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# Vanadate lasers with σ-polarised radiation

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***Abstract*. Luminescent and lasing properties at the $^4F_{3/2}-{}^4I_{11/2}$ transition of *a*-cut Nd : YVO$_4$, Nd : GdVO$_4$, Nd : Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y$_x$VO$_4$ vanadate crystals are experimentally studied for π- and σ-polarisations. Polarisation dependences of the lasing characteristics of passively *Q*-switched Nd : YVO$_4$, Nd : Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y$_x$VO$_4$ lasers with Cr$^{4+}$ : YAG and V$^{3+}$ : YAG *Q*-switches are investigated. It is shown that the laser wavelengths are different for π- and σ-polarizations. The best characteristics are achieved for the Nd : YVO$_4$ laser with a Cr$^{4+}$ : YAG passive saturable absorber for σ-polarisation (minimum pulse duration shorter than 3 ns, maximum peak power up to 10 kW, maximum peak energy ∼ 35 μJ at a slope efficiency up to 32 %).**

***Keywords***: *Nd:YVO$_4$, Nd:GdVO$_4$, Nd:Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y$_x$VO$_4$ vanadates; luminescent and lasing properties; π- and σ-polarised radiation.*

## 1. Introduction

The neodymium-doped YVO$_4$ [1], GdVO$_4$ [2], Gd$_{1-x}$Y$_x$VO$_4$ [3], and Sc$_{1-x}$Y$_x$VO$_4$ [4] vanadate crystals are excellent materials for diode-pumped lasers. They have some advantages compared to other widespread crystals, Nd : YAG and Nd : YLF; namely, they have large absorption and stimulated emission cross sections and broad absorption lines at pump wavelengths. The combination of the spectral and mechanical properties of these crystals allows the creation of highly efficient cw lasers. Due to the lattice anisotropy of vanadate crystals, it is possible to obtain polarised radiation, while the high heat conductivity leads to better cooling of the active medium.

Most well-known papers are devoted to *a*-cut vanadate crystals emitting π-polarised ($E \| c$) radiation at the $^4F_{3/2}-{}^4I_{11/2}$ transition since the gain in this case is maximum. On the other hand, the large stimulated emission cross section in the case of π-polarisation is an important drawback hindering the laser operation in the passive *Q*-switching regime with widely used Cr$^{4+}$ : YAG and V$^{3+}$ : YAG saturable absorbers. The high gain of the active medium in this case limits inversion accumulation and, hence, decreases the laser pulse energy and peak power. The difference in the properties of vanadate crystals along different axes allows one, if needed, to choose directions with not very high gain cross sections. In this case, one can use *C*-cut crystals [5, 6] or σ-polarisation ($E \perp c$) of generated radiation [7]. The problems related to large stimulated emission cross sections can also be solved by using mixed vanadates Nd : Y$_x$Gd$_{1-x}$VO$_4$ [8, 9].

The wide use of the anisotropic properties of vanadates requires refining their spectral properties. The luminescence spectra available in the literature for *a*-cut vanadate crystals at the $^4F_{3/2}-{}^4I_{11/2}$ transition in the case of σ-polarisation are significantly different [10 – 22]. A characteristic feature of many of these luminescence spectra is that the absolute maxima for the π- and σ-polarisations lie at the $^4F_{3/2}-{}^4I_{11/2}$ transition wavelength. In addition, it is obvious that, in the case of σ-polarisation, the spectral shape should be the same for *a*-cut and *c*-cut vanadate crystals [23, 24], because the field *E* is perpendicular to the *C* axis ($E \perp c$) in both cases. The refinement of luminescence spectra is of both fundamental and purely practical interest. In the case of coincidence of the positions of the absolute maxima in the luminescence spectra for π- and σ-polarisations, it possible to amplify σ-polarised pulses in the direction of the π-polarisation. If theses maxima do not coincide, it is possible to design simple schemes for two-frequency lasing with orthogonal polarisations [25, 26].

