

PACS numbers: 42.55.Rz; 42.70.Hj; 42.25.Ja
DOI: 10.1070/QE2012v042n05ABEH014785

Two-frequency vanadate lasers with mutually parallel and orthogonal polarisations of radiation

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Luminescent and lasing properties of *a*-cut Nd:YVO_4, Nd:$GdVO_4$, Nd:$Gd_{1-x}YxVO_4$, and Nd:$Sc_{1-x}Y_xVO_4$ vanadate crystals are experimentally studied for the π- and σ-polarisations of the emission at the $^4F_{3/2}$–$_4F_{11/2}$ transition. Two-frequency lasing was obtained with mutually orthogonal and parallel polarisations of radiation in the cw, *Q*-switching, and mode-locking regimes. A scheme of a laser–amplifier of two-frequency pulses is realised.

Keywords: *two-frequency lasers, vanadate crystals, polarisation.*

1. Introduction

The terahertz frequency range extends from hundreds of terahertz to hundreds of gigahertz. This range is a rather interesting, wide, and informative spectral region for investigating a large number of objects (solids, liquids, biological objects). The terahertz radiation has no ionising effect in contrast to radioactive (X-ray) radiation, and the use of the harmless terahertz frequencies instead of X-ray radiation may considerably change the market of diagnostic medical equipment. The terahertz radiation can be used for continuous monitoring of living objects, for example, in tomography, safety systems, and control equipment.

For recent years, several different methods have been proposed and developed for generating electromagnetic pulses of micro- and millimetre wavelength regions [1–5]. However, despite the successful use of femtosecond laser pulses for generating terahertz radiation in a wide frequency range (from tens and hundreds of gigahertz to terahertzs), such sources did not find wide application mainly due to a significant complexity and a high cost of femtosecond lasers.

At present, investigations aimed at further improvement of terahertz sources are performed in different ways. A promising and rapidly developing method to obtain terahertz radiation is to create two-frequency lasers and then use the difference frequency in nonlinear crystals or optoelectronic terahertz emitters.

The method of using two lasers to obtain a difference frequency for generating terahertz radiation has already been used previously [6–10]. Another approach consists in using radiation at two wavelengths from one and the same laser rather than from two different lasers. In this case, there is no need to synchronise the frequencies of two lasers and then to match the laser beams in time and space, owing to which the system can be more compact and reliable. In the future, this must lead to the creation of compact frequency-tuneable terahertz sources, which will be less expensive than available systems based on femtosecond lasers.

Diode-pumped solid-state lasers are more advantageous compared to gas and lamp-pumped solid-state lasers. They can operate both in the pulsed (*Q*-switching or mode-locking) and cw regimes with high efficiencies and a high stability of the radiation frequency, have small weight and size, low energy consumption, and a long service life. Nonlinear conversions make it possible to widen the spectral range of these lasers and extend the field of their application.

The YVO_4 [11], $GdVO_4$ [12], Nd:$Gd_{1-x}Y_xVO_4$ [13], and Nd:$Sc_{1-x}Y_xVO_4$ [14] vanadate crystals are excellent materials for diode-pumped lasers. In comparison with the widely used Nd:YAG and Nd:YLF crystals, vanadate crystals have some advantages, namely, large absorption and stimulated emission cross sections, as well as wide absorption lines at the pump wavelength. The combination of the spectral and mechanical properties of these crystals leads to a high efficiency of lasers in the cw and pulsed regimes. The anisotropy of the vanadate crystal lattice allows one to obtain polarised radiation, while the high thermal conductivity allows better cooling of the active medium. Most known works on vanadate crystals consider *a*-cut crystals for π-polarised ($E \parallel c$) laser radiation, because the gain in this case is maximum. The difference in the properties of vanadate crystals along different axes allows one, if needed, to choose directions with transforming luminescence spectra and changing gain cross sections [15, 16].

The wide use of anisotropic properties of vanadates requires refining their spectral characteristics. A characteristic feature of many vanadates is that the absolute maxima in the luminescence spectra correspond to the $^4F_{3/2}$–$^4I_{11/2}$ transition for the π- and σ-polarisations. In [15–17], we showed that the shape of the luminescence spectra of *a*-cut vanadate crystals for the σ-polarisation coincides with the shape of the spectra of *c*-cut ($E \perp c$) crystals. The positions of the absolute maxima in the luminescence spectra for the σ-polarisation are shifted to longer wavelengths with respect to the maxima for the π-polarisation, which makes it possible to design simple schemes of two-frequency lasing with orthogonally polarised beams [18, 19].

