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Multiwavelength UV-IR laser system based on *a*-cut Nd : YVO$_4$ – YVO$_4$ composite vanadate crystals with σ-polarised radiation[*]

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Abstract. **Lasing properties of *a*-cut Nd : YVO$_4$ – YVO$_4$ composite vanadate crystals are experimentally studied for the π and σ polarisations of radiation at the $^4F_{3/2}$ – $^4I_{11/2}$ transition. Polarisation dependences of the lasing characteristics of passively *Q*-switched Nd : YVO$_4$ – YVO$_4$ lasers with Cr^{4+} : YAG *Q*-switches are investigated. It is shown that the laser operates with the highest efficiency in the case of the σ-polarised radiation (minimum pulse duration shorter than 1.5 ns, maximum peak power up to 25 kW, maximum peak energy about 35 μJ at a slope efficiency up to 32 %). Frequency conversion to the second and fourth harmonics is demonstrated. Based on this study, a multiwavelength laser with bactericidal and therapeutic effects is developed for treatment of a wide spectrum of diseases.**

Keywords: *composite vanadate crystals, passive Q-switching, harmonic generation.*

1. Introduction

At present, UV lasers are widely used in engineering, science, and medicine. One of the interesting applications in biology and medicine consists in irradiation of various microorganisms by low-intensity UV lasers. The treatment of patients suffering from fibrous-cavernous pulmonary tuberculosis still remains a complicated and important problem in modern medicine. The Central TB Research Institute, Russian Academy of Medical Sciences, in collaboration with the General Physics Institute, Russian Academy of Sciences, studied the action of UV laser radiation on various cultures of microorganisms. In particular, a method of endocavitary laser irradiation was developed for treatment of patients with pulmonary tuberculosis. Initially, a nitrogen UV laser (337 nm) was used [1]. However, it is known [2] that the peak of bactericidal activity lies in the wavelength region of 200–300 nm. Experiments with 266-nm laser radiation confirmed that this radiation more strongly affects microorganisms. Further experiments showed that the combined action of multiwavelength radiation in the ultraviolet, visible, and infrared regions is even more efficient for these purposes [3].

Thus, it seems reasonable to create inexpensive and simple multiwavelength (UV–visible–IR) laser systems for medicine and use them for further development of different methods of laser irradiation of microorganisms for the treatment of patients with tuberculosis and other diseases.

There exists a multiwavelength laser system based on a solid-state laser with active (acoustooptic or electrooptic) *Q*-switching for bactericidal and therapeutic treatment of suppurative inflammatory processes in soft tissues and internal organs [3]. The use of acoustooptic and electrooptic *Q*-switches requires special control voltage generators, which leads to additional energy consumption and increases the mass and size of the system. In addition, such *Q*-switches and control systems are rather expensive. Moreover, sinusoidal voltage generators for acoustooptic *Q*-switches are high-power sources of high-frequency (50–80 MHz) signals, while control voltage generators for electrooptic *Q*-switches require a high voltage (2–4 kV).

The cheapest and simplest solution for the creation of needed medicine laser systems is to use passive *Q*-switches based on, for example, Cr^{4+} : YAG or V^{3+} : YAG crystals. Vanadate crystals (yttrium vanadate YVO$_4$ [4], gadolinium vanadate GdVO$_4$ [5], and mixed vanadates Nd : Gd$_{1-x}$Y$_x$VO$_4$ [6] and Nd : Sc$_{1-x}$Y$_x$VO$_4$ [7]) are excellent materials for diode-pumped lasers.

In [8], we studied the polarisation dependences (for σ- and π- polarisations) of lasing characteristics of Nd : YVO$_4$, Nd : GdVO$_4$, 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 saturable absorbers. It was shown that these lasers most efficiently operate with Cr^{4+} : YAG passive *Q*-switches in the case of the σ-polarisation. In the case of the π-polarisation, the lasers generated a sequence of pulses with a duration and frequency an order of magnitude larger than in the case of the σ-polarisation. The pulse energies and peak powers were also considerably different. Therefore, the frequency conversion to the second and fourth harmonics for the σ-polarised radiation is also expected to be much higher.

The frequency conversion efficiency in nonlinear crystals is determined by the beam quality, which, in turn, strongly depends on the thermal lens in the active laser element. To reduce the thermal lens effect, one usually uses direct pumping [9, 10], composite crystals [11, 12], and modulation of the pump radiation [13].