In this work, we experimentally study the luminescent properties of *a*-cut Nd : YVO$_4$, Nd : GdVO$_4$, Nd : Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y*x*VO$_4$ vanadate crystals at the $^4F_{3/2}-{}^4I_{11/2}$ transition for the π- and σ-polarisations in order to refine the wavelengths of lasers with σ-polarisation and obtain two-frequency lasing. In addition, we compare the lasing characteristics of diode-pumped vanadate lasers emitting radiation with different polarisations and test the possibility of obtaining efficient passively *Q*-switched regime of these lasers with Cr$^{4+}$ : YAG and V$^{3+}$ : YAG passive *Q*-switches.

## 2. Luminescent parameters of *a*-cut vanadate crystals in the case of σ-polarisation

To refine the wavelengths of σ-polarised radiation of vanadate lasers, we experimentally studied the π- and σ-polarised luminescence spectra of *a*-cut Nd : YVO$_4$,

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$Nd:GdVO_4$, $Nd:Gd_{1-x}Y_xVO_4$, and $Nd:Sc_{1-x}Y_xVO_4$ vanadate crystals at the $^4F_{3/2} - {}^4I_{11/2}$ transition.

The crystals were grown by the Czochralski method at the General Physics Institute, Russian Academy of Sciences. The spectroscopic characteristics of the crystals were studied using a spectrometer based on a UF-90 autocollimation chamber (reciprocal linear dispersion 0.1 nm $mm^{-1}$) with a TCD130JK (Toshiba) linear multichannel photodetector. In the standard luminescence measurement scheme, we introduced a Glan prism, which was positioned so that the radiation polarisation direction coincided with the direction of the spectrometer slit, and an aperture limiting the radiation detection angle to 1°. The crystals were excited by a fibre-coupled HLU30F200 (LIMO) diode system with the maximum output power of 10 W at a wavelength of 808 nm. The pump beam was focused into the active element to a spot 400 – 600 μm in diameter.

Figure 1 shows the normalised fragments of luminescence spectra of *a*-cut $Nd:GdVO_4$, $Nd:YVO_4$, $Nd:Gd_{0.7}Y_{0.3}VO_4$, and $Nd:Sc_{0.011}Y_{1.003}V_{0.986}Y_1O_{3.986}$ vanadate crystals at the $^4F_{3/2} - {}^4I_{11/2}$ transition for π- and σ-polarisations. One can see that the luminescence spectra of these crystals are considerably different.

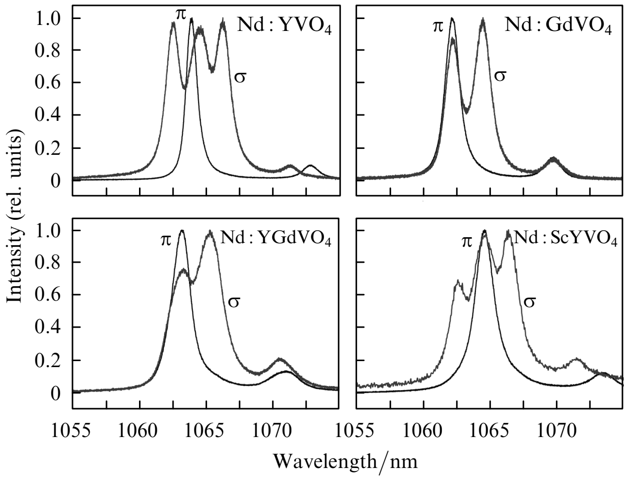

**Figure 1.** Fragments of luminescence spectra of *a*-cut crystals at the $^4F_{3/2} - {}^4I_{11/2}$ transition for π and σ-polarisations.

The absolute maxima of luminescence of *a*-cut $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{0.7}Y_{0.3}VO_4$, and $Nd:Sc_{1-x}Y_xVO_4$ crystals in the case of the σ-polarisation are shifted to longer wavelengths and, hence, the wavelengths of lasers based on these crystals should be different for π- and σ-polarisations.

