# LD pumped quasi-three-level 928 nm laser with $Nd:Gd_{0.69}Y_{0.3}TaO_4$ mixed crystal

Wenming Yao[1], Renpeng Yan[2], Wentao Wu[2], Kang Li[3], Xin Yu[2], Yufei Ma[2], Fang Peng[4], Qingli Zhang[4], Renqin Dou[4], Nigel Copner[3] and Jing Gao[1,5*]

[1]*Jiangsu Key Laboratory of Medical Optics, Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences, Suzhou Jiangsu 215163, China*
[2]*National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150080, China*
[3]*Wireless and Optoelectronics Research and Innovation Centre (WORIC), Faculty of Computing, Engineering and Science, University of South Wales, Cardiff, CF37 1DL, United Kingdom*
[4]*The Key Laboratory of Photonic Devices and Materials, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031, China*
[5]*Tianjin Guoke Yigong Medical Technology Development Co., Ltd, Tianjin 300399, P. R. China*
**owengaojing@126.com*

**Abstract:** We report on a 928 nm laser based on quasi-three-level transition of $^4F_{3/2}\rightarrow^4I_{9/2}$ in a $Nd:Gd_{0.69}Y_{0.3}TaO_4$ mixed single crystal. With LD pumping at 808 nm, an output energy of 29.8 mJ at 928 nm is achieved with an optical-to-optical efficiency of 16.5% and a slope efficiency of 21.2%. In comparison, using 879 nm LD pumping, the maximum output energy at 928 nm reaches 48.5 mJ with an optical-to-optical efficiency of 33.4% and a slope efficiency of 38.0%.

**Key words:** LD pumped, Nd:GYTO, direct pumping.

## 1. Introduction

Quasi-three-level transition in $Nd^{3+}$-doped crystal provides an efficient way to generate lasers around 900 nm, which can be applied in differential absorption lidar (DIAL) for water vapor detection [1-3]. In addition, by frequency doubling blue lasers are produced to be used in under water detection and communication, laser display and bio-medical applications [4, 5]. All solid-state lasers have advantages of high-efficiency, compactness and robustness. In 1989, Fan and Byer presented the first solid-state Nd:YAG 946 nm laser via quasi-three-level $^4F_{3/2}\rightarrow$ $^4I_{9/2}$ transition[6]. In recent years, plenty of researches on laser diode (LD) pumped $Nd^{3+}$-doped quasi-three-level lasers and frequency doubled blue lasers have been conducted with different host materials in continuous-wave and pulsed operation [7-9].

Mixed laser materials with structural disorder are supposed to have broadened fluorescence spectra and longer lifetime, which is favorable in ultra-short laser generation. During the past years, various $Nd^{3+}$-doped mixed laser crystals have been developed and investigated such as $Nd:GdYVO_4$[10], $Nd:LuYVO_4$[11], $Nd:GaYAlO_4$[12], Nd:GYSGG[13], and Nd:LuYAG[14]. Orthotantalate ($LnTaO_4$) is an efficient laser material due to its large emission cross section and broad absorption spectrum [15]. In 2015, 1066 nm laser performance with a novel Nd: $Gd_{0.69}Y_{0.3}TaO_4$ (Nd:GYTO) mixed crystal pumping at 808 nm is studied with a ~2.4 W output power and an optical-to-optical efficiency of 36.5%[16]. It is interesting that the transition $^4F_{3/2}\rightarrow^4I_{9/2}$ has a higher fluorescence branching ratio (46.5%) in neodymium doped orthotantalate compared with 25% in Nd:YAG, which is beneficial for an efficient laser operation around 900 nm [15, 17]. However, to the best of our knowledge, there is no report about quasi-three-level laser performance using neodymium doped orthotantalate crystal. In LD end-pumped solid-state lasers, quantum defect induced by the difference between pump and laser wavelengths is the main factor restricting laser efficiency. Direct pumping into emitted level is an effective approach to reduce quantum defect and increase laser efficiency [18]. In

$Nd^{3+}$-doped quasi-three-level lasers, direct pumping has been proved to be an effective method to improve output performance and increase laser efficiency [19, 20].