The aim of the present work is to experimentally study a laser based on yttrium vanadate crystals Nd : YVO$_4$ – YVO$_4$ with passive *Q*-switching by a Cr^{4+} : YAG *Q*-switch and σ-polarised radiation and to achieve efficient frequency conversion to the second and fourth harmonics. This study is important for solving the problem of creating a compact and inexpensive

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multiwavelength laser system for bactericidal and therapeutic treatment of a wide spectrum of diseases, which, due to its design, will have a higher output power in the IR, visible, and UV wavelength regions, as well as a low mass and size and a high degree of safety for the staff and patients.

2. Passive *Q*-switching

In this work, we present the results of investigation of lasers based on *a*-cut composite vanadate crystals Nd : YVO_4–YVO_4 operating at the $^4F_{3/2}$–$^4I_{11/2}$ transition and emitting σ-polarised radiation both in the cw and passive *Q*-switching regimes. A specific feature of operation with σ-polarised radiation is that this requires using selective units for separation from the π-polarised radiation, which has a fivefold higher luminescence cross section. To separate the π- and σ-polarisations, we used a scheme from [8] based on the birefringence of vanadate crystals (Fig. 1).

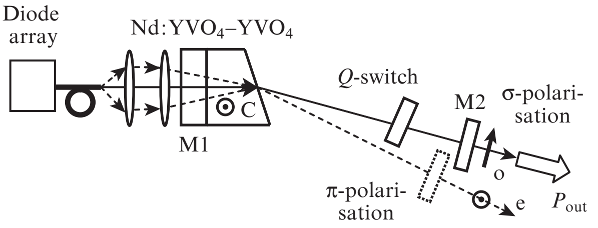

Figure 1. Scheme of separation of polarisations due to the birefringence in vanadate crystals.

As active laser elements (AEs), we used *a*-cut yttrium vanadate crystals 4×4×2 mm in size with a neodymium concentration of 1.1 at% and composite Nd : YVO_4– YVO_4 crystals with the same neodymium concentration and dimensions 4×4×(2+4) mm (the length of the undoped part of the composite crystals was 2 mm). One face of each active element was cut at an angle of ~2° to separate the π- and σ-polarised beams. The high atomic concentration of neodymium was chosen to obtain the minimum cavity length to decrease the pulse duration.

The laser crystal wrapped into indium foil was mounted in a water-cooled copper heatsink. The crystal was excited by a fibre-coupled (core diameter 200 μm, numerical aperture NA = 0.22) LIMO HLU30F200 laser diode array with the maximum output power up to 30 W. The pump beam 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 an antireflection coating at the pump wavelength 808 nm) attached to the AE face and a plane output mirror (transmittance at the fundamental frequency $T = 15\%$). The opposite face of the AE was antireflection coated for radiation with $\lambda = 808$ and 1064 nm ($R \approx 0.02\%$).

To realise a pulsed regime of the Nd:YVO_4–YVO_4-laser, we used passive Cr^{4+} : YAG *Q*-switches. The optimal initial transmittance of the *Q*-switch and the transmittance of the output mirror were 80% and 25%, respectively. The cavity length for Nd:YVO_4 and Nd : YVO_4–YVO_4 crystals was about 5 and 10 mm, respectively.

