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New possibilities of neodymium-doped vanadate crystals as active media for diode-pumped lasers

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***Abstract*. The spectral and lasing parameters of Nd : $GdVO_4$, Nd : YVO_4, and Nd : $Gd_{0.7}Y_{0.3}VO_4$ vanadate crystals cut along the *c* axis are studied. Lasing is obtained for the first time in a nonselective resonator at the $^4F_{3/2}-{}^4I_{11/2}$ transition at 1065.5 nm in a Nd : $GdVO_4$ crystal. Tuning is realised in the range from 1062.3 to 1066.1 nm and two-frequency lasing is obtained.**

Keywords: *Nd : $GdVO_4$, Nd : YVO_4, Nd : $Gd_{1-x}Y_xVO_4$ crystals, diode pumping.*

1. Introduction

The development of highly efficient solid-state lasers, the extension of their functional possibilities and methods for controlling their operating regimes, the generation of two-frequency and tunable radiation are of great scientific and practical interest. Progress in this direction of laser physics is related to the use of laser diodes for pumping semiconductor lasers, the development of new active media, and the elucidation of new possibilities of the known active media. Active media based on gadolinium Nd : $GdVO_4$ [1], yttrium Nd : YVO_4 [2], and mixed Nd : $Gd_{0.5}La_{0.5}VO_4$ [3], and Nd : $Gd_{1-x}Y_xVO_4$ [4, 5] vanadate crystals are widely applied at present in various diode-pumped lasers due to the optimal combination of their spectral, lasing, thermal properties.

Mixed vanadate crystals Nd : $Gd_{0.5}La_{0.5}VO4$ and Nd : $Gd_{1-x}Y_xVO_4$ preserve the properties of their predecessors, and at the same time, by varying the concentration ratios of Y, Gd, and La in them, it is possible to change the luminescence and absorption cross sections, the absorption and luminescence linewidths, and the lifetime of upper laser levels.

Vanadate crystals have a strong anisotropy and therefore their spectral and thermal parameters strongly depend on the orientation along different crystallographic axes. The absorption and luminescence spectra of vanadate and mixed vanadate crystals cut along the *a* axis (for the σ and π polarisations) and along the *c* axis are considerably different. Lasing occurs most efficiently in crystals cut along the *a* axis (the π polarisation) and therefore studies are usually performed for this crystal orientation. The induced transition cross sections along other directions are considerably lower. For example, these cross sections for Nd : $GdVO_4$ crystals cut along the *a* and *c* axes are 7.6×10^{-19} and 1.2×10^{-19} cm^2, respectively [6].

The Nd : $GdVO_4$ crystals cut along the *c* axis proved to be preferable for *Q*-switching with the help of passive Cr^{4+} : YAG *Q* switches compared to crystals with the usual orientation [6].

In this paper, we studied the properties of yttrium, gadolinium, and mixed vanadate crystals cut along the *c* axis and analysed the possibility of developing efficient tunable and two-frequency diode-pumped lasers on the $^4F_{3/2}-{}^4I_{11/2}$ transition in neodymium ions in these crystals.

2. Luminescence spectra in the lasing region of crystals with different orientations

Vanadate crystals were grown by the Czochralski method on Kristall-2 and Kristall-3M industrial facilities at the A.M. Prokhorov General Physics Institute, RAS.

The spectral properties of laser crystals were studied by using a Shimadzu UV-3101PC spectrophotometer and a spectrometer based on a UV-90 autocollimation tube (with the reciprocal linear dispersion 0.1 nm mm^{-1}) equipped with a Toshiba TCD130JK linear multichannel photodetector. The absorption spectra of vanadate crystals cut along the *a* (the π polarisation) and *c* axes differ insignificantly.