In this paper, a LD end-pumped quasi-three-level 928 nm laser with Nd:GYTO mixed crystal is presented for the first time to our best knowledge. In order to achieve high efficiency 928 nm laser output, the influences of transmission of output mirror and cooling temperature on laser performance are investigated with 808 nm LD pumping. The output energy at 928 nm reaches 29.8 mJ with an optical-to-optical efficiency of 16.5% and a slope efficiency of 21.2% when the absorbed pump energy is 178 mJ at 10 Hz. By comparing the 928 nm laser performances with Nd:GYTO crystal under direct and indirect pumping, efficiency enhancement is achieved using 879 nm LD direct pumping. Finally, an output energy of 48.5 mJ in the 928 nm laser under 879 nm LD pumping is obtained with an optical-to-optical efficiency of 33.4% and a slope efficiency of 38.0%.

## 2. Experimental Setup

Nd:GYTO crystal is grown by using (Czochralski) Cz method. The raw materials of $Nd_2O_3$ (6N), $Gd_2O_3$(5N), $Y_2O_3$(4N) and $Ta_2O_5$(4N) compounds are weighted according to the chemical formula $Nd_{0.01}Gd_{0.69}Y_{0.3}TaO_4$. The Nd:GYTO crystal is anistropic similar as Nd:$GaTaO_4$. The concentration of $Nd^{3+}$ ions in 1.0at.% Nd:$GaYTaO_4$ is $1.67\times10^{20}$ $cm^{-3}$, higher than $1.38\times10^{20}$ $cm^{-3}$ of Nd:YAG. The fluorescence lifetime is measured to be 182.4 μs, higher than 178.4 μs for Nd:$GdTaO_4$ single crystal. The emission spectrum of Nd:GYTO in near-infrared region was researched but it did not give show the details for the emission from $^4F_{3/2}$ to $^4I_{9/2}$ due to the low response of InGaAs around 900 nm [16, 21, 22]. Fig. 1 shows the fluorescence spectrum of Nd:GYTO around 920 nm measured by using a fiber-coupled optical spectrum analyzer (Ocean Optics, HR4000, 900-1070nm) with a resolution of 0.1 nm. In consideration of the spectral intensity response of the detector, the emission spectrum is calibrated with the help of a standard lamp. Two emission peaks near 921 nm and 928 nm are corresponding to the transitions R2($^4F_{3/2}$)→Z5($^4I_{9/2}$) and R1($^4F_{3/2}$)→Z5($^4I_{9/2}$) for Nd:GYTO. The terminal laser level of 928 nm laser at room temperature is ~605 $cm^{-1}$ above the ground state, lower than 857 $cm^{-1}$ of Nd:YAG [1]. The population of the lower laser level leads to a reabsorption losses and increases laser threshold.