The intensities of σ-polarised luminescence lines in mixed vanadates depend on the relation between Y, Ga, and Sc concentrations. A change in this relation ($Gd_{1-x}Y_x$ or $Sc_{1-x}Y_x$) changes the gain profile in the wavelength region 1.063 – 1.066 nm. The spectra of $GdVO_4$ and $YVO_4$ crystals in the case of π-polarisation are wider by more than a factor of 1.5. The absolute luminescence maxima of the $Nd:Gd_{0.7}Y_{0.3}VO_4$ and $Nd:Sc_{0.011}Y_{1.003}V_{0.986}Y_1O_{3.986}$ crystals in the lasing region were found to lie at 1065.4 and 1066.1 nm, while their half-widths were measured to be 4.2 and 5.4 nm, respectively. These broad luminescence bands allow one to realise additional functional possibilities of σ-polarised lasers based on *a*-cut vanadate crystals.

It is necessary to note that the σ-polarised luminescence spectra of *a*-cut vanadate crystals exactly coincide with the corresponding spectra of *C*-cut crystals, which we previously measured in [23, 24]. Therefore, all the possibilities of lasers based on *C*-cut vanadate crystals [23, 24] can also be realised in the case of σ-polarised laser radiation. This includes radiation at new wavelengths, continuous frequency tuning, two-frequency lasing for terahertz applications, and shortening of the laser pulse duration to hundreds of femtoseconds. In addition, the difference in the wavelengths in the case of π- and σ-polarisations allows one to create two-frequency lasers with orthogonal polarisations, which is important for consequent conversion of radiation to the terahertz wavelength region in, for example, GaSe crystals.

## 3. Lasing properties of *a*-cut vanadate crystals in the case of σ-polarisation

In our experiments, lasing in *a*-cut $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{0.7}Y_{0.3}VO_4$ and $Nd:Sc_{0.011}Y_{1.003}V_{0.986}Y_1O_{3.986}$ vanadate crystals at the $^4F_{3/2} - {}^4I_{11/2}$ transition for the π- and σ-polarisations was studied in both cw and passively *Q*-switched regimes.

In the case of σ-polarised luminescence, it is necessary to use selecting devices to separate it from the π-polarised luminescence, whose cross section is fivefold higher. For this purpose, we used a scheme based on the birefringence of vanadate crystals (Fig. 2). The active element (AE) of the laser was made in the form of a prism with the front face cut at an angle of 1.5 – 2°. Due to the difference in the refractive indices $n_o$ and $n_e$, the ordinary and extraordinary waves out of the crystal propagate in directions differing by $\Delta\alpha \approx a(n_o - n_e)$, where α is the angle of inclination of the front face. If $\alpha = 2°$, then $\Delta\alpha = 25'$ (for $Nd:YVO_4$, $n_o = 1.9573$ and $n_e = 2.1652$ at the wavelength 1064 nm). Lasing of the ordinary or extraordinary wave corresponds to the π- or σ-polarisation of emitted radiation. In a cavity with plane mirrors and a skewed crystal, it is enough to rotate the output mirror by the angle Δα to switch from π- to σ-polarisation and vice versa.

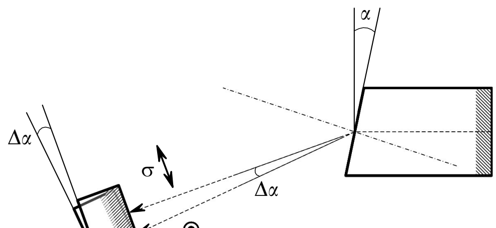

**Figure 2.** Scheme of the cavity for separating π- and σ-polarised beams.

As laser AEs, we used *a*-cut $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{0.7}Y_{0.3}VO_4$, and $Nd:Sc_{0.011}Y_{1.003}V_{0.986}Y_1O_{3.986}$ vanadate crystals with a neodymium atomic concentration of 0.5 % and dimensions 4 × 4 × 6 or 4 × 4 × 8 mm. One of the AE faces was cut at an angle of 1.5 – 2°, and both faces were antireflection coated for wavelengths of 1064 and 808 nm ($R \approx 0.02$ %).