Figure 1 presents the fragments of normalised luminescence spectra at the $^4F_{3/2}-{}^4I_{11/2}$ transition for Nd : $GdVO_4$, Nd : YVO_4, and Nd : $Gd_{0.7}Y_{0.3}VO_4$ crystals cut along the *a* and *c* axes. One can see that the luminescence spectra of these crystals cut along the *a* or *c* axes are substantially different. The frequency shift and redistribution of the luminescence intensity among transitions between Stark levels are observed. For the Nd : $GdVO_4$ and Nd : $Gd_{0.7}Y_{0.3}VO_4$ crystals cut along the *c* axis, the overlap of two adjacent sublevels is observed. Of special interest is the Nd : $GdVO_4$ crystal because the intensity of the 1065.5-nm line exceeds that of the 1063.2-nm luminescence line at which lasing is usually observed in a crystal cut along the *a* axis. This suggests that lasing can be observed in a non-

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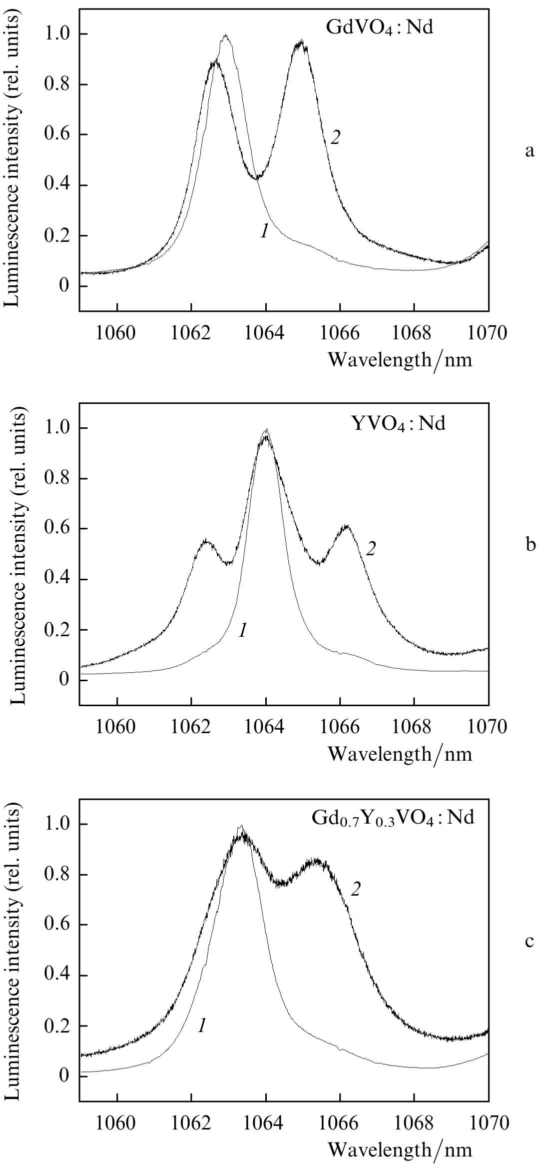

Figure 1. Luminescence spectra at the $^4F_{3/2} - ^4I_{11/2}$ laser transition in Nd : $GdVO_4$ (a), Nd : YVO_4 (b), and Nd : $Gd_{0.7}Y_{0.3}VO_4$ (c) crystals cut along the *a* (the π polarisation) [curves (*1*)] and *c* [curves (*2*)] axes.

selective resonator at 1065.5 nm in Nd : $GdVO_4$ crystals cut along the *c* axis.

The intensity of luminescence lines in the mixed vanadate depends on the ratio of Y and Gd concentrations in the crystal. As this ration is changed, the gain profile in the 1063–1064-nm region changes. In this case, the Stark transition lines broaden by more than a factor of 1.5 compared to linewidths in $GdVO_4$ and YVO_4.

The luminescence line of the Nd : $Gd_{0.7}Y_{0.3}VO_4$ crystal in the lasing region is located at 1063.4 nm and its half-width is 5.1 nm. For Nd : YVO_4 crystals cut along the *c* axis, the overlap of three Stark transition lines in the lasing region is observed, the half-width of the total gain band being 4.7 nm.

Such broadened luminescence bands provide new functional possibilities of laser based on vanadate crystals cut along the *c* axis such as tuning, two-frequency lasing, and generation of subpicosecond pulses [7, 8].

