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Diode-pumped quasi-three-level 456-nm Nd : GdVO$_4$ laser

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Abstract. **A diode-pumped quasi-three-level Nd : GdVO$_4$ laser emitting at a wavelength of 912 nm corresponding to the $^4F_{3/2} - {^4I_{9/2}}$ transition of the neodymium ion and at the second-harmonic linewidth of 456 nm after intracavity frequency doubling in a KNbO$_3$ crystal is studied. The maximum output power at the fundamental frequency was 2.96 W and the conversion efficiency amounted to 48 %. The second-harmonic output power achieved 220 mW for the conversion efficiency of 15 %.**

Keywords: *Nd : GdVO$_4$ laser, diode pump, intracavity second-harmonic generation.*

1. Introduction

Simple and compact solid-state lasers emitting in the blue spectral region can find applications in a variety of devices where argon lasers are used at present such as data storage devices, displays, medical instruments, etc. It is possible that diode lasers will find wide applications in the future in this field, but now doubled quasi-three-level neodymium-doped crystal lasers are main solid-state lasers emitting high-power radiation in the blue region.

The first lasers of this type were 946-nm quasi-three-level Nd : YAG lasers emitting at 473 nm after frequency doubling [1]. To obtain lasing at shorter wavelengths, the Nd : YalO$_3$ (930 nm) [2]. Nd : YVO$_4$ (915 nm) [3], and Nd : GdVO$_4$ (912 nm) [4] crystals can be used. The Nd : GdVO$_4$ laser emitting at the $^4F_{3/2} - {^4I_{9/2}}$ transition of a neodymium ion produces the shortest-wavelength radiation [5]. In addition, this crystal emits efficiently at 1063 and 1340 nm, both at the fundamental frequency and second harmonic [6, 7].

The aim of this paper is to study the possibility of the development of a high-power, highly efficient, diode-pumped Nd : GdVO$_4$ laser emitting at 912 nm and in the blue region at 456 nm after frequency doubling.

2. Properties of a Nd : GdVO$_4$ crystal

We studied quasi-three-level lasing at the $^4F_{3/2}- {^4I_{9/2}}$ transition of a neodymium ion in Nd : GdVO$_4$ crystals grown by the Czochralski method at the Scientific Center of Laser Materials and Technologies at the General Physics Institute, Russian Academy of Sciences. Active rods were cut perpendicular to the *a* axis. Fig. 1 shows the absorption and luminescence spectra of a Nd : GdVO$_4$ crystal demonstrating a strong polarisation dependence. The spectroscopic and lasing parameters of Nd : YAG, Nd : YalO$_3$, Nd : YVO$_4$, and Nd : GdVO$_4$ crystals used in quasi-three-level lasers are presented in Table 1.

One can see that a gadolinium vanadate crystal offers a number of advantages compared to other crystals. This crystal emits the shortest-wavelength radiation at the $^4F_{3/2} - {^4I_{9/2}}$ transition. The heat conduction of Nd : GdVO$_4$ crystals is twice that of Nd : YVO$_4$ crystals and is comparable with that of Nd : YAG crystals in the $\langle 110 \rangle$ direction. The laser radiation is linearly polarised, which is important for frequency doubling. Nd : GdVO$_4$ crystals can be doped with neodymium up to 3 %, almost without a decrease in the lasing efficiency.

One of the drawbacks of a Nd : GdVO$_4$ crystal is a small splitting (409 cm^{-1}) of the lower level compared to that (857 cm^{-1}) in a Nd : YAG crystal. The Boltzmann ratio for the lower laser level in Nd : GdVO$_4$ at room temperature is ~ 5 % (and 0.7 % for Nd : YAG). Because the lower laser level is the upper sublevel of the $^4I_{9/2}$ multiplet, this sublevel is thermally coupled with the ground state and should be efficiently populated with increasing temperature. This in turn leads to an increase in the ground-state absorption losses, an increase in passive intracavity losses, reducing the output energy of the laser and increasing the lasing threshold.

3. Pump systems

Due to a relatively low cross section for the induced $^4F_{3/2} - {^4I_{9/2}}$ transition and considerable reabsorption losses, the lasing threshold of such lasers is rather high. Therefore, to obtain efficient quasi-three-level lasing in Nd : GdVO$_4$ crystals, it is necessary to use a high-power, high-brightness pump source and provide a low level of passive intracavity losses. These losses are mainly determined by the quality of optical elements of the laser and the degree of cooling of active elements.