The laser crystal with an indium foil gasket was mounted on a water-cooled copper heatsink. The crystal was pumped by a fibre-coupled (core diameter 200 μm, numerical aperture NA = 0.22) HLU30F200 (LIMO) diode system with the maximum output power up to 30 W. The pump radiation was focused into the active element to a spot 250–400 μm in diameter.

The laser cavity was formed by a plane highly reflecting mirror (with a dielectric coating highly reflecting at the wavelength 1064 nm and antireflecting at the pump wavelength 808 nm) and a plane output mirror (transmittance at the fundamental frequency $T = 4.8\,\%$ and 8 %).

In lasers with this cavity (Fig. 3), we recorded lasing in *a*-cut vanadate crystals at the $^4F_{3/2} - {}^4I_{11/2}$ transition with π- and σ-polarisations at different wavelengths, which correlated with the measured luminescence spectra. These experiments confirmed the correctness of the measurement of luminescence spectra of *a*-cut crystals in the case of σ-polarisation.

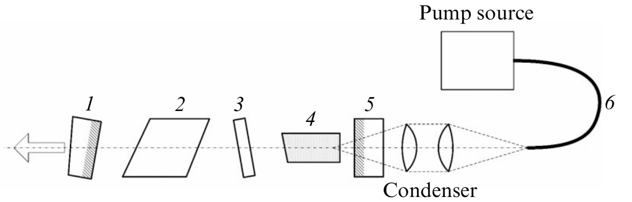

**Figure 3.** Scheme of a nanosecond $Nd^{3+}:YVO_4$ laser with passive and active *Q*-switching: (*1*, *5*) cavity mirrors; (*2*) passive (active) *Q*-switch; (*3*) Fabry–Perot interferometer; (*4*) active element; (*6*) fibre 200 μm in diameter.

In a nonselective cavity, lasing occurs at the wavelength corresponding to the maximum gain; therefore, as follows from Fig. 1, a laser based on an *a*-cut $Nd:GdVO_4$ crystal emits σ-polarised radiation at a wavelength of 1065.5 nm and π-polarised radiation at a wavelength of 1063.2 nm. The *a*-cut $Nd:YVO_4$ and $Nd:Sc_{0.011}Y_{1.003}V_{0.986}Y_1O_{3.986}$ crystals (see Fig. 1) generate σ-polarised radiation at a wavelength of 1066.1 nm and π-polarised radiation at a wavelength of 1064.1 nm. In the case of the $Nd:Gd_{0.7}Y_{0.3}VO_4$ crystal, the laser wavelength in the case of σ-polarisation is 1065.4 nm. Rotation of the output mirror changes both the polarisation and wavelength of the laser.

As a selecting element for continuous frequency tuning of lasers based on *a*-cut vanadate crystals emitting σ-polarised radiation, we used an intracavity Fabry–Perot interferometer (see Fig. 3), namely, a plane-parallel YAG plate about 80 μm thick with coatings with $R = 60\,\%$). Similar to [23, 24], we obtained tuning and two-frequency lasing in *a*-cut crystals of yttrium ($Nd:YVO_4$), gadolinium ($Nd:GdVO_4$), and mixed ($Nd:Gd_{0.7}Y_{0.3}VO_4$ and $Nd:Sc_{1-x}Y_xVO_4$) vanadates with σ-polarisation.

## 4. Passive *Q*-switching of lasers based on *a*-cut vanadate crystals in the case of σ-polarisation

Analysis a passively *Q*-switched laser was performed in [27, 28]. The quality of operation of a passive *Q*-switch in a laser can be estimated using the relation

$$\frac{\ln(1/T_0^2)}{\ln(1/T_0^2) + \ln(1/R) + L}\,\frac{\sigma_{gs}}{\sigma}\,\frac{A}{A_s} \gg \frac{\gamma}{1-\beta}, \tag{1}$$

where $R$ is the output mirror reflectance; $T_0$ is the *Q*-switch initial transmission; $L$ is the optical loss in the cavity; $A/A_s$ is the ratio of the effective areas of the beam waists in the active medium and the *Q*-switch; $\sigma_{gs}$ is the absorption cross section from the ground state of the passive *Q*-switch; $\sigma$ is the stimulated emission cross section of the active medium; $\beta$ is the ratio of the ground state absorption cross section to the excited state absorption cross section in the passive *Q*-switch; and $\gamma$ is the inversion coefficient.