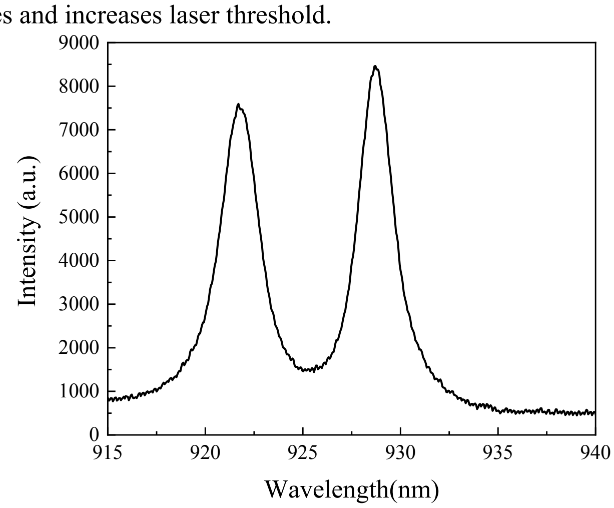


**Fig. 1**. Emission spectrum around 920 nm of Nd:GYTO crystal

Fig. 2 shows the experimental setup of LD end pumped Nd:GYTO quasi-three-level 928 nm laser. The pump sources are fiber-coupled LDs at 808 nm and 879 nm from the end of a fiber with 400 μm and a N.A. of 0.22. The pump beam is coupled into the gain medium by the coupling optics system with two plano-convex lenses. By comparing laser performances with different coupling system, it is found that tight pumping is preferable to achieve high pumping density and overcome reabsorption losses brought by population in lower laser level in 928 nm laser operation. The pump beam waist radius is chosen to be ~140 μm in the laser crystal. An a-cut Nd:GYTO crystal is utilized as the laser medium with a dimension of 2(Width)×2(Height)×4.2(Length) $mm^3$ and a $Nd^{3+}$ concentration of 0.63 at.%. The laser medium is wrapped with a 0.05 mm thick indium foil, mounted in a micro-channel heat sink and cooled by water. Both facets of laser rod are coated with high transmission (HT) at 808nm, 879 nm and 928 nm (T>99%). A linear cavity with a geometric length of 20 mm is employed, which contains a plane mirror $M_1$ and an output coupler $M_2$. The plane mirror $M_1$ is coated with HT at 808 nm (or 879 nm) and high reflection （HR） at 928 nm. The mirror $M_1$ used for 879 nm pumping has HT coating (T> 98%) at 879 nm and HR coating (R>99.5%) at 928 nm. The output coupler $M_2$ is partially transmissive at 928 nm. All the facets of laser rod and mirrors are coated with HT at 1066 nm (R<10%) to prevent parasitic oscillation around 1066 nm. Considering with the low thermal conductivity of the crystal and tight pumping required for quasi-three-level laser operation, the LD is driven with a pump duration up of 2 ms long enough for a steady state while the repetition rate of 10 Hz provides sufficient time for heat dissipation.

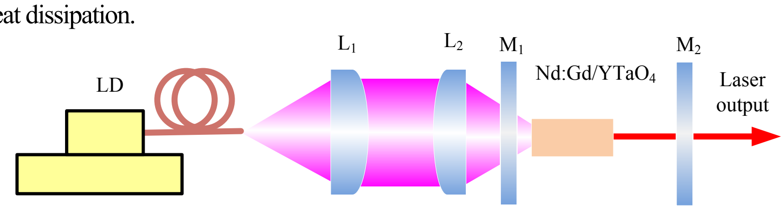


**Fig. 2**. Experimental setup of LD pumped Nd:GYTO 928 nm laser

## 3. Experimental results and discussions

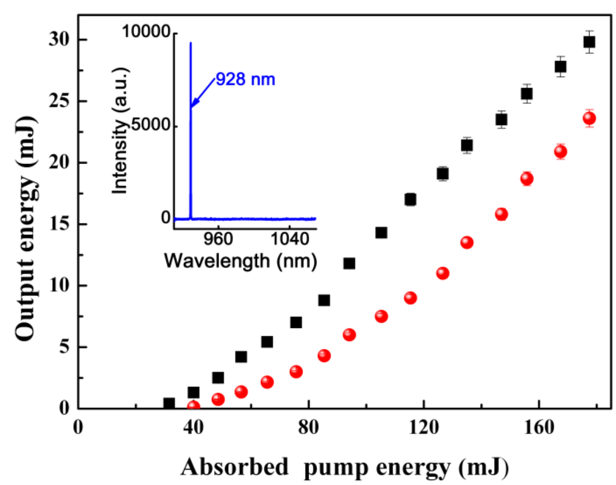


**Fig. 3.** Comparison of 928 nm laser output performances with different output coupling mirrors. Insertion: Emission spectrum of 928 nm laser under 808 nm LD pumping. (Square: plane mirror with T=2.8%. Circle : concave mirror with T=3.5% and $R_O$=200mm.)