In this paper, we present two series of experiments with two pump sources. In the first series, we used a Polaroid

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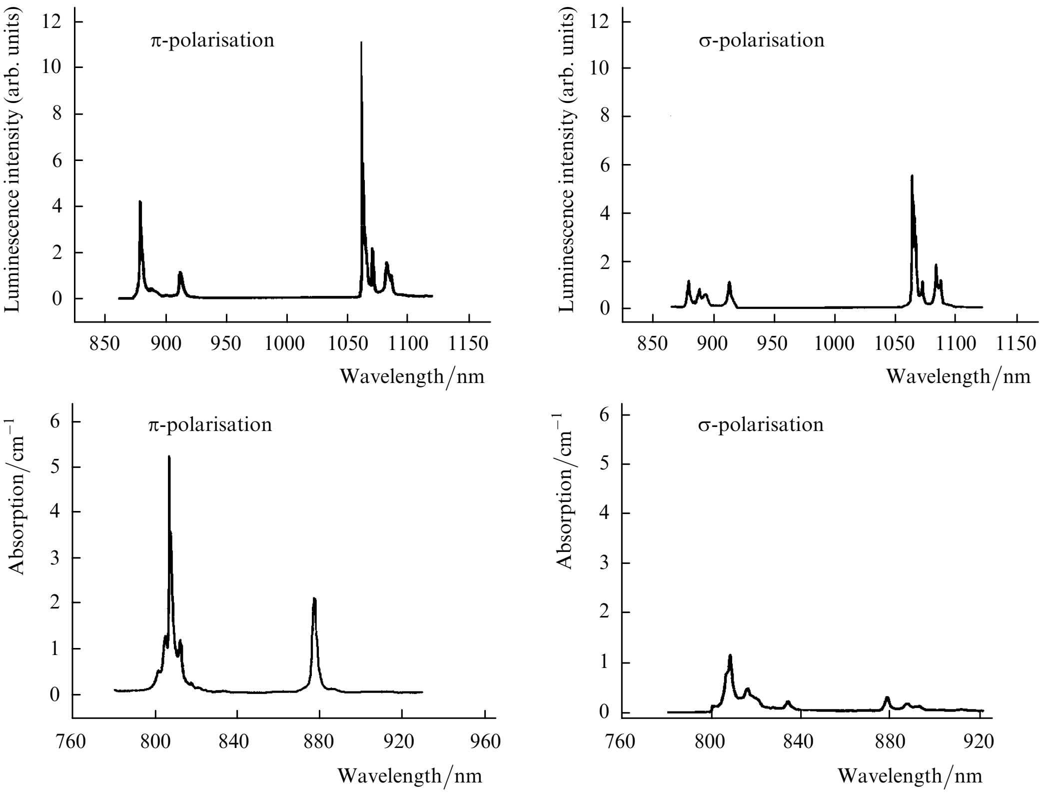

Figure 1. π and σ polarised luminescence and absorption spectra of a Nd : $GdVO_4$ crystal.

diode pump system with a fibre coupler (the fibre core diameter was 120 μm and the numerical aperture was NA= 0.22) providing the 808-nm output power up to 3 W. A focusing system ensured the beam-waist diameter in the crystal within 80 – 200 μm. In the second series of experiments, we used a high-power LIMO HLU25F200 pump system with a fibre coupler (with the core diameter of 200 μm and NA= 0.22) providing the output power up to 25 W. The laser radiation was focused by objectives to obtain the beam-waist diameter in the crystal between 150 and 400 μm.

Active elements and nonlinear crystals used in the experiments were mounted with the help of an indium foil in copper blocks whose temperature was controlled with Peltier thermoelectric microcoolers or by water cooling.

4. Experimental results

The results of the first series of experiments are shown in Figs 2 and 3. The Nd : $GdVO_4$ crystals of length 2 mm and cross section 3 × 3 mm containing 0.6 % of neodymium ions were used as an active element. The laser cavity was formed by a dielectric mirror deposited directly on the active element and by a concave output mirror with the radius of curvature $R = 52$ mm and reflectivity $r = 96\,\%$ at the fundamental frequency. The opposite side of the active

Table 1. Basic parameters of laser crystals [8].