In this work, we experimentally study the luminescent parameters of *a*-cut Nd:YVO_4, Nd:$GdVO_4$, Nd:$Gd_{1-x}Y_xVO_4$, and Nd:$Sc_{1-x}Y_xVO_4$ vanadate crystals for the π- and

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Received 28 November 2011; revision received 12 March 2012
Kvantovaya Elektronika **42** (5) 420–426 (2012)
Translated by M.N. Basieva

σ-polarisations of radiation at the $^4F_{3/2}-^4I_{11/2}$ transition in order to obtain two-frequency lasing with mutually parallel and orthogonal polarisations of the radiation.

2. Luminescent parameters of *a*-cut vanadate crystals for the σ-polarisation

To refine the wavelengths of vanadate lasers with the σ-polarisation, we previously [17] experimentally studied the luminescence spectra of *a*-cut $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{1-x}Y_xVO_4$, and $Nd:Sc_{1-x}Y_xVO_4$ vanadate crystals for the π- and σ-polarisations of radiation at the $^4F_{3/2}-^4I_{11/2}$ transition.

All the studied crystals were grown by the Czochralski method in 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. The crystals were excited by a fibre-coupled LIMO HLU30F200 diode system (depolarised emission) with the maximum output power up to 30 W at a wavelength of 808 nm. The pump beam was focused into the crystal to a spot 200–600 μm in diameter.

Figure 1 shows fragments of normalised luminescence spectra of *a*-cut vanadate crystals for the π- and σ-polarisations, as well as the laser spectra for different polarisations of radiation in a nonselective cavity. The absolute luminescence maxima of the $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{0.7}Y_{0.3}VO_4$, and $Nd:Sc_{0.03}Y_{0.97}VO_4$ in the case of the σ-polarisation are shifted to longer wavelengths, and, hence, the wavelengths of lasers based on these crystals are different for the π- and σ-polarisations.

It should be noted that the luminescence spectra of *a*-cut vanadate crystals in the case of the σ-polarisation exactly coincide with the spectra of *c*-cut crystals measured by us in [15, 16]. Therefore, all the capabilities of lasers based on *c*-cut vanadate crystals 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 for the π- and σ-polarisations allows one to create two-frequency lasers with orthogonal polarisations of the radiation, which is important for consequent frequency conversion to the terahertz region in, for example, GaSe crystals.

3. Lasing properties of vanadate crystals for the σ-polarisation

We experimentally studied lasing in $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{0.7}Y_{0.3}VO_4$, and $Nd:Sc_{0.03}Y_{0.97}VO_4$ vanadate crystals at the $^4F_{3/2}-^4I_{11/2}$ transition for the π- and σ-polarisations