3. Lasing in Nd : $GdVO_4$ crystals with different orientations

Active laser elements were made of Nd : $GdVO_4$ crystals of sizes 4 × 4 × 6 and 4 × 4 × 8 mm with the atomic concentration of neodymium equal to 0.5 % which were cut along the *a* and *c* axes.

A laser crystal was mounted in a water-cooled copper unit with the help of an indium foil. Pumping was performed by a 30-W LIMO HLU25F400 diode array with a fibre pigtail (the fibre diameter was 400 μm and the numerical aperture was NA = 0.22). The pump radiation was focused in the active element to a spot of diameter from 250 to 400 μm. The laser tuning was performed with the help of an intracavity Fabry–Perot etalon or a Lyot filter. For a Fabry–Perot interferometer a 120-μm-thick plane–parallel YAG plate without coatings was used. We also used a single-step ($h = 1.2$ mm) or three-step Lyot filters consisting of crystal quartz plates oriented at the Brewster angle with respect to the resonator axis.

Figure 2 shows the scheme of the laser setup. The laser resonator is formed by a highly reflecting spherical mirror (with an AR dielectric coating for the 808-nm pump radiation wavelength with the high reflectivity at 1064 nm) and a plane (transmission $T = 4.8$ % or 8 % at the fundamental frequency) or a spherical output mirror (the radius of curvature 52 mm, $T = 5$ % or 8 %). Both sides of the active element had AR coating for a wavelength of 1064 nm. The pump radiation was focused into a spot of diameter 400 μm. The resonator stability for plane mirrors was provided by a thermal lens formed in the crystal by pumping. The passive loss level was determined first of all by the quality of laser crystals and optical elements used in the laser.

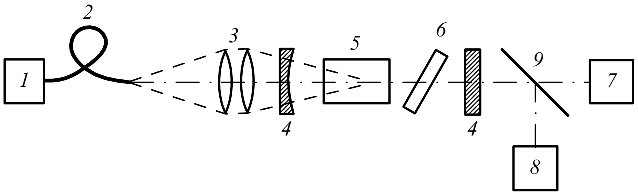

Figure 2. Scheme of a tunable laser: (*1*) LIMO System pump source; (*2*) fibre of diameter 400 μm; (*3*) collimator; (*4*) resonator mirrors; (*5*) active element; (*6*) Fabry–Perot interferometer; (*7*) power meter; (*8*) spectrometer; (*9*) mirror.

Lasing experiments with Nd : $GdVO_4$ crystals cut along the *a* (the π polarisation) and *c* axes showed that the laser based on a Nd : $GdVO_4$ crystal cut along the *c* axis emits at 1065.5 nm, whereas the laser based on this crystal cut along the *a* axis emits at 1063.2 nm.

Figure 3 shows the dependences of the output power of the laser based on Nd : $GdVO_4$ crystals cut along the *a* ($\lambda = 1063.2$ nm) and *c* ($\lambda = 1065.5$ nm) axes on the absorbed cw pump power. Because the induced transition cross section for this crystal cut along the *c* axis is considerably lower than that for the crystal cut along the *a* axis (the π polarisation), the lasing thresholds are also different. In the first case, the lasing threshold was 1.45 W, whereas in the second case, it was 0.46 W.

The radiation conversion efficiency in Nd : $GdVO_4$ crystals cut along the *a* and *c* axes was 41 % and 33 %

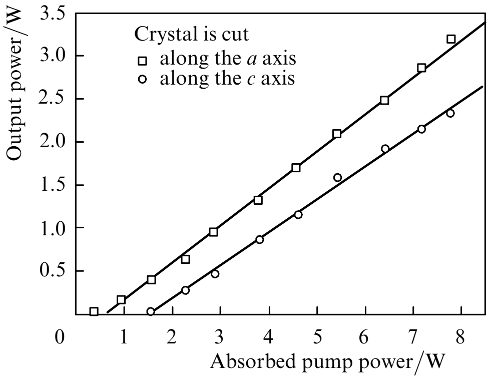

Figure 3. Output power of the Nd : GdVO$_4$ laser at the $^4F_{3/2}-^4I_{11/2}$ transition for crystals cut along the *a* (the π polarisation) and *c* axes as a function of the absorbed pump power.

for the slope efficiency equal to 43 % and 41.5 %, respectively.