The output performances of 928 nm laser pumped by traditional 808 nm LD with different output mirrors are investigated, as presented in Fig. 3. The absorption bands (FWHM) of a-cut Nd:GYTO at 808 nm and 879 nm are 6, and 1.5 nm, respectively. The absorption efficiency of Nd:GYTO with 808 nm LD pumping is measured to be ~90%. Because of small emission cross section in quasi-three-level transition of Nd:GYTO, the gain is weak and low transmissivity of output mirror is adopted to achieve 928 nm laser output. The output performance of 928 nm laser is better using an output mirror with the lower transmission of T=2.8%, than using a concave mirror with a radius of curvature ($R_O$) of 200 mm and T=3.5%. Higher transmissivity of output mirror leads to a higher intracavity losses and reduces 928 nm laser efficiency. At the absorbed pump energy of 178 mJ, an output energy of 29.8 mJ at 928 nm is obtained with an optical-to-optical efficiency of 16.5% and a slope efficiency of 21.2% by using the T=2.8% output mirror. The emission spectrum is measured with a spectrometer as shown in the insertion of Fig. 3. The laser peak wavelength is at ~928.8 nm with no laser emission around 1060 nm. Lower cooling temperature could reduce the reabsorption loss and to enhance laser performance in $Nd^{3+}$-doped quasi-three-level laser [23]. Fig. 4 gives the output powers of 928 nm laser with Nd:GYTO at different cooling temperature with a coupler mirror transmission of T=2.8%. Nearly the same threshold pump energies at different cooling temperatures indicate that the reabsorption losses don't change with the temperature variation. When the pump energy is above 100 mJ, the output energy difference appears. When the cooling temperature is set at 20°C, the maximum output energy at 928 nm reaches 26.9 mJ at the absorbed pump energy of 178 mJ, lower than that at 15°C due to the higher losses at higher temperature.

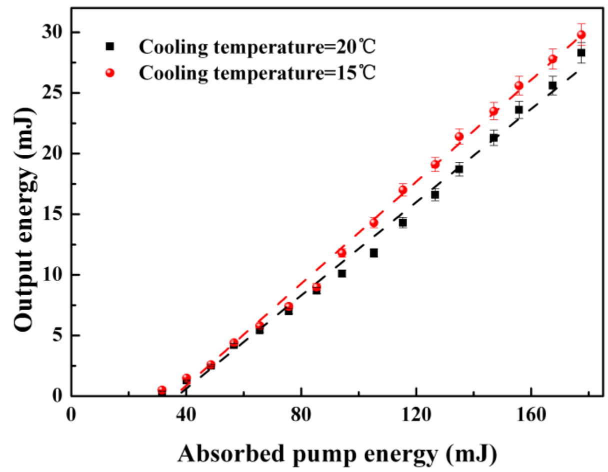


**Fig. 4.** Output energies of 928 nm laser versus pump energy at different cooling temperature.

The output characters of 928 nm laser with direct LD pumping at 879 nm and traditional LD pumping at 808 nm LD are compared. The pump coupling system and resonator parameters of 928 nm laser wtih879 nm pumping is same as 808 nm LD pumping. The output mirror is a plane mirror with T=2.8% and the cooling temperature is 15°C. With the help of a volume Bragg grating (VBG), the emission wavelength of LD is stabilized at 879.2 nm with a spectrum width of 0.6 nm matching the absorption peak for Nd:GYTO well. The absorption efficiency for Nd:GYTO under 879 nm pumping is measured to be ~60%. Fig. 5 illustrates the output energies at 928 nm under direct pumping and indirect pumping. It can be found that the laser performance at 928 nm is improved using direct pumping at 879 nm. The threshold pump energy under direct pumping is nearly 1.4 times lower than that under indirect pumping while the slope efficiency increases to 25.6% by 1.2 times. With the absorbed pump energy of ~140 mJ, the maximum laser pulse energy is ~31 and 22.4 mJ under 879 and 808 nm LD pumping, respectively. The laser performance enhancement is mainly because direct pumping reduces quantum defect by more than half and then decreases heat loading. It can be seen that there is no efficiency decrement and pumping saturation for both pumping conditions at high pumping power, which is ascribed to pulsed pumping. Pulsed pumping diminishes the influence induced by thermal effects; otherwise thermal effects and diffraction losses would rise with pump power in continuous wave pumping condition. In further research, the thermal characteristic of Nd:GYTO crystal, including the temperature-dependent stress-induced birefringence, bulging of the end faces, and the thermooptic effect, will also be investigated to analyze its influence on laser performance.