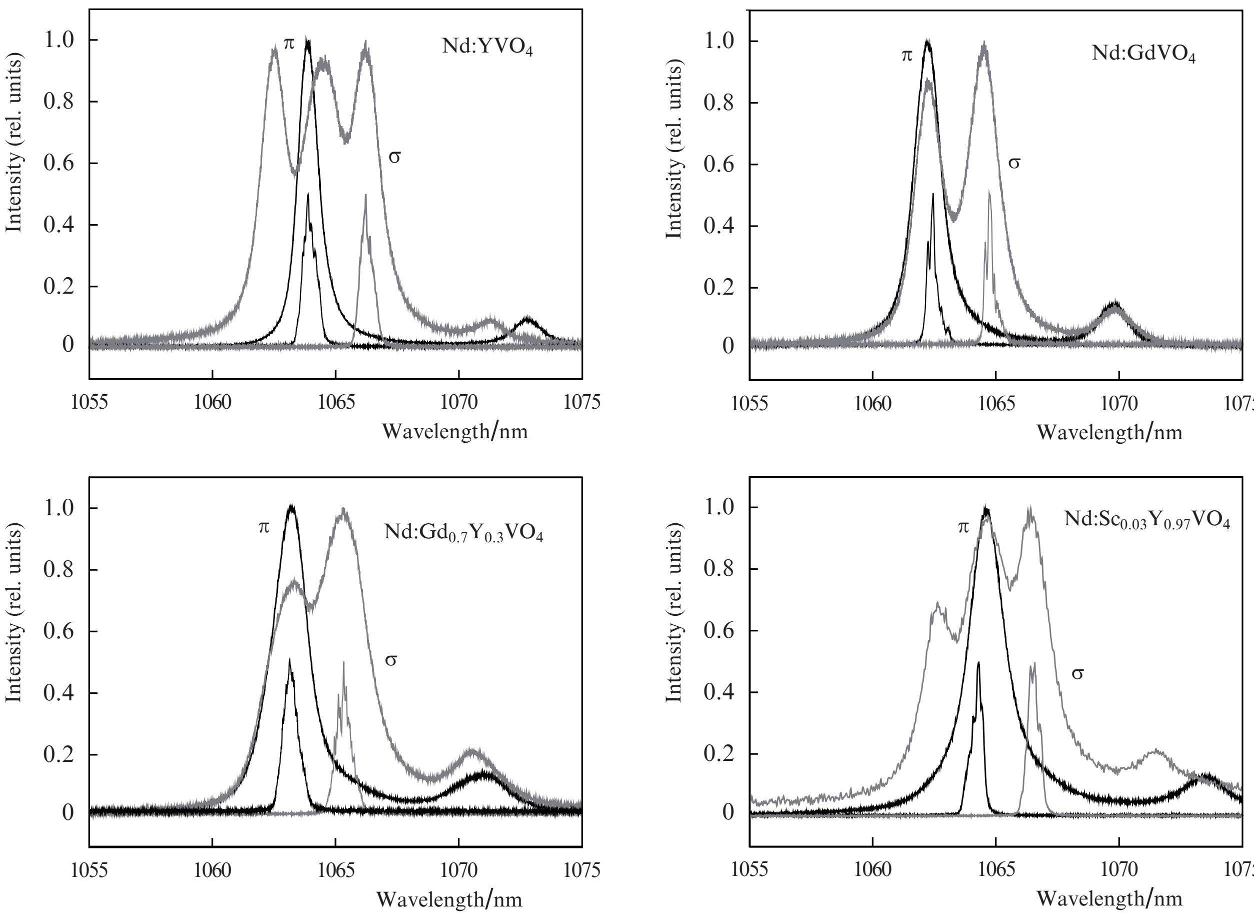

Figure 1. Fragments of the luminescence spectra of the $^4F_{3/2}-^4I_{11/2}$ transition of *a*-cut vanadate crystals for the π- and σ-polarisations and lasing spectra in nonselective cavities.

both in the cw and in the passive and active Q-switching regimes.

When working with the σ-polarised radiation, one must use selective devices to suppress lasing of radiation with the π-polarisation, for which the luminescence cross section is fivefold higher. For spatial separation of the beams with the π- and σ-polarisations, we used the scheme [17] based on the birefringence of vanadate crystals (Fig. 2). The active element of the laser was made in the form of a prism with the front face cut at an angle of 1.5–2°.

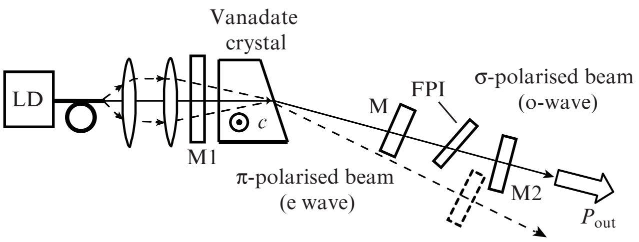

Figure 2. Cavity scheme with spatial separation of beams with the π- and σ-polarisations for lasers based on a-cut vanadates. (M) modulator, (FPI) Fabry–Perot interferometer, (LD) laser diode.

Due to the difference in the n_o and n_e refractive indices (for Nd : YVO_4, n_o = 1.9573 and n_e = 2.1652 at a wavelength of 1064 nm), the ordinary and extraordinary waves out of the crystal propagate in directions differing by $\Delta\alpha \approx \alpha(n_o - n_e)$, where α is the angle of inclination of the front face. Lasing of the extraordinary or ordinary wave corresponds to the emission of π- or σ-polarised radiation. In a cavity with plane mirrors and an oblique face of the crystal, it is enough to rotate the output mirror by the angle $\Delta\alpha$ to switch the laser radiation polarisation.

As active laser elements, we used a-cut Nd : YVO_4, Nd : $GdVO_4$, Nd :$Gd_{0.7}Y_{0.3}VO_4$ and Nd : $Sc_{0.03}Y_{0.97}VO_4$ vanadate crystals with an atomic neodymium concentration of 0.5% and dimensions 4×4×6 mm or 4×4×8 mm. One of the crystal faces was cut at an angle of 1.5–2°, and both faces were antireflection coated for wavelengths of 1064 and 808 nm (R ≈ 0.02%).

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

The laser cavity was formed by a plane highly reflecting mirror M1 (with a dielectric coating highly reflecting at the wavelength 1064 nm and with an antireflection coating for the pump wavelength 808 nm) and a plane output mirror M2 (transmittance T = 10% at the fundamental frequency). Two faces of the active element were antireflection coated for wavelengths of 808 and 1064 nm.

Lasing in a nonselective cavity occurs at the wavelength corresponding to the gain maximum, because of which, as follows from Fig. 1, the 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 : $Sc_{0.03}Y_{0.97}VO_4$ crystals (see Fig. 1) generate σ-polarised radiation at a wavelength of 1066.1 nm and π-polarised radiation at 1064.1 nm. The wavelength of σ-polarised radiation of the Nd : $Gd_{0.7}Y_{0.3}VO_4$ crystal is 1065.4 nm. Rotation of the output mirror changes both the polarisation and wavelength of the laser radiation.

