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Two-frequency picosecond laser based on composite vanadate crystals with σ-polarised radiation

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Abstract. **A two-frequency picosecond laser based on *a*-cut Nd : YVO_4–YVO_4 composite vanadate crystals is experimentally studied for the σ-polarised radiation at the $^4F_{3/2}$–$^4I_{11/2}$ transition with frequency tuning using Fabry–Perot etalons of different thickness. The difference between the radiation wavelengths was tuned within the range of 1.2–4.4 nm. In the mode-locking regime, the two-frequency radiation power was 280 mW at an absorbed pump power of 12 W.**

Keywords: *two-frequency laser, Nd : YVO_4– YVO_4 composite crystal, terahertz radiation.*

1. Introduction

Tunable two-frequency lasers are of scientific and practical interest for location, spectroscopy, and development of monitoring and control systems. At present, extensive studies are performed on the creation of two-frequency terahertz (THz) lasers with difference frequency generation in nonlinear crystals [1–3] or optoelectronic antennas [4, 5]. The main advantage of using a two-frequency laser system instead of two lasers to obtain a difference frequency is the perfect matching of the laser beams both in space and time. The use of a tunable laser operating at two wavelengths will allow one to obtain narrow-band THz radiation at wavelengths within the transparency window of water vapour in air.

Since the conversion efficiency into the THz wavelength region is low, one needs laser sources with a high peak power. To achieve the maximum peak power of a two-frequency laser, in this work we developed a longitudinally diode-pumped picosecond Nd_3+ : YVO_4–YVO_4 laser operating in a combined regime–with active *Q*-switching and active mode locking. This operation regime makes it possible to increase the laser peak power almost by two orders of magnitude compared to the power of a quasi-cw picosecond laser.

The main goal of our investigations was to obtain tuneable two-frequency picosecond laser radiation using Fabry–Perot (FP) etalons with different thicknesses.

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2. Experimental setup

The scheme of the laser system with two tunable frequencies is shown in Fig. 1.

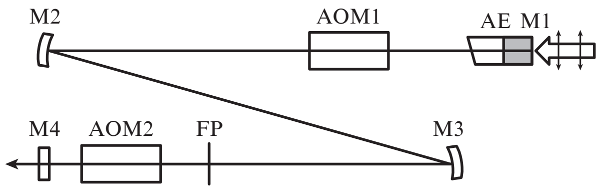

Figure 1. Scheme of the two-frequency Nd : YVO_4–YVO_4 laser: (AE) active element; (M1)–(M4) mirrors; (AOM1), (AOM2) acousto-optical modulators; (FP) Fabry–Perot etalon.

As was shown in [6, 7], the luminescence linewidth of an *a*-cut Nd : YVO_4 crystal (σ-polarisation) is comparable with the luminescence linewidth of a *c*-cut crystal, which allows tuning of laser radiation over the entire gain profile.

When working with σ-polarised radiation, one must use selecting elements to separate it from π-polarised radiation, whose luminescence cross section is fivefold larger. To separate the π- and σ-polarisations in our experiments, we used the scheme from [7, 8] based on the birefringence of vanadate crystals.

Frequency conversion in nonlinear crystals and laser efficiency strongly depend on the thermal lens induced in the active element (AE). To reduce the thermal lens effect, one usually uses pumping into the ground state [9, 10], composite crystals [11, 12], and pump radiation modulation [13].

As a laser AE, we used an *a*-cut composite vanadate crystal Nd : YVO_4–YVO_4 (with doped and undoped regions) with an atomic neodymium concentration of 0.5% and dimensions of 4×4×(2 + 6) mm. The undoped part of the composite crystal was 2 mm long. To separate the π- and σ-polarised radiation, one AE face was cut an angle of ~2°.