For $Nd^{3+}$ lasers with $Cr^{4+}:YAG$ or $V^{3+}:YAG$ passive *Q*-switches, the right-hand side of the inequality can be taken to be close to unity due to $\gamma = 1$ for four-level systems. For the $Cr^{4+}$ ion in a YAG crystal, we have $\beta \sim 1/7$ (this ratio for $V^{3+}$ in YAG is even smaller, 1/21). The ratio

$$\frac{\ln(1/T_0^2)}{\ln(1/T_0^2) + \ln(1/R) + L}$$

characterises the passive properties of the cavity and is invariably smaller than unity. Thus, the absorption cross section ratio $\sigma_{gs}/\sigma$ shows the possibility of using an active medium in a scheme with passive *Q*-switching. Table 1 presents the stimulated emission cross sections and ratios $\sigma_{gs}/\sigma$ for $Nd:YAG$, $Nd:YVO_4$, and $Nd:GdVO_4$ crystals for π- and σ-polarisations.

**Table 1.** Stimulated emission cross sections $\sigma$ and ratios $\sigma_{gs}/\sigma$ for different crystals.

| Crystal | Polarisation | $\sigma/10^{-19}$ cm$^2$ | $\sigma_{gs}/\sigma$<br>Passive *Q*-switch<br>$Cr^{4+}:YAG$ | <br><br>$V^{3+}:YAG$ |
|---|---|---|---|---|
| $Nd:YAG$ | | 2.8 | 11.4 | 10.7 |
| $Nd:YVO_4$ | π | 14 [11] | 2.6 | 24 |
| | σ | 2.8 [11] | 9 | 8.7 |
| $Nd:GdVO_4$ | π | 10.3 [17] | 3.1 | 2.9 |
| | σ | 2.1 [17] | 15.2 | 14.3 |

One can see that the ratio $\sigma_{gs}/\sigma$ for $Nd:YVO_4$ and $Nd:GdVO_4$ crystals at the π-polarisation is small, so that inequality (1) can hardly be satisfied. This is caused by the fact that, to obtain acceptable characteristics of lasers based on crystals with a small $\sigma_{gs}/\sigma$ ratio, it is necessary to increase the ratio $A/A_s$, i.e., to decrease the beam waist diameter in the passive *Q*-switch crystal with increasing pump mode cross section, which is not always possible. At the same time, in the case of σ-polarisation of generated radiation, the above inequality can be satisfied much better, which indicates that the laser can operate in an acceptable regime.

In order to create efficient pulsed $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{1-x}Y_xVO_4$, and $Nd:Sc_{1-x}Y_xVO_4$ lasers and to obtain shorter pulse durations, we studied the passive *Q*-switching regime in the case of π- and σ-olarisations with the use of $Cr^{4+}:YAG$ and $V^{3+}:YAG$ *Q*-switches.

For brevity, below we present the results only for the $Nd:YVO_4$ laser with $Cr^{4+}:YAG$ and $V^{3+}:YAG$ *Q*-switches.

In the experiments, we used a laser scheme with a skewed crystal (Fig. 2) and a passive *Q*-switch positioned near the output mirror. The $Nd^{3+}:YVO_4$ active element and the pumping system were described above. To obtain a pulsed regime of the $Nd^{3+}:YVO_4$ laser, we used $Cr^{4+}:YAG$ passive *Q*-switches with initial transmission of 90 %, 81 %, and 76 % at the wavelength 1.06 μm. The optimal initial transmission of the $Q$-switch and the output mirror transmission were 81 % and 75 %, respectively; the cavity length was ~ 20 mm.