4. Frequency tuning of the σ-polarised radiation of vanadate lasers

As a selective element for continuous frequency tuning of the σ-polarised radiation of vanadate lasers, we used an intracavity Fabry–Perot interferometer (see Fig. 2) in the form of a plane-parallel YAG plate 80 μm thick with reflecting coatings (R = 60%). Similar to [15, 16], in the present work we obtained for the first time frequency tuning of the σ-polarised radiation of the yttrium (Nd : YVO_4), gadolinium (Nd : $GdVO_4$), and mixed (Nd : $Gd_{0.7}Y_{0.3}VO_4$ and Nd : $Sc_{0.03}Y_{0.97}VO_4$) vanadate crystals and realised two-frequency lasing.

For example, the wavelength of σ-polarised radiation of the Nd : YVO_4 crystal at the absorbed pump power P_p = 8 W was continuously tuned from 1062.3 to 1067.4 nm, while tuning of the π-polarised radiation was possible only within 0.9 nm around a wavelength of 1064.2 nm.

A similar tuning character was observed for crystals of gadolinium and mixed vanadates. The maximum tuning range of 5.4 nm was achieved for the Nd : $Sc_{0.03}Y_{0.97}VO_4$ crystal.

5. Methods of obtaining two-frequency lasing

There are three methods of obtaining two-frequency radiation of lasers based on vanadate crystals: (1) to introduce additional spectrally selective losses into the cavity; (2) to control the gain of the active medium; and (3) to use a double cavity to separate radiation with different polarisations.

5.1. Two-frequency regime achieved by introducing spectrally selective losses into the cavity

In crystals with comparatively broad gain spectra (for example, Nd : YVO_4, Nd:$GdVO_4$, Nd : $Gd_{0.7}Y_{0.3}VO_4$ and Nd : $Sc_{1-x}Y_xVO_4$ crystals), one can obtain two-frequency lasing by introducing into the cavity selective elements equalising the cavity Q-factor for different ranges of the luminescence spectrum of the active medium due to additional losses. As such elements, we used a Lyot filter, a Fabry–Perot etalon, and a Brewster prism.

If the cavity Q-factor at a wavelength λ_1 is higher than at a wavelength λ_2, lasing will occur at λ_1, and vice versa. If the cavity Q-factors at these wavelengths are equal, the laser will emit radiation at two wavelengths simultaneously.

5.1.1. σ-polarised two-frequency cw lasing in vanadate crystals. In this work, to obtain two-frequency radiation, we used, similar to [15, 16], Fabry–Perot etalons in the form of plane-parallel plates (120 and 83 μm thick) made of YAG crystals without coating. These selectors allowed us to obtain two-frequency radiation at wavelength differing by 2.3 and 3.7 nm, respectively. In this laser scheme (see Fig. 2), the polarisations of the two laser beams were parallel. Two-frequency lasing in Nd : YVO_4, Nd : $GdVO_4$, and mixed Nd : $Gd_{0.7}Y_{0.3}VO_4$ and Nd : $Sc_{1-x}Y_xVO_4$ crystals with σ-polarised radiation was obtained for the first time.

The dependences of the cw output power on the pump power is shown in Fig. 3. The maximum output power for the cw regime reached 1.5 W at a pump power of 12 W. Figure 4 shows the spectrum of the two-frequency output radiation, as well as the spectrum of its second harmonics and their sum.

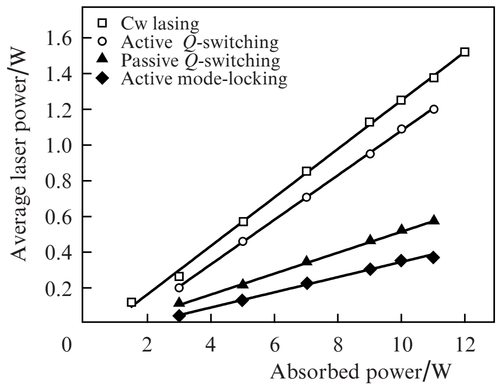

Figure 3. Dependences of the output power of a laser based on an *a*-cut $Nd^{3+}:YVO_4$ crystal on the pump power in the cw, active and passive *Q*-switching, and mode-locking regimes (σ-polarised radiation).