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

The laser cavity was Z-shaped for the sake of compactness and lasing stability. It was formed by a plane highly reflecting mirror M1 deposited on one of the AE faces (with a high-reflection dielectric coating for the wavelength of 1064 nm and an antireflection coating for the pump wavelength of 808 nm) and a plane output mirror M4 (transmittance $T = 5\%$ at the fundamental frequency). The other AE face was antireflection coated for wavelengths of 808 and 1064 nm ($R \approx 0.02\%$). Between the plane mirrors, we placed spherical mirrors M2 and M3 with a curvature radius of 340 mm at a distance of 460 mm from each other. This configuration and the use of a composite $Nd:YVO_4-YVO_4$ crystal ensured more stable laser operation than the scheme used previously [6].

As a Q-switch, we used an AOM1 (M3-321M) modulator controlled by a GSN 50-30I sinusoidal voltage generator with a high-frequency signal power up to 30 W. Mode locking simultaneously with Q-switching was achieved by introducing an additional AOM2 (AS-1) modulator with a high-frequency signal power of 1.5–8 W into the cavity. The AOM2 was placed near the output mirror and was thermally stabilised with an accuracy of 0.1 °C using a Peltier element. The modulation frequency was 50.139 MHz, which corresponds to the geometric cavity length of 1440 mm and the laser pulse repetition rate of 100.278 MHz. A pulse train emitted by the laser was detected by an LFD-2a avalanche photodiode and a Tektronix TDS3052 oscilloscope. Figure 2 shows the output pulse oscillogram.

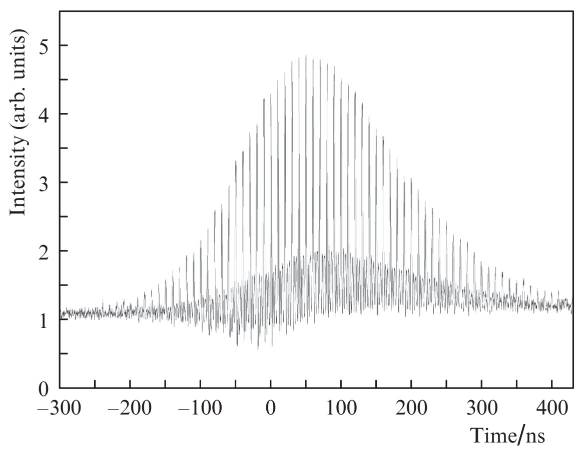

Figure 2. Oscillogram of the output pulse train.

3. Two-frequency lasing

To obtain two-frequency radiation, we used a method [14] based on the introduction of additional spectrally selective losses equalising the laser cavity Q-factor at different regions of the AE luminescence spectrum. As selective elements for this purpose, we used FP etalons.

The difference in the wavelengths of the transmission maxima of FP etalons is determined by their dispersion range, $\lambda_1 - \lambda_2 = \lambda^2/(2nd)$, where n is the refractive index, d is the etalon thickness, and $\lambda = (\lambda_1 + \lambda_2)/2$. A change in the inclination angle of the FP etalon leads to a shift of the transmission maxima. The laser will generate radiation simultaneously at two wavelengths when the cavity Q-factors for these wavelengths are identical.

Two-frequency radiation was observed in the cw laser operation regime, as well as in the Q-switching and mode-locking regimes.

4. Experimental results

The use of Fabry–Perot etalons with different thicknesses makes it possible to measure and control the difference of laser frequencies. We used etalons made of YAG crystals in the form of plane-parallel plates with thicknesses of 80, 97, 130, and 270 μm without coatings.

Figure 3 shows the cw output spectra of a laser with a FP in the cavity. The wavelength difference depends on the thickness and the inclination angle of the plates.

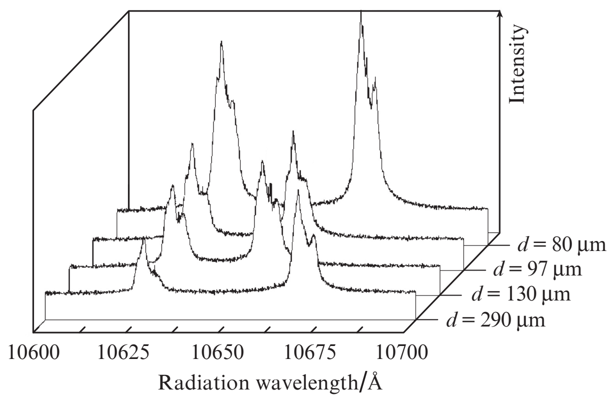

Figure 3. Spectra of the two-frequency $Nd:YVO_4-YVO_4$ laser with FP etalons of different thicknesses.

