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Investigation on 1.3 μm laser performance with Nd:$Gd_{0.69}Y_{0.3}TaO_4$ and Nd:$Gd_{0.68}Y_{0.3}NbO_4$ mixed crystals

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Abstract: Laser performances around 1.3 μm are investigated in 879 nm laser diode (LD) end pumped Nd^{3+} doped mixed crystals with Nd:$Gd_{0.69}Y_{0.3}TaO_4$ and Nd:$Gd_{0.68}Y_{0.3}NbO_4$ crystals for the first time to our best knowledge. The maximum average power in LD end pumped Nd:$Gd_{0.69}Y_{0.3}TaO_4$ 1328 nm laser reaches 435 mW at 50 Hz with an optical-to-optical efficiency of 5.0% and a slope efficiency of 6.9%. In comparison, the highest average power of LD end pumped Nd:$Gd_{0.68}Y_{0.3}NbO_4$ laser at 1337 nm is 190 mW at 50 Hz, corresponding to an optical-to-optical efficiency of 3.5% and a slope efficiency of 4.2%.

OCIS codes: (140.3580) Lasers, solid-state; (140.3530) Lasers, neodymium; (140.3480) Laser, diode-pumped.

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1. Introduction

Laser sources at 1.3 µm are widely used in many fields including telecommunication systems, remote sensing, and fiber sensing [1–3]. By nonlinear conversion, lasers in visible and ultraviolet region can be produced and used in applications of laser display, optical cooling, and trapping of lithium [4–7]. Laser diode (LD) pumped neodymium doped laser via the $^4F_{3/2}\rightarrow{}^4I_{13/2}$ transition is an effective approach to generate lasers around 1.3 μm. In recent years, research on LD pumped Nd^{3+}-doped lasers at 1.3 μm has been conducted with different host materials [8–11].

Mixed laser crystals with structural disorder have specific characteristics of broad absorption and fluorescence spectrum and longer lifetime compared with single crystals. They are promising in ultrashort mode-locking lasers [12,13]. Owning to similar ionic radii, Y^{3+}, Gd^{3+} and Lu^{3+} ions are often used to generate mixed laser materials. Various Nd^{3+}-doped mixed crystals such as Nd:$LuGdVO_4$ [14], Nd:$GdYVO_4$ [15], Nd:$CaYAlO_4$ [16] and Nd:GYSGG [17] have been produced and investigated in continuous-wave (cw) and pulsed laser operation. Recently, Nd^{3+}-doped orthotantalate and niobate have been proven to be promising laser materials by efficient 1.06 μm laser operation. In 2015, Peng presented a LD end pumped cw Nd:$GdTaO_4$ 1066 nm with an optical-to-optical efficiency of 34.6% and a slope efficiency of 36% [18]. In 2017, Ding showed a novel Nd:$GdNbO_4$ crystal grown by the Czochralski (Cz) method and got an efficient 1066 nm laser via the $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transition [19]. Nd:$Gd_{0.69}Y_{0.3}TaO_4$ (abbreviated as Nd:$GdYTaO_4$ or Nd:GYTO) and Nd:$Gd_{0.68}Y_{0.3}NbO_4$ (abbreviated as Nd:$GdYNbO_4$ or Nd:GYNO) obtained by the Cz method were also employed to generate lasers around 1.06 μm and performance enhancement was achieved compared with single crystals [20–22]. The large energy gap between pump and laser leads to low Stokes efficiency and high thermal loading in LD pumped Nd^{3+}-doped 1.3 μm laser. Direct pumping to the upper laser level of Nd^{3+} ion is an effective approach to reduce Stokes factor and increase laser efficiency [23,24]. Recently direct pumping has been widely used in Nd^{3+}-doped lasers with the development of laser diode around 880 nm [25–27]. Owning to broad absorption bandwidths around 880 nm, Nd:GYTO and Nd:GYNO crystals have advantages in reduction of the requirement of pumping light and efficiency enhancement under direct pumping [21,22]. It is meaningful to research on LD directly-pumped 1.3 μm laser performance with Nd:GYTO and Nd:GYNO crystals for their unique properties. In addition, new ultraviolet wavelengths could be obtained based on the $^4F_{3/2}\rightarrow{}^4I_{13/2}$ transitions of Nd:GYTO and Nd:GYNO by using high order frequency conversion [28].

