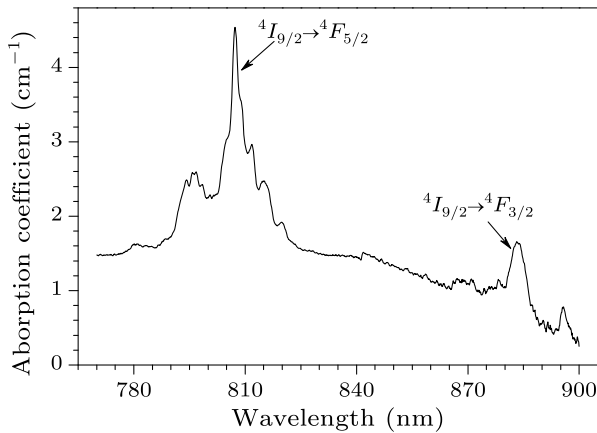

Fig. 3. Absorption spectrum of Nd:CNGG (doping of 0.5 at.%) at room temperature, which describes the excitation of the band pumping and the direct pumping.

The Nd:CNGG crystal in thickness 6 mm and with concentration of 0.5 at.% for Nd^{3+} ion used in our experiments was grown by the Czochralski method. Both crystal surfaces were high transmission (HT) coated for the pumping wavelength of 860–900 nm. In order to remove the heat generated in the gain medium, the Nd:CNGG crystal was wrapped with indium foil and mounted in a water cooled copper heat sink. The temperature of water was maintained at 7°C during the experiments.

The schematic of the experimental setup is shown in Fig. 2. The fibre-coupled high-power cw diode laser emits light at 808 nm with FWHM spectrum width of 2.5 nm. The diameter of the fibre core was 200 μm with the numerical aperture of 0.22. The 808 nm pump beam was collimated and focused into the Nd:CNGG crystal with a diameter of 200 μm by two coupling lenses, which gave a coupling efficiency of 90%. We tested the direct pumping of Nd:CNGG by using a tunable (700–920 nm), narrow-linewidth cw Ti:sapphire laser and the maximum power was about 1 W. The Ti:sapphire laser beam was focused into the crystal with a 30 cm focal length lens, yielding a spot size of 200–250 μm diameter, therefore, the overlap efficiency between the laser beam and the pumped volumes are approximately the same for the pumping with diode laser and Ti:sapphire laser. The absorption spectrum of Nd:CNGG at room temperature is shown in Fig. 3, which was measured by a spectrometer with a resolution of 0.1 nm (the limit of 0.05 nm). In order to reduce the influence of the crystal thermal effect on the stability of the lasing and couple the Ti:sapphire laser beam into the linear cavity that is similar to that of 808 nm pumping, the length of the cavity was set to be 75 mm. The rear mirror was coated with HT at 808 nm ($T > 95\%$) and high reflection (HR) at 1061 nm ($R > 99.9\%$). The output coupler (OC) was a concave mirror with a curvature radius of 200 mm and a transmission of 6% at 1061 nm. The TEM_{00} laser mode diameter inside the crystal is 140–180 μm and the distance between the rear mirror and the crystal surface is about 7 mm. The output power of the laser was recorded by a laser power meter and the transverse mode of the output was recorded by a laser beam analyser (OPHIR).
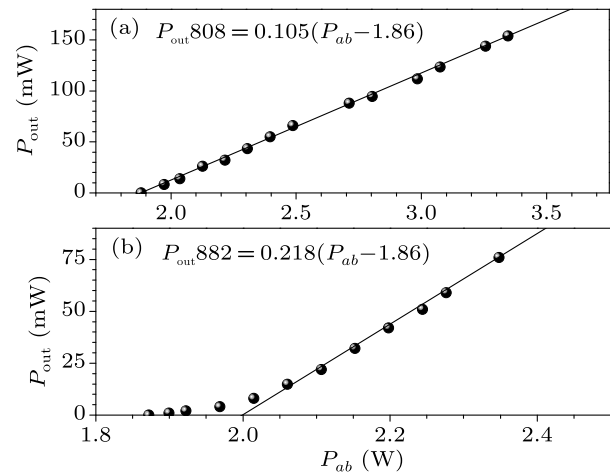

Fig. 4. Output power versus absorbed pump power for Nd:CNGG under 808 nm and 882 nm pumping for a 6% transmission output mirror in the double pumping scheme.