Figure 4 shows the energy dependences for the $Nd^{3+}:YVO_4$ laser in cw and pulsed regimes with the use of $Cr^{4+}:YAG$ and $V^{3+}:YAG$ $Q$-switches. One can see that the lasing threshold in the case of π-polarisation is considerably lower and the efficiency is higher than in the case of σ-polarisation. This is caused by the difference in the stimulated emission cross sections in the case of π- and σ-polarisations. The slope efficiency for the σ-polarisation reached 58 % and 32 % for cw and pulsed regimes, respectively.

Figure 5 presents the measured characteristics (pulse duration, pulse repetition rate, pulse energy, and peak power) of the $Nd:YVO_4$ laser with a $Cr^{4+}:YAG$ passive $Q$-switch for π- and σ-polarisations.

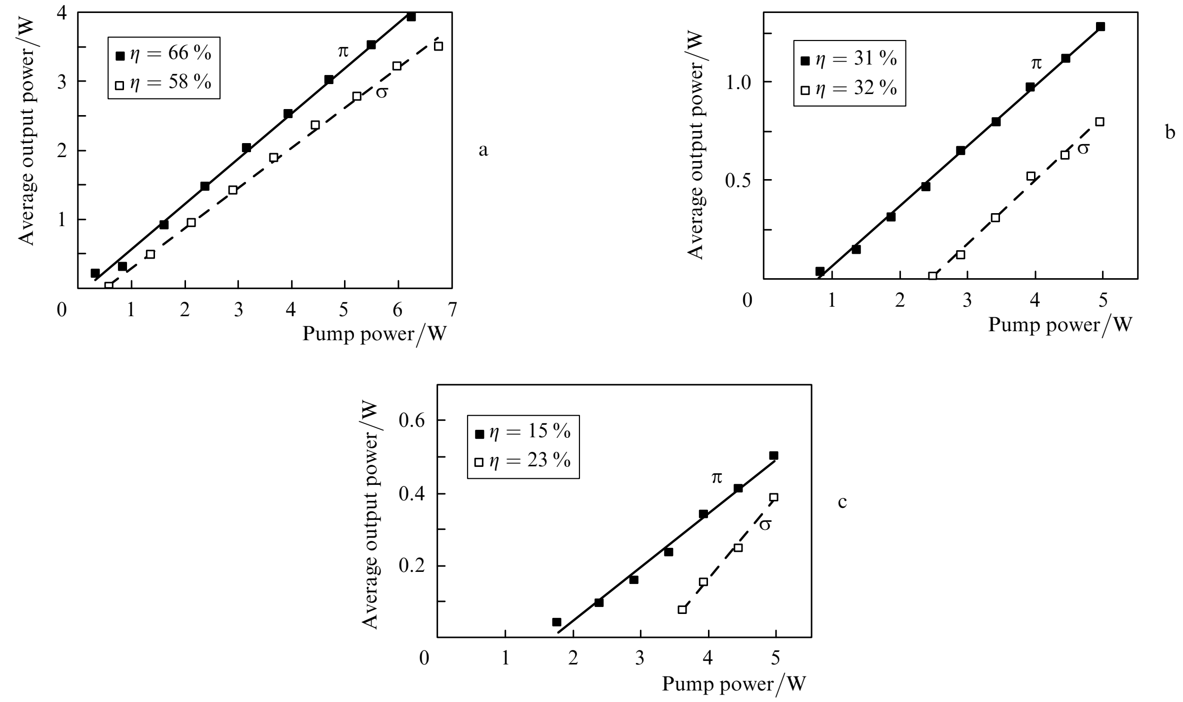

**Figure 4.** Average output power of a $Nd:YVO_4$ laser in the cw (a) and pulsed regimes with $Cr^{4+}:YAG$ (b) and $V^{3+}:YAG$ (c) passive $Q$-switches.