In this paper, laser performances at 1.3 μm with novel Nd:GYTO and Nd:GYNO mixed crystals are studied for the first time to our best knowledge. The laser emission wavelength is measured to be 1328 nm in the LD pumped Nd:GYTO $^4F_{3/2}\rightarrow{}^4I_{13/2}$ laser while it is 1337 nm for Nd:GYNO crystal. The maximum average output power of 1328 nm laser is 435 mW at 50 Hz with an optical-to-optical efficiency of 5.0% and a slope efficiency of 6.9%. The beam quality factors of 1328 nm laser at 50 Hz are measured to be $M_x^2 = 1.5$ and $M_y^2 = 1.8$ by using the travelling knife-edge method. In comparison, an output pulse energy of 3.8 mJ is obtained at 50 Hz for Nd:GYNO 1337 nm laser, corresponding to an optical-to-optical efficiency of 3.5% and a slope efficiency of 4.2%. The beam quality factors of Nd:GYNO 1337 nm laser at 50 Hz are measured to be $M_x^2 = 2.2$ and $M_y^2 = 2.3$ in orthogonal directions.

2. Experimental setup

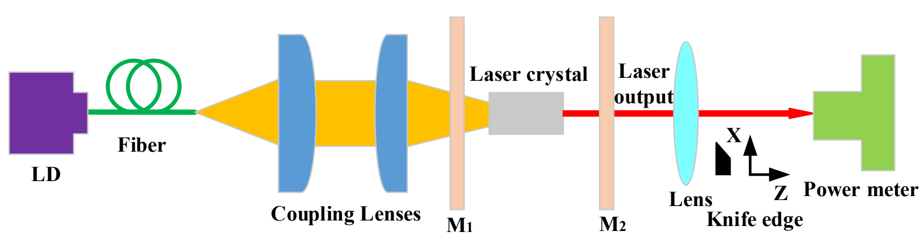

Fig. 1. Experimental setup of LD pumped 1.3 μm laser with Nd:GYTO and Nd:GYNO crystals.

Figure 1 shows an experimental setup of 879 nm LD end pumped 1.3 μm laser with mixed crystals. Pump source is a fiber-coupled 879 nm LD (Pear™ P16, *n*LIGHT Inc.) with a fiber diameter of 400 μm and a N.A. of 0.22. With the help of a volume Bragg grating (VBG), the output laser wavelength is stabilized at approximately 879.2 nm with a full width at half maximum (FWHM) of 0.6 nm. The LD works in quasi-continuous-wave operation with a pump duration of 1 ms to reduce influence of thermal effects on laser performance. A pair of aspherical lens with focal lengths of f_1 = 32.1 mm and f_2 = 22.4 mm are used to reimage the pump laser into the laser rod with a pump beam waist radius of ω_p = 140 μm. Tight pumping is preferable to achieve efficient 1.3 μm laser output as $^4F_{3/2}\rightarrow{}^4I_{13/2}$ transition is a four-level laser system with a smaller emission cross section [29]. The laser crystal is wrapped with 0.05 mm indium foil, placed in a micro-channel heat sink and kept at 18 °C by water-cooling. The dimension of Nd:GYTO is 2x2x5 mm^3 and it is 2x2x4 mm^3 for Nd:GYNO. Both end facets of laser rods are coated with high transmissivity (HT) at 879 nm, 1066 nm, 1328 nm and 1337 nm (T>99%). A linear cavity with a geometrical length of 30 mm is utilized. The plane mirror M_1 is HT coated at 879 nm (T>95%) and high-reflectivity coated at 1328 nm and 1337 nm. The output mirror M_2 is coated with partial transmission at 1328 nm and 1337 nm. The reflectivities of output mirror M_2 are R = 97.0% and T = 96.0% at 1328 nm while they are T = 96.4% and T = 95.2% for Nd:GYNO 1337 nm laser. Both the mirrors M_1 and M_2 are HT coated (T>90%) at 1.06 μm to suppress oscillation of the high gain $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transition. A convex lens is used to measure the beam radius variation and calculates the beam quality factors for 1.3 μm lasers by the travelling knife-edge method [30].