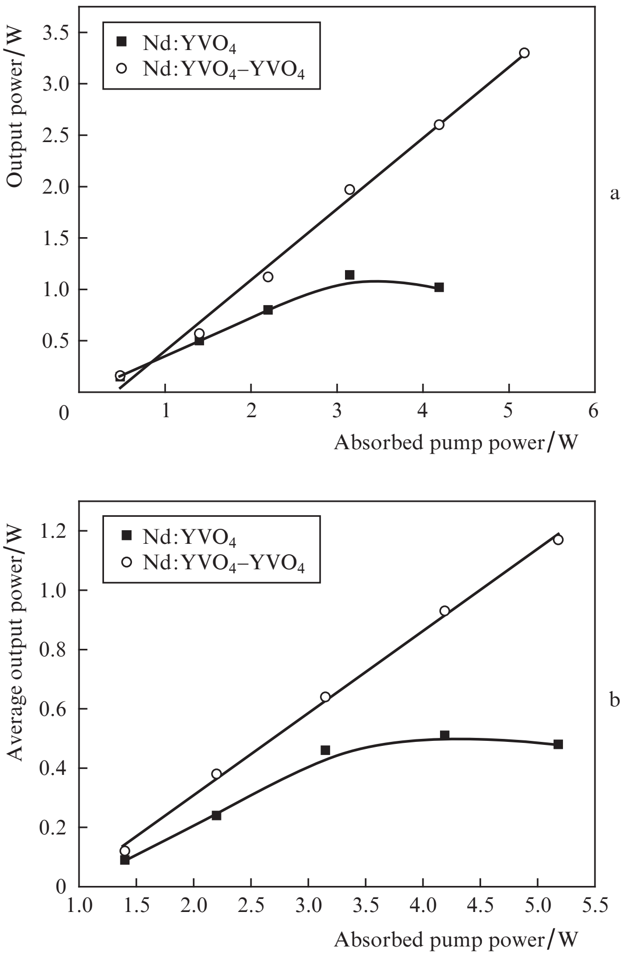

Figure 2. Average output power of Nd : YVO_4 and Nd : YVO_4–$NdVO_4$ lasers in the cw (a) and pulsed (with a Cr^{4+} : YAG passive *Q*-switch) (b) regimes. The thickness of the Nd : YVO_4 AE is 2 mm.

Figure 2 presents the power characteristics of the Nd : YVO_4 and Nd : YVO_4–YVO_4 lasers in the cw and pulsed regimes. The slope efficiency reached 62% in the cw and 31.5% in the pulsed regime. For Nd : YVO_4 crystals, the thermal lens effect was observed at an absorbed pump power exceeding 3 W.

Figure 3 shows the measured laser characteristics (pulse duration, pulse repetition rate, pulse energy, and peak power) of the Nd : YVO_4 and Nd : YVO_4–YVO_4 lasers for the σ-polarisation in the passive *Q*-switching regime. The lasers emit a stable train of pulses with constant amplitude and frequency almost in the entire range of absorbed pump powers. The minimum pulse duration of 1.5 ns was obtained for the Nd : YVO_4 laser (AE 2 mm thick) at a pulse repetition rate of 15–20 kHz. The maximum pulse power, which exceeded 25 kW at a pulse energy higher than 52 μJ, was achieved for the Nd : YVO_4–YVO_4 composite crystals. Thus, Fig. 3 shows that the use of composite crystals is preferable due to a weaker effect of a thermal lens on the lasing characteristics. At longer pulses, it is possible to achieve higher pulse energy and power for these crystals.

3. Frequency conversion

High peak powers of lasers based on *a*-cut vanadate crystals Nd : YVO_4–YVO_4 with Cr^{4+} : YAG passive *Q*-switches allow one to achieve efficient frequency conversion to the visible and UV wavelength regions. We studied three schemes of frequency conversion to the fourth harmonic (Fig. 4).