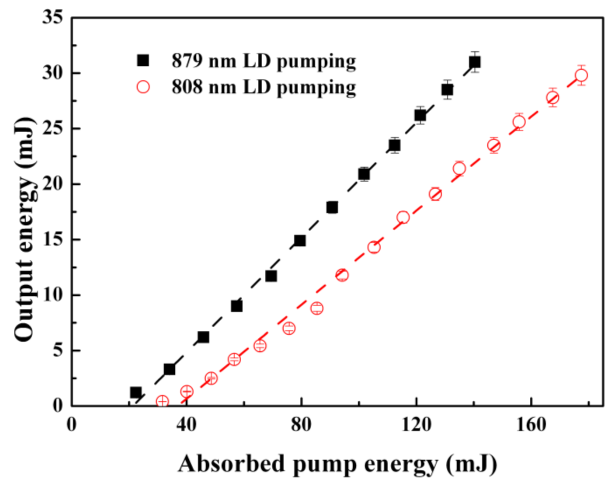


**Fig. 5.** Comparison of 928 nm output energies with Nd:GYTO under 808 nm (Circle) and 879 nm (Square) LD pumping. (Laser parameters: cooling temperature is 15°C, Plane output mirror: T=2.8%.)

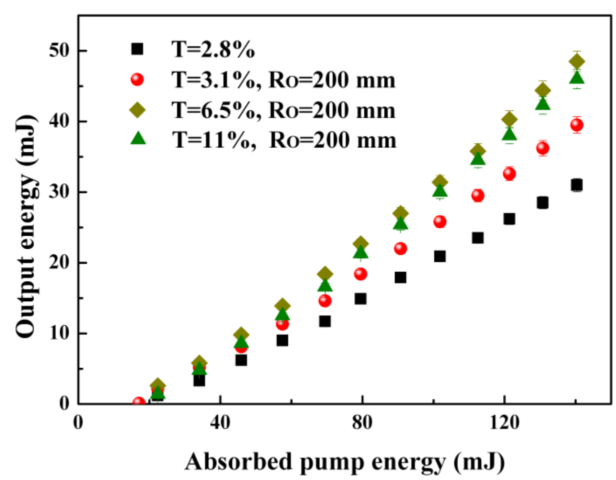


**Fig. 6.** 928 nm output energy versus pump energy under 879 nm LD pumping with different output mirrors. (the square denotes plane mirror with T=2.8%, the circle denotes concave mirror with T=3.5% and $R_O$ =200 mm, the diamond denotes concave mirror with T=6.5% and $R_O$ =200 mm, the triangle denotes concave mirror with T=11% and $R_O$=200 mm)

Further improvement of the 928 nm laser under 879 nm pumping is also conducted. The laser output characteristics as function on the incident pump energy in 879 nm LD pumped Nd:GYTO quasi-three-level laser is shown in Fig. 6. The dependence reflects slope efficiency increases with average pump power due to the reabsorption saturation in quasi-three-level laser operation. The laser performance is optimum with a coupling mirror with a transmissivity of T=6.5% at 928 nm and $R_O$=200 mm. The threshold pump energy is ~22.4 mJ while the slope efficiency reaches ~38%. The output energy at 928 nm reaches 48.5 mJ with an optical to optical efficiency of 33.4%. The available optimal transmssivity of output mirror for 879 nm LD pumped 928 nm laser is higher than that under 808 nm LD pumping, demonstrating that a higher gain or a lower losses is obtained when direct pumping is used to reduce heat loading. The beam quality of the 928 nm laser under 879 nm LD pumping is investigated by using the travelling knife-edge method. The dependence of beam radius on location around beam waist is measured with the help of a focusing lens, as shown in Fig. 7. The beam quality factors of the 928 nm laser at the maximum output energy are calculated to be $M_x^2$=1.74 and $M_y^2$=1.91 by fitting the data to Gaussian beam propagation expression. The insertion of Fig. 7 is the beam spatial distribution of the 928 nm measured by a laser beam analyzer (LBA-712PC-D, Spiricon Inc.). The intensity distribution of the beam has good symmetry in both directions. The ellipticity of the laser beam is ~0.9.