Nd:GYTO and Nd:GYNO mixed crystals are both grown by using the Cz method. The raw materials of Nd_2O_3, Gd_2O_3, Y_2O_3 and Ta_2O_5 compounds are weighted according to the chemical formula $Nd_{0.01}Gd_{0.69}Y_{0.3}TaO_4$. Similarly, the raw materials of Gd_2O_3, Y_2O_3, Nb_2O_5, and Nd_2O_3 compounds are weighted according to the chemical formula $Nd_{0.02}Gd_{0.68}Y_{0.3}NbO_4$. Nd:GYTO and Nd:GYNO are both monoclinic crystals similar as the single crystals (Nd:$GdTaO_4$ and Nd:$GdNbO_4$) [31, 32]. The crystals are *a*-axis oriented and cut perpendicular to crystallographic axes due to the issue of processing difficulty. Because the thermal expansion coefficient along *a*-axis is smaller than those along *b*-axis and *c*-axis for these two crystals, *a*-cut laser rods are chosen to reduce the thermal lensing effect. Table 1 gives a comparison of characteristics of Nd:GYTO and Nd:GYNO crystals. The doping concentration of Nd:GYTO is measured to be 1.67 × 10^{20} cm^{-3} by using the X-ray fluorescence (XRF) analysis, which is higher than 6.1 × 10^{19} cm^{-3} of Nd:GYNO crystal. The peak absorption cross section of Nd:GYTO is approximate 1.3 × 10^{-20} cm^2 around 879 nm while it is ~1.5 × 10^{-20} cm^2 for Nd:GYNO crystal. The absorption bandwidths for these two crystals at 879 nm are broader than 1 nm, so there is good overlap between LD emission and crystal absorption spectrum. According to the Füchtbauer-Ladenburg method [33], the maximum emission cross sections around 1.3 μm are calculated to be 4.1 × 10^{-20} cm^2 and 4.8 × 10^{-20} cm^2 for Nd:GYTO and Nd:GYNO crystals [20,21].

Table 1. Comparison of characteristics of Nd:GYTO and Nd:GYNO

Crystals	Concentration (cm^{-3})	σ_a(cm^2)@ 879nm	Fluorescence lifetime(μs)	Emission peak wavelength(nm) @1.3μm	σ_e(cm^2) @1.3μm	k(W/mK)
Nd:GYTO	1.67 × 10^{20}	1.3 × 10^{-20}	182	1328	4.1 × 10^{-20}	3.5-5.2
Nd:GYNO	6.1 × 10^{19}	1.5 × 10^{-20}	156	1337	4.8 × 10^{-20}	———

3. Experimental results and discussions

The laser performance at 1.3 μm with Nd:GYTO under 879 nm LD pumping with different output mirrors is studied at a pump repetition rate of 10 Hz and a pump duration of 1 ms. With an output mirror of R = 97.0%, the maximum output energy at 1.3 μm reaches 9.8 mJ

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with a slope efficiency of 5.7% at the incident pump energy of ~175.1 mJ. In comparison, an output energy of 14.6 mJ at 10 Hz is obtained with an output mirror of R = 96.0%, corresponding to an optical-to-optical efficiency of 8.3% and a slope efficiency of 8.8%. Figure 2 presents the laser emission spectrum of Nd:GYTO crystal via the $^4F_{3/2}\rightarrow^4I_{13/2}$ transition ranging from 1300 nm to 1450 nm recorded by using a laser spectrum analyzer (Model 721, Bristol Instruments Inc.). The laser emission wavelength via the $^4F_{3/2}\rightarrow^4I_{13/2}$ transition is approximate 1328 nm for Nd:GYTO crystal. No 1066 nm emission is observed when a fiber-coupled spectrometer (HR4000, Ocean Optics Inc.) is used with a spectrum range of 200-1100 nm.