The output power versus absorbed power of the 882 nm Ti:sapphire laser together with the 808 nm diode laser in the double pumping scheme for the 0.5 at.% Nd:CNGG is presented in Fig. 4, where the absorbed power of the diode laser is 1.86 W (the

threshold for 808 nm pumping operating at 1061 nm) with holding constant. In order to show the efficiency benefits of the direct pumping, the result of the 808 nm diode pumping is also shown in this figure.
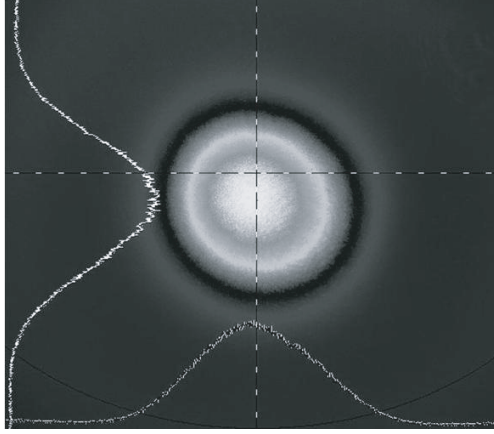

Fig. 5. Typical CCD photo of transverse mode corresponding to the output power of 74 mW with double pumping of 1.86 W 808 nm diode laser and 470 mW 882 nm Ti:sapphire cw laser.

An important property of an optically pumped laser is its slope efficiency, defined as the slope of the curve obtained by plotting the laser output versus the pump power. The slope efficiency of a four-level cw laser is given by[4]

$$P_{\text{out}} = \eta(P_{ab} - P_{th}),$$

where P_{out}, P_{ab} and P_{th} are output power, the absorbed power, and the absorbed power at threshold, respectively, and η is the slope efficiency. With the present setup the slope efficiency η and the threshold P_{th} for the traditional 808 nm pumping are 10.5% and 1.86 W, respectively. For the direct pumping in the double pumping scheme, the absorbed power is $P_{ab} = P_{th}^{808} + P'_{ab}$, where P_{th}^{808} is the threshold (1.86 W) for lasing at 1061 nm with 808 nm diode laser pumping and P'_{ab} is the absorbed power of the Ti:sapphire laser. The slop efficiency η increases to 21.8% for pumping at 882 nm. The far-field beam spatial profile of the 1061 nm laser was measured using a laser beam analyser (OPHIR) at a distance 20 cm behind the OC. The transverse distribution of the laser beam intensity was found to be Gaussian for all the output power range. Figure 5 shows the typical CCD photo of the transverse mode corresponding to the output power of 74 mW. This result indicates that the laser oscillates in the fundamental transverse mode.

In simple situations, the slope efficiency is essentially determined by the product of the pump absorption efficiency, the ratio of the laser and pump photo energies, the quantum efficiency of the gain medium, and the cavity loss including the output coupling efficiency. It can be elucidating to compare the slope efficiency with the wavelength of the pumping laser in order to judge the potential for further device improve-

ment. The disordered nature of the Nd:CNGG crystal provides significant inhomogeneous broadening in the absorption and emission spectra. We obtain the lasing at 1061 nm for different wavelength of the Ti:sapphire pumping from 860 to 900 nm in the double pumping scheme. The results, as shown in Fig. 6, are vertically shifted for clarity. The slope efficiency is improved under pumping at 878 nm (18.5%), 882 nm (21.8%) and 888 nm (10.7%) and the maximum output power (76 mW) and the slope efficiency are obtained at the 882 nm pumping.
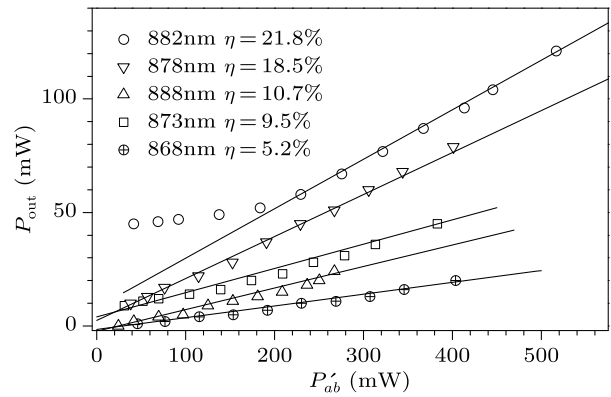

Fig. 6. Output power versus absorbed pump power for Nd:CNGG with different pump wavelengths of the cw Ti:sapphire laser in the double pumping scheme. All the data are vertically shifted for clarity. The slope efficiencies are shown in the figure.

In conclusion, under direct pumping the Nd^{3+} ions into the upper lasing level in a double pumping scheme with the tunable Ti:sapphire cw laser and the traditional diode laser, Nd:CNGG laser operating at 1061 nm is demonstrated. As is expected, the direct pumping scheme gives rise to a more efficient lasing, such as higher slope efficiency, more preferable transverse mode and excellent thermal stability. The influence of the pump wavelength on lasing is discussed. The slope efficiency is improved from 10.5% with traditional band pumping at 808 nm to 21.8% with direct pumping at 882 nm.

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