The dependence of the frequency difference on the etalon inclination angle is shown in Fig. 4 on the example of a 290-μm-thick plate. The wavelength difference was tuned within the range of 1.2–4.4 nm. This tuning is possible in a discrete set of ranges with continuous tuning within each of them. The presented spectra were also observed in the case of laser operation in the Q-switching and mode-locking regimes.

Using the available set of Fabry–Perot etalons, we demonstrated two-frequency laser radiation and the possibility to obtain difference frequencies in nonlinear crystals near 0.58, 0.63, 0.64, 0.71, 1, 1.02, and 1.12 THz.

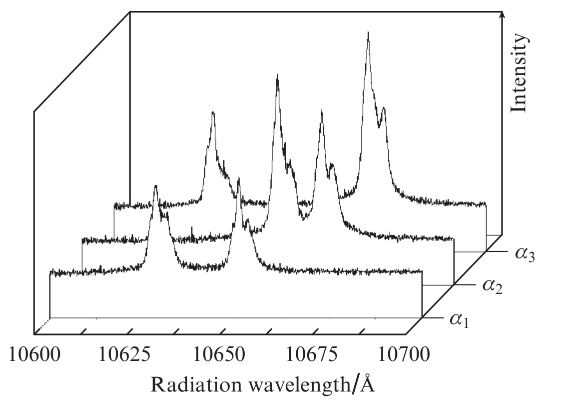

Figure 4. Spectra of the two-frequency $Nd:YVO_4-YVO_4$ laser with an FP etalon 290 μm thick for different etalon inclination angles.

Figure 5 show the absorption spectrum of water vapour in the atmosphere under normal conditions in the THz region (taken from the HITRAN database). This spectrum contains regions with minimal absorption, and, hence, the difference frequency should be tuned to these regions. The arrows indicate the frequencies in the THz spectral region which can be obtained in nonlinear crystals by conversion of difference frequencies demonstrated in this work.

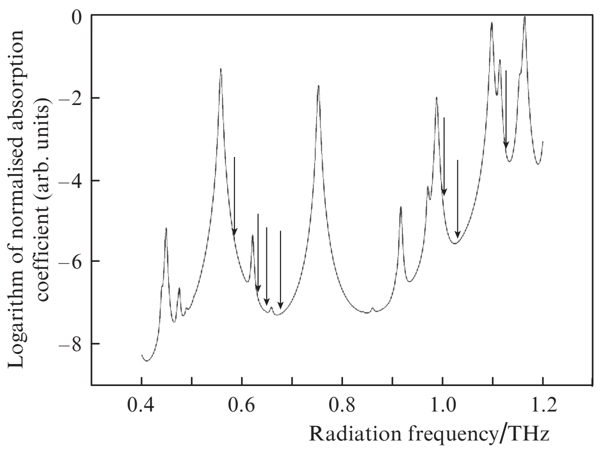

Figure 5. Absorption of THz radiation by water vapour in the atmosphere under normal conditions.

The output power of the laser operating in the two-frequency regime was almost the same at different spectral peaks and equal to 360 mW in the cw regime, 300 mW in the *Q*-switching regime at a pulse repetition rate of 12 kHz and a pulse duration of 40–60 ns, and 280 mW in the mode-locking regime at a pulse repetition rate of 100 MHz and a pulse duration of 40–60 ps at an absorbed pump power of 12 W.

Thus, we demonstrated operation of a solid-state two-frequency picosecond laser based on *a*-cut composite vanadate crystals $Nd:YVO_4-YVO_4$ emitting σ-polarised radiation at the $^4F_{3/2}-^4I_{11/2}$ transition. The possibility of wavelength tuning using Fabry–Perot etalons with different thicknesses is experimentally studied.

The difference between the two laser radiation wavelengths was continuously tuned from 1.2 to 4.4 nm.

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