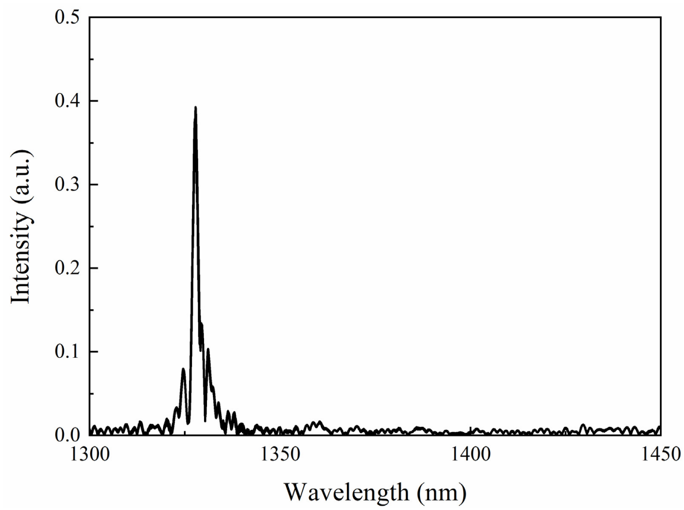

Fig. 2. Emission spectrum of LD pumped Nd:GYTO 1328 nm laser.

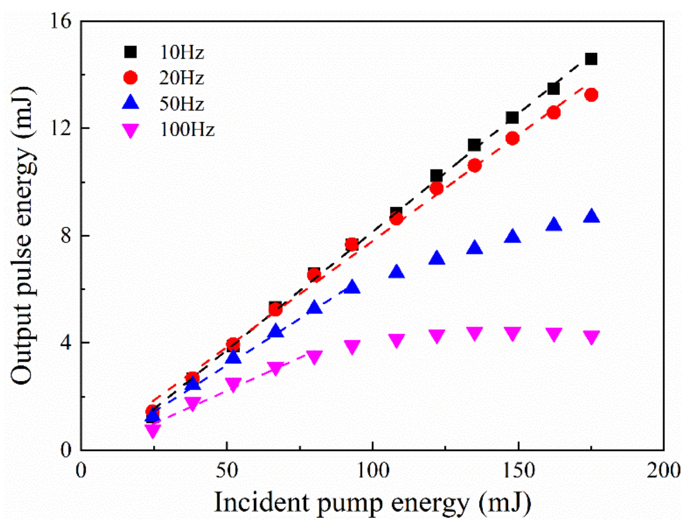

Fig. 3. Dependence of output energies on incident pump energy in LD pumped Nd:GYTO 1328 nm laser at different repetition rates.

Output characteristic of LD pumped Nd:GYTO 1328 nm laser at different pump repetition rates is investigated with an output mirror of R = 96.0%, as shown in Fig. 3. It can be seen that the pulse energy of 1328 nm laser increases linearly with the incident pump energy at 10 Hz and 20 Hz. At repetition rates of 50 Hz and 100 Hz, saturation of output energy occurs when the pump energy is higher than 100 mJ. The duty cycle of pumping source is 1% at 10

Hz and increases to 10% at 100 Hz. At 100 Hz, output energy decreases at high pump energy because of the increased thermal lensing effect of the mixed crystal with the lower specific heats and thermal conductivity. The maximum average power at 1328 nm laser reaches 435 mW at 50 Hz with an optical-to-optical efficiency of 5.0% and a slope efficiency of 6.9%. The beam quality factors of 1328 nm laser at 50 Hz under 879 nm LD pumping are measured by the travelling knife-edge method. Figure 4 presents the beam radius variation of 1328 nm laser at an output average power of 435 mW. The beam quality factors are calculated to be $M_x^2 = 1.5$ and $M_y^2 = 1.8$ by fitting these data to Gaussian beam propagation expression. The asymmetry of beam quality factors in two directions is caused by the anisotropy of thermal conductivity ($k_a = 4.4$ W/mk, $k_b = 3.5$ W/mk, $k_c = 5.2$ W/mk) of Nd:GYTO mixed crystal.