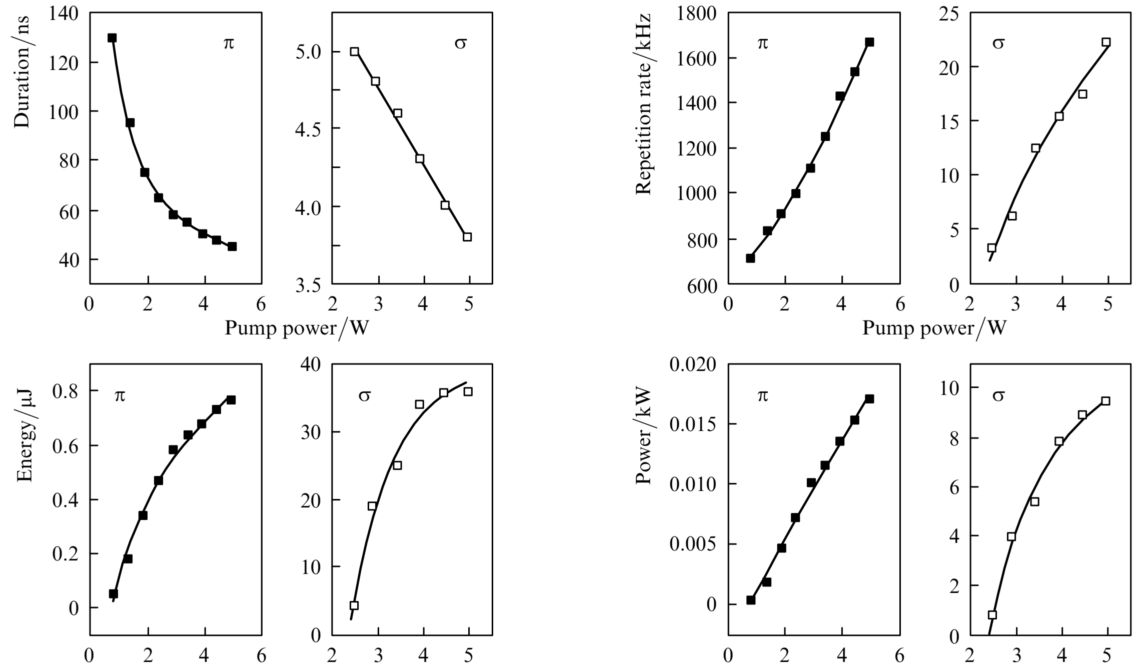

**Figure 5.** Dependences of the duration, repetition rate, energy, and power of π- and σ-polarised output pulses of a $Nd:YVO_4$ laser with a $Cr^{4+}:YAG$ passive $Q$-switch on the absorbed pump power.