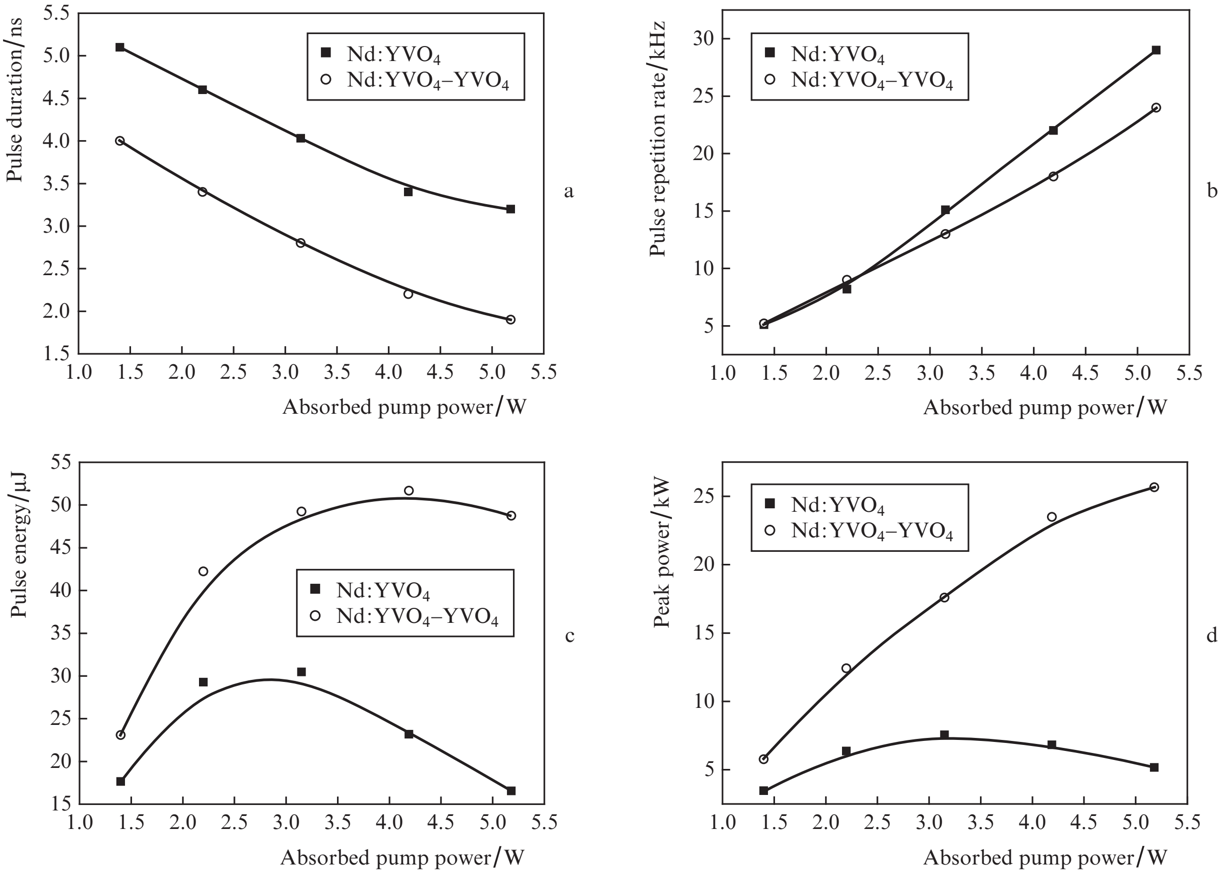

Figure 3. Dependences of the duration (a), repetition rate (b), energy (c), and peak power (d) of σ-polarised output pulses of Nd : YVO$_4$ and Nd : YVO$_4$ – YVO$_4$ lasers with Cr^{4+} : YAG passive *Q*-switches on the absorbed pump power. The Nd : YVO$_4$ AE is 2 mm thick.

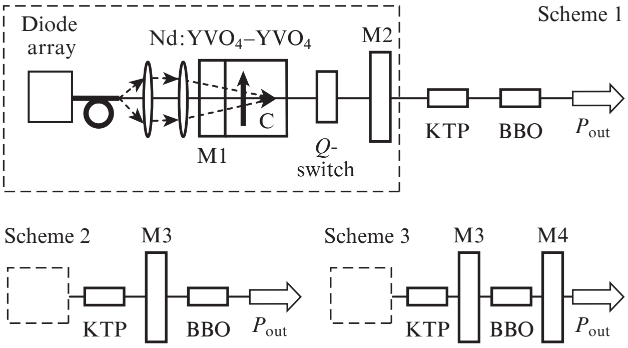

Figure 4. Scheme of passively *Q*-switched UV lasers based on *a*-cut vanadate crystals with σ-polarised radiation (scheme 1), with the intracavity frequency conversion to the second harmonic (scheme 2), and with the intracavity conversion to the second harmonic and the multipass conversion to the fourth harmonic (scheme 3).

For the second harmonic generation, we used a nonlinear KTP crystal placed directly behind the output mirror M2. The crystal was mounted on a Peltier microcooler, whose temperature was stabilised with an error of ±0.1 °C. For frequency conversion to the fourth harmonic, we used nonlinear BBO crystals without thermal stabilisation.

In scheme 1, the KTP (3×3×10 mm) and BBO (3×3×7 mm) crystals were placed coaxially one after the other directly behind the output mirror. The conversion occurred for one pass. The laser cavity 12 mm long consisted of mirror M1 (with a high reflectance at $\lambda \approx 1.06$ μm and an antireflection coating for 808 nm) attached to the active element and mirror M2 with a reflectance of 85%. At an absorbed pump power of 5.2 W, the average power was 740 mW at the fundamental frequency ω, 124 mW at the frequency 2ω, and 5.2 mW at the frequency 4ω (see Fig. 5).