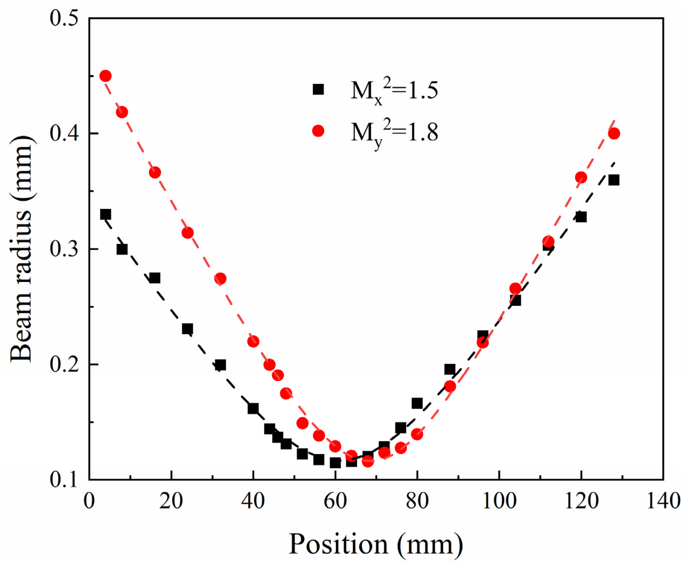

Fig. 4. Beam radius variation of 1328 nm laser at the maximum average output power of 435mW.

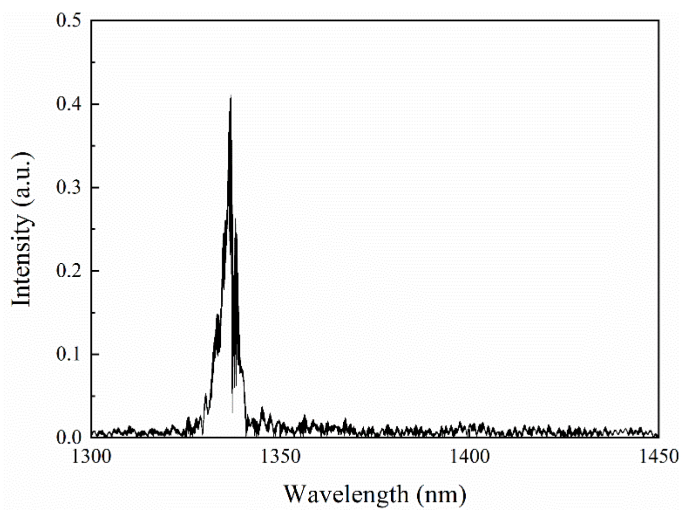

Fig. 5. Emission spectrum of LD pumped Nd:GYNO laser via the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition.

In our work, 1.3 μm laser performance with the Nd:GYNO crystal is also studied utilizing the same pumping parameters as Nd:GYTO 1328 nm laser. The reflectivity of output mirror is R = 95.2% at 1337 nm. The emission spectrum of Nd:GYNO crystal between 1300 nm and 1450 nm is recorded in Fig. 5 and the emission peak wavelength is approximate 1337 nm, corresponding to the transition R1($^4F_{3/2}$)→X3($^4I_{13/2}$). Output performance of LD pumped Nd:GYNO 1337 nm laser at different repetition rates is given in Fig. 6. The output energy of Nd:GYNO laser shows linear dependence on pump energy at 10 Hz and 20 Hz when the pump energy is less than ~138 mJ. When the incident energy is higher than ~140 mJ, the increase of the pump energy greatly hampers the output energy because of the poor thermal conductivity of Nd:GYNO crystal. The highest output energies of 1337 nm laser are 6.8 mJ and 6.2 mJ at 10 Hz and 20 Hz. The output energy at 50 Hz reaches 3.8 mJ at the pump energy of ~108.2 mJ, corresponding to an optical-to-optical efficiency of 3.5% and a slope efficiency of 4.2%. It could be found that Nd:GYNO 1337 nm laser suffers a more serious thermal effects compared with Nd:GYTO at the same pump power. The beam quality factors are measured to be M_x^2 = 2.2 and M_y^2 = 2.3 in orthogonal directions for Nd:GYNO 1337 nm laser at 50 Hz.