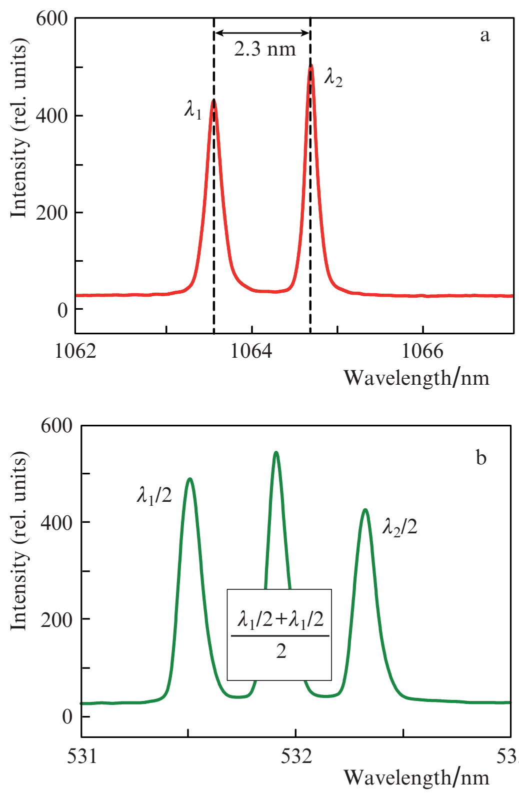

Figure 4. Spectrum of two-frequency σ-polarised cw radiation of an *a*-cut $Nd^{3+}:YVO_4$ crystal (a) and the spectrum of the second harmonic of this radiation (b).

5.1.2. Passive and active Q-switching of two-frequency lasers. In order to increase the efficiency of conversion of two-frequency laser radiation to the terahertz frequency region, we studied the passive and active *Q*-switching regimes. The optical scheme of a pulsed two-frequency $Nd^{3+}:YVO_4$ laser is shown in Fig. 2. The active element of the $Nd^{3+}:YVO_4$ laser, the pumping system, and the Fabry–Perot etalon were described above.

As a *Q*-switch, we used a $Cr^{4+}:YAG$ saturable absorber (initial transmission 80%, thickness 2 mm) placed near the output mirror M2 (transmittance 85%). The use of this *Q*-switch made the laser very compact (cavity length ~40 mm). At this cavity length, the average power of the two-frequency $Nd^{3+}:YVO_4$ laser reached 560 mW (see Fig. 3) with a pulse duration of 15–20 ns and a pulse repetition rate of 8–14 kHz. The replacement of the passive *Q*-switch by an ML-321 acoustooptic modulator lead to an increase in the cavity length to 90 mm. After optimisation of the cavity mirrors, the average two-frequency power of the laser with this cavity and active *Q*-switching reached 1.2 W, the pulse duration was 25 ns, and the pulse repetition rate was 12 kHz (Fig. 3).

For the sake of better energy characteristics and convenience of using (independent control of the pulse repetition rate), further experiments on the frequency conversion to the terahertz region were performed with two-frequency nanosecond $Nd^{3+}:VO_4$ and $Nd^{3+}:GdVO_4$ lasers with active *Q*-switching. However, the cheapest and most compact sources of terahertz radiation can be created based on these lasers with passive *Q*-switching. They can be used as master oscillators for solid-state or fibre amplifiers.

We checked the synchronism of laser pulses at two wavelengths (Fig. 4) using a KTP second harmonic generator. We recorded three peaks with wavelengths $\lambda_1/2$, $\lambda_2/2$ and $(\lambda_1/2 + \lambda_2/2)/2$. The existence of radiation at the frequency $(\lambda_1/2 + \lambda_2/2)/2$ indicates that the pulses at the two wavelengths are generated synchronously.

5.1.3. Combined operation of two-frequency lasers with simultaneous acoustooptic mode locking and active Q-switching. To achieve the maximum peak power of a diode-pumped solid-state two-frequency laser, we studied a longitudinally diode-pumped picosecond $Nd^{3+}:YVO_4$ laser operating in a combined regime, i.e. with simultaneous active *Q*-switching and active mode-locking. This regime of operation allows one to increase the output peak power of the laser almost by two orders of magnitude compared to the power of a quasi-cw picosecond laser.

The optical scheme of the $Nd^{3+}:YVO_4$ laser is shown in Fig. 5. The active element was placed near the highly reflecting mirror, through which the pump light was coupled into the cavity. The pump beam was focused into the active element to a spot with a radius of ~400 μm. To eliminate parasitic reflections, we turned all the faces of optical elements at the Brewster angle to the cavity axis or used wedge-shaped substrates. The Z-shaped cavity was formed by four mirrors: a plane output mirror M4 with a reflection coefficient of 95%, a plane mirror M1, and spherical mirrors M2, M3 with a high reflection at a wavelength of 1.064 μm. An iris aperture 1 mm