Laser parameters	Nd : $GdVO_4$	Nd : YVO_4	Nd : YAG	Nd : $YAlO_3$
Radiation wavelength at the $^4F_{3/2} - {}^4I_{9/2}$ transition/nm	912	915	946	930
Induced transition cross section/10^{-19}cm^2	0.7 (π) 0.6 (σ)	0.5 (π) 0.4 (σ)	0.64 –	0.53 –
Absorption cross section/10^{-19}cm^2	5.2 (π) 1.3 (σ)	2.7 (π) –	0.7 –	0.5 –
Heat conduction/W mK^{-1}	11.7 (‖c) 9.63 (⊥c)	5.23 (‖c) 5.10 (⊥c)	11.1 –	9.1 –
Lifetime of the upper laser level at the neodymium concentration 1 %/ms	94	110	220	150
Pump wavelength/nm	808.4	808.5	807.5	794.5
Absorption coefficient at the neodymium concentration 1 %/cm^{-1}	57	40.7	8	7
Polarisation	‖c	‖c	–	‖c
Absorption linewidth at the 75-% level/cm^{-1}	13.5	15.7	2.5	3.1
Splitting of the lower level/cm^{-1}	409	439	857	670

element had an AR coating for 912, 1064, and 1340 nm and a reflection coating for the pump wavelength 808 nm. The backward reflection of the pump radiation transmitted through the active element provided the increase in the pump-power absorption and reduced ground-state absorption losses in the crystal, resulting in the enhancement of the lasing efficiency. All the elements of the cavity in this and subsequent experiments had AR coatings for 1064 and 1340 nm to suppress lasing at these wavelengths. The pump radiation was focused into a spot of diameter 100 μm.

The dependence of the output power at 912 nm on the absorbed pump power is shown in Fig. 2. The maximum output power of 670 mW was achieved when the absorbed pump power was 2 W. The lasing threshold was 510 mW. In this case, the slope lasing efficiency achieved 48 % (the total efficiency was 33 %). Note that this lasing efficiency is comparable with the maximum efficiency of Nd : YAG lasers [9, 10].

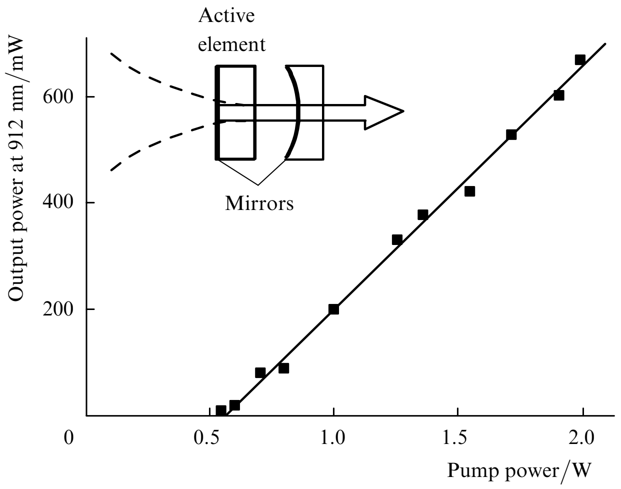

Figure 2. Dependence of the 912-nm output power on the pump power for the laser scheme shown in the inset.

Intracavity frequency doubling was performed in a KNbO$_3$ crystal, which was placed instead of the output mirror (Fig. 3). The nonlinear crystal of length 1.3 mm and cross section of 3×3 mm was cut so that phase matching was achieved at room temperature. Phase matching was adjusted using a thermal stabiliser. The output surface of the crystal had a dielectric coating with a high reflectivity at 912 nm and a high transmission at 456 nm. The opposite side of the nonlinear crystal had an AR coating for 912, 1064, and 1340 nm. The output radiation was coupled out to one side.

Fig. 3 shows the dependence of the 456-nm second-harmonic output power on the absorbed pump power. For the absorbed pump power of 2 W, we obtained the output power of 225 mW at the conversion efficiency equal to 15 %. The lasing threshold was 300 mW.

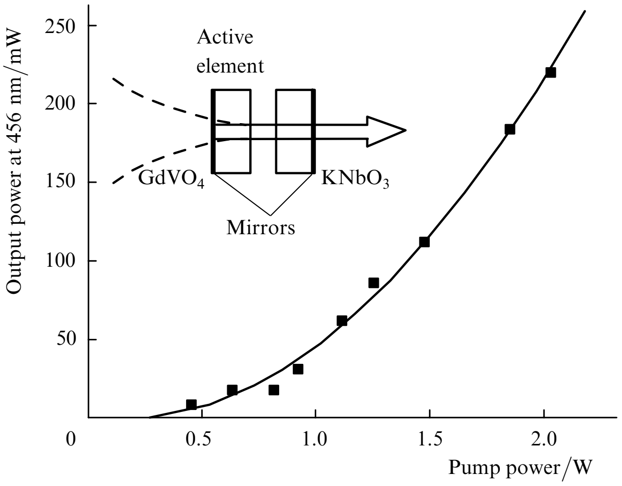

Figure 3. Dependence of the 456-nm second-harmonic output power on the pump power for the laser scheme shown in the inset.