In scheme 2, we achieved intracavity frequency conversion to the second harmonic and single-pass conversion to the fourth harmonic. In this case, the cavity length was increased

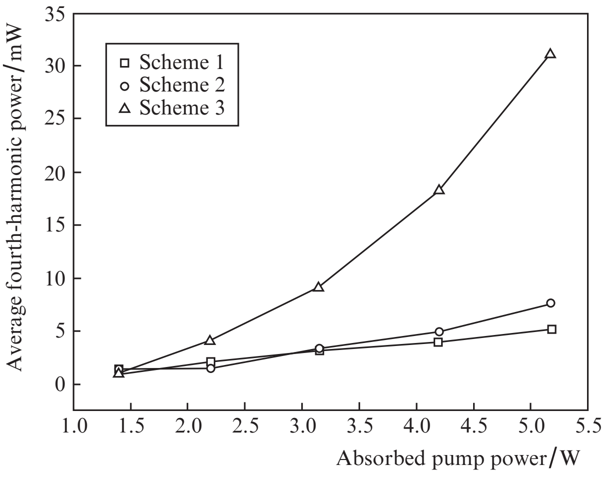

Figure 5. Dependence of the fourth-harmonic power on the absorbed pump power for the three conversion schemes shown in Fig. 4.

to 32 mm in order to include a KTP crystal and a return mirror M2 (with a high reflectance at $\lambda \approx 0.53$ μm and an antireflection coating at $\lambda \approx 1.06$ μm). The output mirror M3 had a high reflectance at $\lambda \approx 1.06$ μm and an antireflection coating at $\lambda \approx 0.53$ μm. Due to the increase in the cavity length and the introduction of additional intracavity losses, the pulse duration was larger. In this case, the average power reached 364 mW for the second harmonic and 7.4 mW for the fourth harmonic (Fig. 5).

In scheme 3, we obtained intracavity frequency conversion to the second harmonic and multipass conversion [14] to the fourth harmonic. The coating of mirror M3 had a high reflectance at 0.266 μm, while the coating of mirror M4 had a high reflectance for $\lambda \approx 0.53$ μm and was antireflective at $\lambda \approx 0.266$ μm. Due to the multipass conversion in the BBO crystal, the average fourth-harmonic power reached 32.2 mW (Fig. 5)

Thus, scheme 2 with a more complex cavity gives an insignificant increase in the fourth harmonic generation efficiency. To create a UV laser with a power up to 5 mW, it is more advantageous to use scheme 1. For average powers up to 30 mW and higher, the more complex scheme 3 is more efficient.

4. Medical laser system ‘Livadiya’

The multiwavelength laser system ‘Livadiya’ for bactericidal and therapeutic treatment of infectious diseases, which is based on *a*-cut composite vanadate crystals $Nd:YVO_4-YVO_4$ for the σ-polarisation, operates in the *Q*-switching regime with a Cr^{4+}:YAG saturable absorber. The ‘Livadiya’ system contains a solid-state laser with longitudinal diode pumping and passive *Q*-switching, a power supply, a control system, a frequency converter to the visible and UV spectral regions based on nonlinear crystals, a system for selection of spectral regions, and a fibre-optic system for laser radiation transport.

5. Conclusions

Lasing properties of *a*-cut composite vanadate crystals $Nd:YVO_4-YVO_4$ are experimentally studied for the σ-polarisation of radiation at the $^4F_{3/2}-{}^4I_{11/2}$ transition.

The polarisation dependences of the lasing characteristics of $Nd:YVO_4-YVO_4$ lasers operating in the passive *Q*-switching regime with Cr^{4+}:YAG saturable absorbers are investigated. The obtained characteristics are as follows: the minimum pulse duration below 1.5 ns, the maximum peak power up to 10 kW, and the maximum peak energy of about 52 μJ at a slope efficiency up to 32%. Efficient frequency conversion to the visible and UV wavelength regions is realised.

The obtained results served as a basis for the development of a ‘Livadiya’ medical laser system, which is meant for the suppression of pathogenic microflora in the areas of suppurative inflammation in human soft tissues, mucous membranes, and internal organs with simultaneous stimulation of reparative processes in tissues using multiwavelength laser radiation in the UV, visible, and IR wavelength regions. The system can also be used for therapeutic procedures in patient care institutions, preventive treatment institutions, and scientific-research medical institutions of various profiles.

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