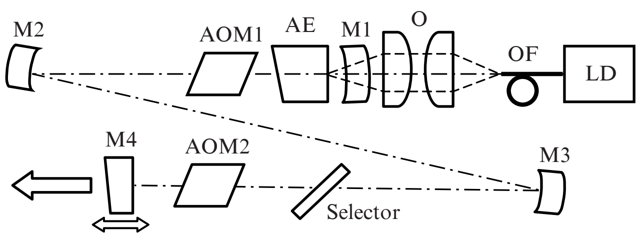

Figure 5. Scheme of a picosecond $Nd^{3+}:YVO_4$ laser with simultaneous active *Q*-switching and active mode-locking: (LD) LIMO30-F200-DL808 pump source; (OF) optical fibre 200 μm in diameter; (O) objective; (M1) – (M4) cavity mirrors; (AE) active element; (Selector) Fabry–Perot interferometer or Lyot filter; (AOM1) acoustooptic modulator for *Q*-switching; (AOM2) acoustooptic modulator for mode-locking.

in diameter placed inside the cavity ensured the laser operation in the fundamental TEM_{00} mode.

For active *Q*-switching of the $Nd^{3+}:YVO_4$ laser, we used an ML-321 acoustooptic modulator with faces antireflection coated for the laser wavelength 1.064 μm. The modulator was controlled by a GSN-50-30i sinusoidal voltage generator with the maximum high-frequency signal power of 30 W. For mode locking we used an AOM SM (AC-1) acoustooptic modulator 45 mm long, which was placed near the output mirror, was temperature stabilised using a Peltier element, and operated at a frequency of 50.139 MHz, which corresponded to the geometric cavity length of 1440 mm (optical length 1495 mm), the pulse repetition rate in this case being 100.278 MHz. The high-frequency signal power of the GSN-50-2 generator was varied from 1.5 to 8 W.

A train of laser pulses was detected by an LFD-2a avalanche photodiode and a Tektronix TDS3052 oscilloscope. The pulse duration was measured using a streak-camera (GPI Photoelectronics Dept. Mod. PN-01/s20, resolution 0.7 ps).

We also studied the dependence of the output power on the pump power (Fig. 3). The maximum output power (360 mW) was achieved at a pump power of 11 W. In this case, the laser emitted pulse trains (train repetition rate 10 kHz) with a duration of 80–120 ns, which contained about 14–20 individual picosecond (30–40 ps) pulses repeating with a rate of ~100 MHz.

5.2. Two-frequency lasing with controlled gain of the active medium

The method of obtaining two-frequency lasing by controlling the active medium gain is similar to the method described above, but the gains in the two spectral regions are equalised by changing the active medium gain rather than by introducing losses. In this work, we propose for the first time two different methods of controlling the gain for *c*-cut (Fig. 6a) and *a*-cut (Fig. 6b) vanadate crystals.

In the case of *c*-cut vanadate crystals, rotation of the active element in the plane of the figure (Fig. 6a) leads to a transformation of the shape of the luminescence spectra. Therefore, the gain in different spectral regions changes. The laser emits simultaneously at two wavelengths if the cavity *Q*-factor is the same for two spectral regions.

A similar angular dependence of the gain for different spectral regions is also observed when an *a*-cut active element is rotated around the cavity axis and the π-polarisation changes for the σ-polarisation (Fig. 6b). In this scheme, it is necessary to fix the polarisation using elements like a Glan prism. One can rotate only the polariser.

Two-frequency lasing was achieved in $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{1-x}Y_xVO_4$ and $Nd:Sc_{1-x}Y_xVO_4$.

5.3. Lasing of two-frequency radiation with mutually orthogonal polarisations of radiation

The difference in the wavelengths of radiation with the π- and σ-polarisations (see Fig. 1) allows one to create two-frequency lasers with mutually orthogonal polarisations of emitted beams, which must be spatially separated. Figure 7 presents the schemes of cavities that allow this separation.

The simplest method (Fig. 7a) is to use birefringence analogously to the scheme in Fig. 2. The active laser element was made in the form of a prism with an oblique (1.5–2°) front face. The pump light was coupled into the cavity through a mirror M1 inclined to the cavity axis at an angle of 45° (this mirror was also responsible for superposition of the two beams). Mirrors M2 and M3, which have high reflection coefficients at a wavelength of ~1066 nm, are highly reflecting mirrors of the cavities emitting the π- and σ-polarised radiation, respectively. The two-frequency radiation was coupled out through a mirror M4.

A drawback of this scheme is that one must use a rather long cavity due to a small difference in the angles of propagation of the ordinary and extraordinary waves outside the crystal. A simpler solution is to use a polariser for spatial separation of the beams with the π- and σ- polarisations (Fig. 7b).