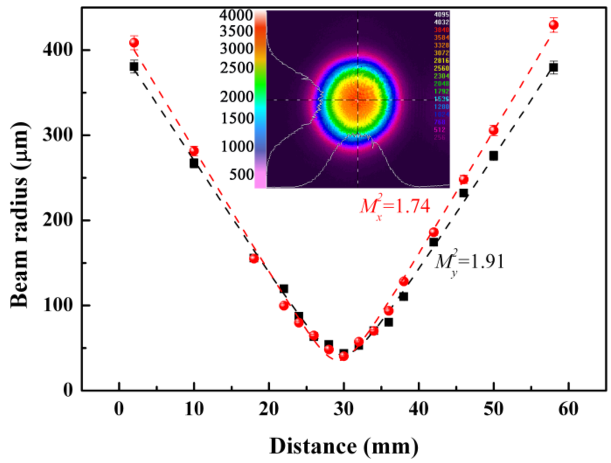


**Fig. 7.** Beam radius variation of 928 nm laser versus location at the maximum output power. Insertion: the spatial beam profile of 928 nm laser.

Table 1. Output characteristic comparison of 928 nm laser with Nd:GYTO and Nd:CLNGG crystals

| | Absorption coefficient | Fluorescence lifetime(μs) | Thermal conductivity $Wm^{-1}k^{-1}$ | 928 nm laser output characteristic | 928 nm laser slope efficiency | Reference |
|---|---|---|---|---|---|---|
| Nd:GYTO | 11.5 $cm^{-1}$ at 809 nm (1.0 at.%); 2.2 $cm^{-1}$ at 879nm (1.0 at.%) | 182 | 4.4 (a-direction) 3.5 (b-direction) 5.2 (c-direction) | 22.4±0.7mJ (808 nm pumping) 31±0.9mJ (879 nm pumping)* | 21.2% (808nm pumping); 38%(879nm pumping) | This work, [16] |
| Nd:CLNGG | 2.86 $cm^{-1}$ at 807 nm (0.5 at.%) | ----- | 2.98 | Continuous wave 1.3W | 11.2%(808nm pumping) | [24-26] |

* The repetition rate is 10 Hz and the absorbed pump energy is ~140 mJ for both 808 nm and 879 nm LD pumping

Table 1 presents comparison of 928 nm laser output characteristic with calcium lithium niobium gallium garnet (Nd:CLNGG) and Nd:GYTO. Compared with Nd:CLNGG crystal, Nd:GYTO has a bigger absorption coefficient around 808 nm and a higher thermal conductivity. The efficiency of 928 nm laser with Nd:GYTO is also higher than that with Nd:CLNGG. But it is difficult to get a continuous wave 928 nm laser output with Nd:GYTO, which is related with quality of available crystals. The internal losses of Nd:GYTO was measured to be 0.083$cm^{-1}$, pretty higher than 0.017 $cm^{-1}$ of Nd:CLNGG [27, 28]. It is possible to improve 928 nm laser performance with a high-quality Nd:GYTO crystal. Moreover, the laser slope efficiencies can be improved using the L-type cavity [29], or the dual-end-pumped geometry for good mode matching between the pump mode and the oscillating mode [30].

## 4. Conclusions

In conclusion, we have investigated a LD end-pumped quasi-three-level 928 nm laser with a novel Nd:GYTO mixed crystal for the first time. The fluorescence spectra of Nd:GYTO around 920 nm is researched with two emission peaks around 928 nm and 921 nm. The influence of parameters on laser performance under 808 nm LD pumping is investigated. The output energy of 808 nm LD pumped 928 nm laser reaches ~29.8 mJ at the absorbed pump energy of 177.5 mJ, corresponding to an optical-to-optical efficiency of 16.5% and a slope efficiency of 21.2%. By direct LD pumping at 879 nm, a 1.2-times efficiency enhancement is achieved compared with traditional 808 nm LD pumping in the same condition. The maximum output energy of ~48.5 mJ is obtained in 879 nm LD pumped 928 nm laser with an optical-to-optical efficiency of 33.4%. The beam quality factors of the 928 nm laser are measured to be $M_x^2$=1.74 and $M_y^2$=1.91 using knife-edge method. 928 nm laser output performances with Nd:CLNGG and Nd:GYTO are compared and discussed. The results indicate that direct 879 nm pumping of the disordered Nd:GYTO crystal leads to marked improvement of the 928 nm CW laser compared with 808 nm diode laser pumping. In condition of improved crystal quality and laser design, this could offer prospect for high performance short or ultrashort laser emission in this wavelength range.