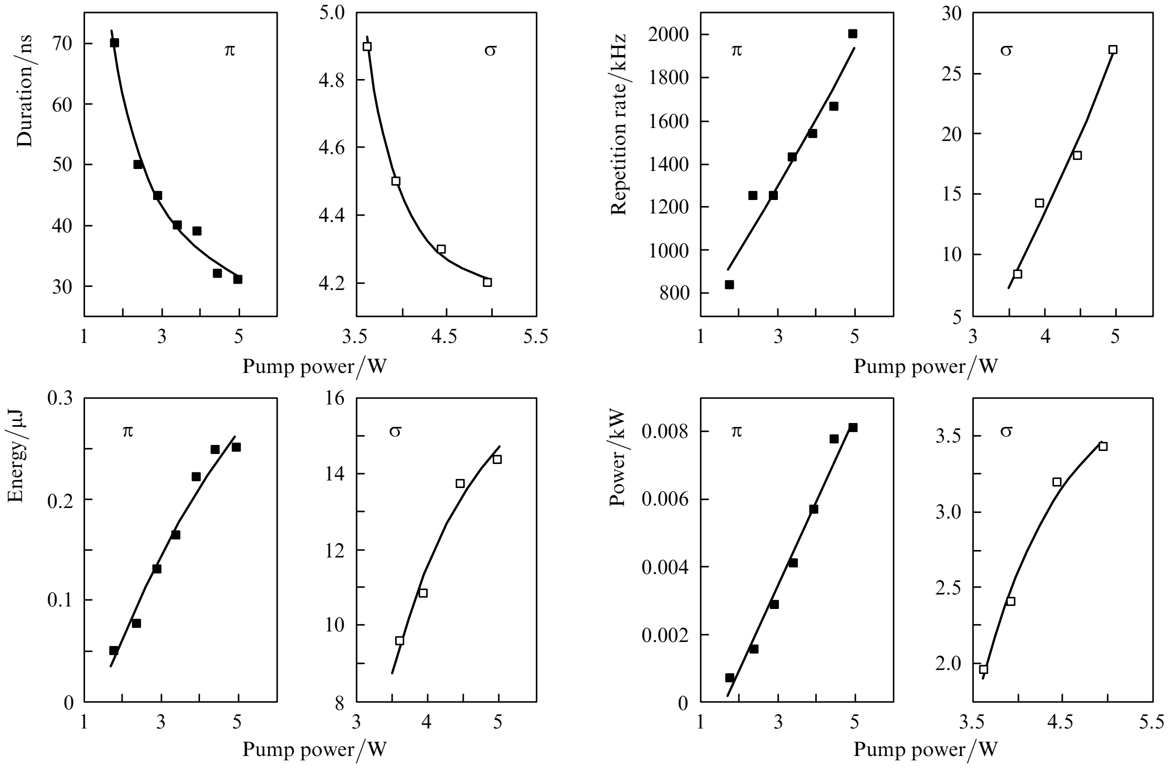

**Figure 6.** Dependences of the duration, repetition rate, energy, and power of π- and σ-polarised output pulses of a Nd : YVO$_4$ laser with a V$^{3+}$ : YAG passive $Q$-switch on the absorbed pump power.

In the case of σ-polarisation, the laser emitted a steady sequence of pulses with a stable amplitude and repetition rate almost in the entire pump power region. The minimum pulse duration reached 3.5 ns at a pulse repetition rate of 15–20 kHz, the pulse power exceeded 9 kW, and the pulse energy was ~ 35 μJ. In the case of π-polarisation, the pulse duration and repetition rate were unstable and differed by more than an order of magnitude.

Figure 6 shows the same dependences for the Nd : YVO$_4$ laser with a V$^{3+}$ : YAG $Q$-switch. The initial absorption of the $Q$-switch was 25 %, and the output mirror transmission was 25 %. Similar to the case with the Cr$^{4+}$ : YAG $Q$-switch, the Nd : YVO$_4$ laser with the V$^{3+}$ : YAG passive $Q$-switch in the case of σ-polarisation generated a steady sequence of pulses with a stable amplitude and frequency almost in the entire pump power region. The minimum pulse duration was 4 ns at a pulse repetition rate of 22 kHz. At the absorbed pump power of about 5 W, the average output power reached 0.4 W, the pulse power was about 3.5 kW, and the maximum pulse energy exceeded 15 μJ. At the π-polarisation, the laser generated an unsteady chaotic sequence of pulses, whose average duration and repetition rate were an order of magnitude larger than in the case of σ-polarisation.

Similar results were obtained at the $^4F_{3/2} - {}^4I_{11/2}$ transitions for $a$-cut Nd : GdVO$_4$, Nd : Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y$_x$VO$_4$ vanadate crystals in the case of π- and σ-polarisations in the passive $Q$-switching regime achieved using Cr$^{4+}$ : YAG and V$^{3+}$ : YAG $Q$-switches.

## 5. Conclusions

The luminescent and lasing properties of $a$-cut NdYVO$_4$, Nd : GdVO$_4$, Nd : Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y$_x$VO$_4$ vanadate crystals at the $^4F_{3/2} - {}^4I_{11/2}$ transition are experimentally studied for π- and σ-polarisations. It is shown that the change from π- to σ-polarisation leads to a change in the laser wavelength.

We studied the polarisation dependences of Nd : YVO$_4$, Nd : Gd$_{1-x}$Y$_x$VO$_4$, and Nd : Sc$_{1-x}$Y$_x$VO$_4$ lasers in the passive $Q$-switching regime with Cr$^{4+}$ : YAG and V$^{3+}$ : YAG $Q$-switches. The best laser characteristics are achieved in the case of σ-polarisation (minimum pulse duration shorter than 3 ns, maximum peak power up to 10 kW, maximum peak energy about 35 μJ, slope efficiency up to 32 %).

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