In this work, we obtained for the first time a two-frequency regime of laser operation with mutually orthogonal polarisations of emitted radiation with tuning of the frequency difference. In this cavity scheme (Fig. 7b), we used both *a*- and *c*-cut vanadate crystals. The *c*-cut crystals allowed us to achieve a larger frequency tuning range. A Fabry–Perot etalon introduced into one of the cavity shoulders (Fig. 7b) made it possible to change the difference $\lambda_1 - \lambda_2$ for the emitted radiation. In the future, this approach will allow to create a source of tuneable narrow-band terahertz radiation.

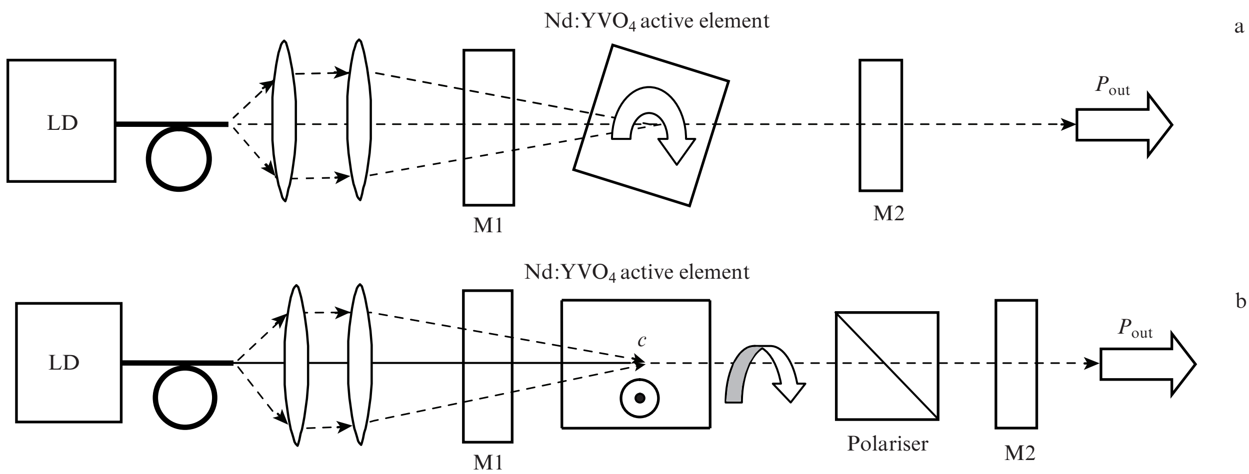

Figure 6. Schemes of two-frequency lasers based on vanadate crystals cut along the *c* (a) and *a* (b) axes with controlled gain of the active medium.