## Acknowledgements

This work was supported by the Natural Science Foundation of Jiangsu Province (SBK2018042103), State Key Project of China (grant number 2016YFB0402202), the National Natural Science Foundation of China (NSFC) (61605032 and 61505042), Key Project of Jiangsu Province (grant numbers BE2016090 and BE2016005-2), and the Opened Fund of the State Key Laboratory on Integrated Optoelectronics (grant number IOSKL2016KF12), General Financial Grant from the China Postdoctoral Science Foundation (Grant No. 2015M80263), the postdoctoral funds of Jiangsu Province (Grant No. 1701046B), the Fundamental Research Funds for Central Universities (Grant No. HIT. NSRIF. 2017018).

## References

[1]. D. Krennrich, R. Knappe, B. Henrich, et al., A comprehensive study of Nd:YAG, Nd:$YAlO_3$, Nd:$YVO_4$ and Nd:$YGdVO_4$ lasers operating at wavelengths of 0.9 and 1.3µm.Part 1: cw-operation, Appl. Phys. B 92(2) (2008) 165–174.

[2]. X. Wang, E.J. Eichler, Z. Zhang, Diode-pumped actively Q-switched Nd:GGG laser operating at 938 nm, Opt. Laser Technol. 44(2) (2012) 476–481.

[3]. F. Chen, D. Xu, Q. Pan, et al., Theoretical study on the characteristics of intracavity frequency doubling of a diode-pumped cesium vapor laser, J. Opt. Soc. Am. B 33(12) (2016) 2445–2449.

[4]. J. Gao, X. Yu, F. Chen, et al., Pulsed 456 nm deep-blue light generation by acousto-optical Q-switching and intracavity frequency doubling of Nd:$GdVO_4$, Laser Phys. Lett. 5(8) (2008) 577–581.

[5]. Z. Quan, Y. Yi, L. Bin, et al., Experimental study of the generation of a blue laser by intracavity frequency doubling of a cw Nd:$GdVO_4$ laser with lithium borate, Appl. Opt. 48(16) (2009) 2979–2982.

[6]. T.Y. Fan, R.L. Byer, Modeling and CW operation of a quasi-three-level 946 nm Nd:YAG Laser, IEEE J. Quantum Electron. 23 (1987) 605–612.

[7]. J. Mackenzie, An efficient high-power 946 nm Nd:YAG planar waveguide laser, Appl. Phys. B 97 (2009) 297–306.

[8]. F. Chen, X. Yu, R. Yan, et al., High-repetition-rate, high-peak-power linear polarized 473nm Nd:YAG/BiBO blue laser by extracavity frequency-doubling, Opt. Lett. 35(16) (2010) 2714–2716.

[9]. F. Chen, X. Yu, K. Zhang, et al., Diode-pumped acousto-optical Q-switched 912 nm Nd:$GdVO_4$ laser and extra-cavity frequency-doubling of 456 nm deep-blue light emission, Opt. Laser Technol. 68 (2015) 36–40.

[10]. L. Qin, X. Meng, L. Zhu, et al., Influence of the different Gd/Y ratio on the properties of Nd:$Y_xGd_{1-x}VO_4$ mixed crystals," Chem. Phys. Lett. 380(3-4) (2003) 273–278.

[11]. H. Yu, H. Zhang, Z. Wang, et al., Characterization of mixed Nd:$Lu_xGd_{1-x}VO_4$ laser crystals, J. Appl. Phys. 101(11) (2007) 113109.

[12]. D. Li, X. Xu, J. Meng, et al., Diode-pumped continuous wave and Q-switched operation of Nd:$CaYAlO_4$ crystal, Opt. Express 18(18) (2010) 18649–18654.