4. Laser tuning

The overlap of luminescence bands (Fig. 1) allows continuous tuning of laser radiation with the total gain band. Figure 4 shows the tuning curves for the laser based on Nd : GdVO$_4$ crystals cut along the *c* axis obtained by using an intracavity Fabry – Perot etalon as a selecting element.

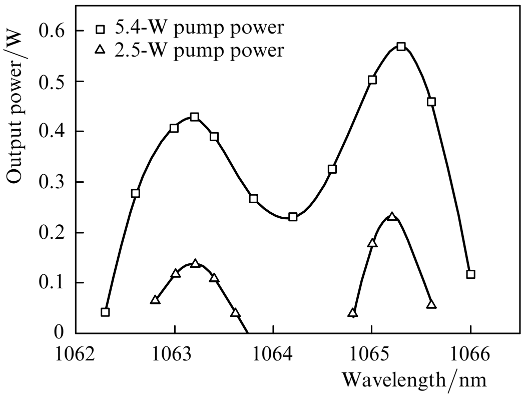

Figure 4. Output tuning curves for the Nd : GdVO$_4$ laser at the $^4F_{3/2}-^4I_{11/2}$ transition for crystals cut along the *c* axis.

The laser wavelength could be continuously tuned from 1062.3 to 1066.1 nm upon 5.4-W pumping. Upon 2.5-W pumping, two separate lasing regions were observed.

For Nd : GdVO$_4$ crystals cut along the *a* axis (the π polarisation), tuning could be performed only within 1.2 nm near 1063.2 nm.

In the laser based on Nd : GdVO$_4$ crystals cut along the *c* axis, a jump from 1063.2 nm to 1065.5 nm occurred upon tuning with the help of the Lyot filter (these wavelength correspond to the two maxima of the luminescence spectrum, Fig. 1a). By tuning precisely the Lyot filter, we obtained simultaneous lasing at wavelengths 1063.2 and 1065.5 nm. This lasing mode (Fig. 5) can find wide scientific and practical applications. One of the promising applications is the development of efficient terahertz radiation sources [9].

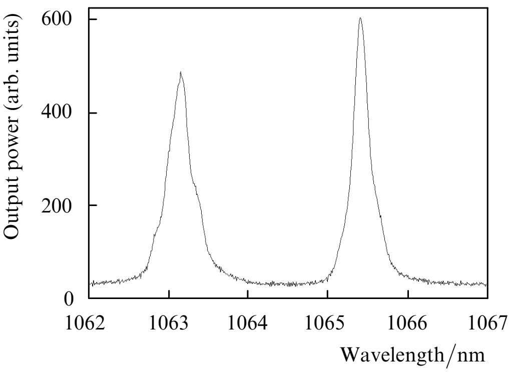

Figure 5. Emission spectrum of the two-frequency Nd : GdVO$_4$ laser.

5. Conclusions

We have studied the spectral and lasing properties of Nd : GdVO$_4$, Nd : YVO$_4$, and Nd : Gd$_{0.7}$Y$_{0.3}$VO$_4$ crystals cut along the *c* axis. Lasing have been obtained at the 1065.5-nm $^4F_{3/2}-^4I_{11/2}$ transition of neodymium ions in the Nd : GdVO$_4$ crystal cut along the *c* axis. Laser radiation could be tuned in the wavelength range from 1062.3 to 1066.1 nm. Two-frequency lasing has been obtained in the Nd : GdVO$_4$ crystal at the lines separated by 2.3 nm. New possibilities of neodymium-doped vanadates as active media for diode-pumped lasers have been demonstrated. It has been proposed, in particular, to use two-frequency lasers as terahertz radiation sources.

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