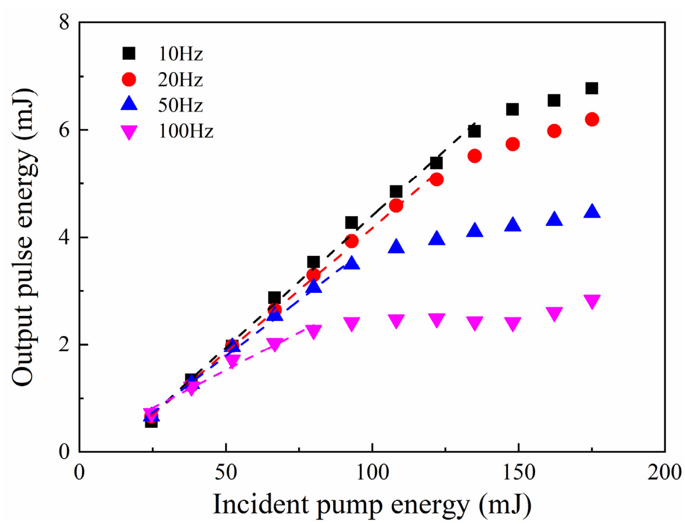

Fig. 6. Output energies of 879 nm LD pumped Nd:GYNO 1337 nm laser versus incident pump energy at different repetition rates.

Table 2. Comparison of 1.3 µm laser performances with Nd:GYTO and Nd:GYNO crystals

Crystals	Laser wavelength(nm)	Maximum average power (mW)	Slope efficiency	Optical-to-optical efficiency	Beam quality factors
Nd:GYTO	1328	435(50Hz)	6.9%	5.0%	M_x^2 = 1.5M_y^2 = 1.8
Nd:GYNO	1337	190(50Hz)	4.2%	3.5%	M_x^2 = 2.2M_y^2 = 2.3

The comparison of output laser performance between Nd:GYTO 1328 nm laser and Nd:GYNO 1337 nm laser is given in Table 2. Nd:GYTO crystal has a superior output performance at 1328 nm compared with Nd:GYNO crystal, which is attributed to the long fluorescence lifetime of 182 µs and big absorption coefficient around 879 nm. However, it is hard to achieve cw laser operation at 1.3 µm with both crystals which is related to the quality of available crystals. By using Findlay-Clay method [34], the internal losses of Nd:GYTO is measured to be 0.083cm^{-1} and it is 0.038cm^{-1} for Nd:GYNO crystal, which are both higher than 0.002 cm^{-1} for Nd:YAG. According to theory, the slope efficiency of laser output could be given as following [35]:

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$$\eta_s = \frac{2(1-R)}{(1+R)(\delta - \ln(R))}\eta_u \eta_p \tag{1}$$

where R is the reflectivity of output mirror, δ is the intrinsic losses, induced by the absorption, diffraction or the non-homogeneous of the laser material, η_u is the upper state efficiency and η_p is overall pumping efficiency. From Eq. (1), high scattering losses has fatal influence on laser efficiency. If the internal losses was reduced to 0.002 cm^{-1}, the efficiencies of Nd:GYTO 1328 nm laser and Nd:GYNO 1337 nm laser would be risen by 2.9 and 1.7 times. Further power scaling of LD pumped 1.3 μm lasers based on the $^4F_{3/2}\rightarrow{}^4I_{13/2}$ transition with Nd:GYTO and Nd:GYNO crystals would be expected by improving the quality of crystal.

4. Conclusion

In conclusion, we have investigated on 879 nm LD end-pumped 1.3 μm lasers with Nd:GYTO and Nd:GYNO mixed crystals for the first time to our best knowledge. The laser emission wavelength is measured to be 1328 nm and 1337 nm for Nd:GYTO and Nd:GYNO mixed crystals, respectively. The maximum average power of Nd:GYNO laser at 50 Hz reaches 190 mW at an incident energy of ~108.2 mJ, corresponding to an optical-to-optical efficiency of 3.5% and a slope efficiency of 4.2%. In comparison, it has an better laser performance for Nd:GYTO crystal with a highest average output power of 435 mW at 50 Hz and an optical-to-optical efficiency of 5.0%. Using the travelling knife-edge method, the beam quality factors of LD pumped Nd:GYTO 1328 nm laser at 50 Hz are measured to be $M_x^2 = 1.5$ and $M_y^2 = 1.8$ while they are $M_x^2 = 2.2$ and $M_y^2 = 2.3$ for Nd:GYNO 1337 nm laser. Investigation on thermal characteristics and improvement of crystal quality will be conducted to improve 1.3 μm laser performance with Nd:GYTO and Nd:GYNO crystals.

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