[13]. K. Zhong, W. Xu, C. Sun, et al., Continuous-wave Nd:GYSGG laser properties in 1.3 and 1.4 µm regions based on $^4F_{3/2}$ to $^4I_{13/2}$ transition," J. Phys. D 46(1) (2013) 315106.

[14]. Q. Cui, J. Lan, Z. Lin, et al., High-power and high-efficiency diode-pumped Nd:LuYAG mixed crystal lasers operating at 939 and 946 nm, Appl. Opt. 55(26) (2016) 7438–7443.

[15]. F. Peng, H. Yang, Q. Zhang, et al., Spectroscopic properties and laser performance at 1066 nm of a new laser crystal Nd:$GdTaO_4$, Appl. Phys. B 118(4) (2015) 549–554.

[16]. F. Peng, H. Yang, Q. Zhang, et al., Growth, thermal properties, and LD-pumped 1066 nm laser performance of $Nd^{3+}$ doped Gd/$YTaO_4$ mixed single crystal, Opt. Mater. Express 5(11) (2015) 2536–2544.

[17]. W. Koechner, Solid-State Laser Engineering, 6th ed. New York, USA: Springer-Verlag, 2006.

[18]. R. Lavi, S. Jackel, Y. Tzuk, et al., Efficient pumping scheme for neodymium-doped materials by direct excitation of the upper lasing level, Appl. Opt. 38(36) (1999) 7382–7385.

[19]. V. Lupei, N. Paval, T. Taira, Highly efficient continuous-wave 946-nm Nd:YAG laser emission under direct 885-nm pumping, Appl. Phys. Lett. 81(15) (2002) 2677–2679.

[20]. J. Gao, X. Yu, F. Chen, et al., 12.0-W continuous-wave diode-end-pumped Nd:$GdVO_4$ laser with high brightness operating at 912-nm, Opt. Express 17 (5) (2009) 3574–3580.

[21]. H. Cong, C. Xue, J. Zheng, et al., Silicon Based GeSn p-i-n Photodetector for SWIR Detection, IEEE Photonics J. 8(5) (2016) 6804706.

[22]. H. Cong, F. Yang, C. Xue, et al., Multilayer Graphene-GeSn Quantum Well Heterostructure SWIR Light Source, Small 14(17) (2018) 1704414.
[23]. R. Zhou, E. Li, H. Li, et al., Continuous-wave, 15.2 W diode-end-pumped Nd: YAG laser operating at 946 nm, Opt. Lett. 31 (12) (2006) 1869–1871.
[24]. Z. Shi, H. Zhang, J. Wang, et al., Growth and characterization of Nd:CLNGG crystal, J. Cryst. Growth 311 (2009) 3792–3796.
[25]. K. He, Z. Wei, D. Li, et al., Diode-pumped quasi-three-level CW Nd:CLNGG and Nd:CNGG lasers, Opt. Express 17(21), (2009) 19292–19297.
[26]. Y. Li, H. Jiang, T. Ni, et al., Diode-pumped quasi-three-level Nd:CLNGG laser at 928 nm, Laser Phys. 21(4) (2011) 648–651.
[27]. H. Yu, H. Zhang, Z. Wang, et al., Continuous-wave and passively Q-switched laser performance with a disordered Nd:CLNGG crystal, Opt. Express, 17(21) (2009) 19015–19020.
[28]. W. Wu, X. Li, R. Yan, et al., Continuous-wave and pulsed 1,066-nm Nd:$Gd_{0.69}Y_{0.3}TaO_4$ laser directly pumped by a 879-nm laser diode, Opt. Express 26(12) (2018) 15705–15717.
[29]. X. Yan, Q. Liu, L. Huang, et al., A high efficient one-end-pumped $TEM_{00}$ laser with optimal pump mode, Laser Phys. Lett. 5(3) (2007) 185-188
[30]. X. Li, X. Yu, F, Chen, et al., Power scaling of directly dual-end-pumped Nd:$GdVO_4$ laser using grown-together composite crystal, Opt. Express 18(7) (2010) 7407-7414