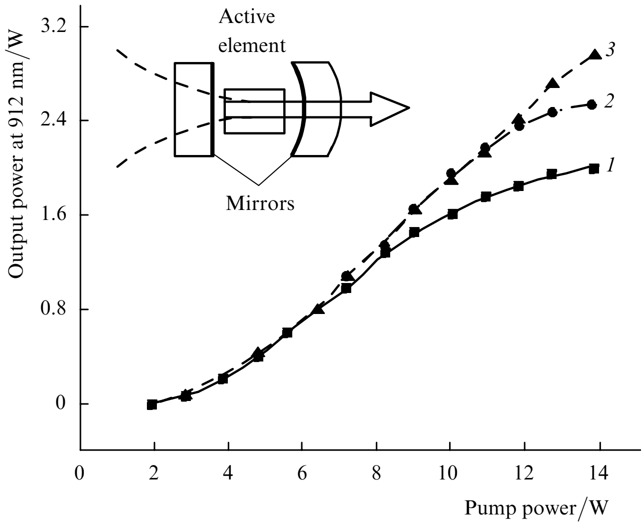

Figure 4. Dependences of the 912-nm output power on the pump power for cw pumping (*1*) and pulsed pumping with the off-duty ratio equal to 50 % (*2*) and 33 % (*3*) for the laser scheme shown in the inset.

High-power pumping experiments were performed with Nd : GdVO$_4$ crystals of length between 1 and 5 mm and cross section of 3×3 mm containing from 0.15 to 2 % of neodymium ions. The best results were obtained for crystals of length 3.5 mm containing 0.3 % of neodymium ions. The scheme of the laser is shown in the inset in Fig. 4. The laser cavity was formed by a plane input mirror with a high reflectivity at 912 nm and a concave output mirror ($R = 52$ mm) with $r = 94\,\%$ at 912 nm. The ends of the active element had AR coatings. The waist diameter of the pump beam focused by an optical system into the crystal was 250 μm.

Curve (*1*) in Fig. 4 shows the dependence of the 912-nm output power of the laser on the absorbed cw pump power. One can see that the dependence is nonlinear, exhibiting saturation for the pump power exceeding 10 W. The output power achieved a maximum value of 2.06 W when the absorbed pump power was equal to 13.8 W. It seems that saturation is caused by a thermal lens and by heating of the active element. To reduce the effect of thermooptic distortions, we used pulsed pumping. Curves (*2*) and (*3*) in Fig. 4 correspond to the off – duty ratio equal to 10 : 10 and 20 : 10, respectively. One can see that, in the case of a lower off-duty ratio, the saturation onset shifts to higher pump powers, whereas for a higher off-duty ratio, the output power increases almost linearly. In this case, the saturation power was 2.96 W and the slope lasing efficiency was 24.3 %. Note that the conversion efficiency was substantially lower than that obtained in the first series of experiments.

Probably this is explained by the fact that we used the longer crystals in the latter experiments, which resulted in the increase in the passive intracavity losses. In addition, the pump radiation transmitted through the crystal was not used again.

Therefore, to increase further the output power of the laser, it is necessary to optimise pumping and the cavity parameters, as well as to find the efficient method for suppressing the thermal lens effect in crystals.

5. Conclusions

We have shown that Nd : $GdVO_4$ crystals can be efficiently used in the quasi-three-level scheme to obtain lasing at 912 nm. Despite a small splitting of the lower laser level, the energy parameters and the conversion efficiency achieved in our experiments with Nd : $GdVO_4$ crystals are comparable with those obtained for Nd : YAG crystals. The maximum output power of the laser was 2.96 W and the slope efficiency at the fundamental frequency achieved 48 %. The first intracavity frequency-doubling experiments have demonstrated the outlook for applications of Nd : $GdVO_4$ crystals for lasing in the blue spectral region. The output power of the laser at 456 nm was 225 mW.

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