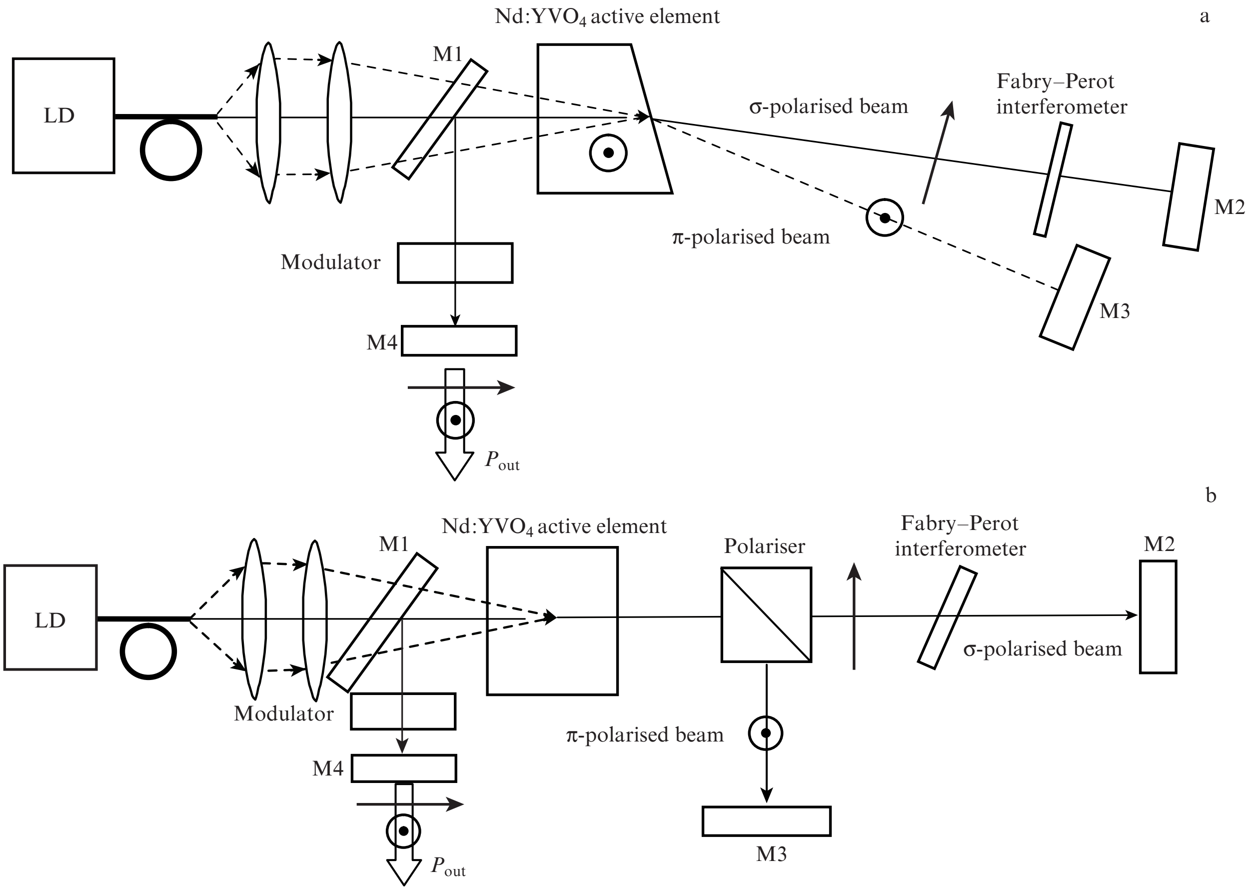

Figure 7. Schemes of two-frequency lasers based on vanadate crystals cut along the *a* (a) and *c* or *a* (b) axes for the π and σ polarisations.

6. Amplifier for a two-frequency laser

A drawback of the above schemes of two-frequency lasers is that one needs both to stabilise the laser power supply and to stabilise the cavity temperature. Any change in the pump parameters makes it necessary to adjust the cavity to keep the two-frequency regime. Therefore, it seems important to create a master oscillator–amplifier system in order to improve the energy parameters of two-frequency lasers. The active medium of the amplifier must ensure matching of the radiation spectra and must be able to operate with orthogonal and parallel polarisations of radiation. The *c*-cut vanadate crystals satisfy these requirements for active media.

In this work, we studied for the first time an amplifier based on a $YVO_4:Nd^{3+}$ crystal cut along the *c* axis (Fig. 8).

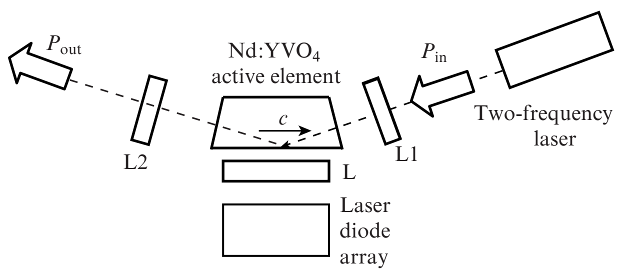

Figure 8. Scheme of an amplifier of two-frequency radiation based on *c*-cut vanadate crystals.

We chose the scheme of a grazing incidence slab amplifier [20]. The $YVO_4:Nd^{3+}$ slab 20×5×2 mm in size was pumped by the radiation of a 45-W laser diode array focused by a cylindrical lens *L* (focal distance 15 mm). The 5×2-mm and 20×2-mm faces were antireflection coated for wavelengths of 1066 nm and 808 nm, respectively. This scheme with the use of cylindrical lenses *L*1 and *L*2 (focal distances 45 mm) allowed us to match the caustics of the beams of the master oscillator and the amplifier. In the single-pass amplifier scheme, we achieved an average power of 1.6 W using a master oscillator based on a two-frequency passively *Q*-switched $Nd^{3+}:YVO_4$ laser (maximum power 0.2 W, pulse duration 25 ns).

7. Conclusions

In this paper, we showed that the luminescence spectra of *c*- and *a*-cut $Nd:YVO_4$, $Nd:GdVO_4$, $Nd:Gd_{1-x}Y_xVO_4$ and $Nd:Sc_{1-x}Y_xVO_4$ crystals coincide in the case of the σ-polarisation. It is demonstrated that the laser radiation wavelengths are different for the π- and σ-polarisations. For the first time, we achieved frequency tuning of laser radiation with the σ-polarisation and realised two-frequency lasing with mutually orthogonal and parallel polarisations of radiation. Stable two-frequency lasing in vanadate crystals with the σ-polarisation was observed in the following regimes: (i) cw (maximum average power 1.5 W), (ii) passive and active *Q*-switching (maximum average power 0.56 and 1.2 W, respectively), and (iii) active mode-locking simultaneously with active *Q*-switching (maximum average power 355 mW).

A laser-amplifier system based on *c*-cut $Nd^{3+}:YVO_4$ crystals is studied for the first time.

This paper is based on the report presented at the 19th International Conference on Advanced Laser Technologies (ALT'11).

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