Quantum Electronics **37** (4) 315 – 318 (2007)

LASERS

PACS numbers: 42.55.Rz; 42.55.Xi; 42.60.Fc
DOI: 10.1070/QE2007v037n04ABEH013443

Active and passive mode locking in a diode-pumped $Nd : Gd_{0.7}Y_{0.3}VO_4$ laser

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Abstract. **Diode-pumped lasers based on mixed $Nd : Gd_{0.7}Y_{0.3}VO_4$ vanadate crystals are studied. Continuous-wave lasing with the slope efficiency of 71 % and the average output power up to 8.2 W is obtained. Active mode locking with an acousto-optic modulator, passive mode locking by the Kerr nonlinearity, and hybrid mode locking are investigated. Picosecond laser pulses of duration 1.7 ps are obtained at an average output power of 340 mW and a pulse repetition rate of 140 MHz.**

Keywords: *mixed* $Nd : Gd_xY_{1-x}VO_4$ *vanadate, mode locking, acousto-optic modulator, Kerr lens, diode pumping.*

1. Introduction

Diode-pumped solid-state lasers are widely used for solving a variety of applied problems. Ultrashort-pulse lasers are promising for machining hard materials such as sapphire, diamond, and various metals and dielectrics in electronic industry and precision mechanics. The application of picosecond lasers considerably improves the quality and precision of machining of materials compared to the use of *Q*-switched nanosecond lasers. To solve such practical problems, highly efficient ultrashort-pulse lasers are required.

Because the minimal duration of a laser pulse is determined by the gain band width, active media with a broad luminescence band are most promising for generating ultrashort laser pulses. Active media based on the $Nd:GdVO_4$ and $Nd:YVO_4$ vanadate crystals are widely used in various diode-pumped lasers because these crystals offer the optimal combination of spectroscopic, laser, and thermal properties. The luminescence bands of the $Nd:YVO_4$ and $Nd:GdVO_4$ crystals are broader than those of the Nd : YAG and Nd : YLF crystals and, therefore, the former crystals can generate shorter radiation pulses [1].

Mixed vanadates – disordered crystals with inhomogeneously broadened spectra, have even broader luminescence bands. A disordered crystal lattice in vanadates is produced due to the amorphous replacement of the Y^{3+} ions in YVO_4 by the Gd^{3+}, La^{3+} or Lu^{3+} ions or their combinations. Similarly, the Gd^{3+} ions in $GdVO_4$ are replaced by the Y^{3+}, La^{3+} or Lu^{3+} ions. Such an isomorphic substitution is used to synthesise mixed vanadate crystals with physical and optical parameters close to those of yttrium vanadate and gadolinium vanadate. In this case, by varying the relative concentrations of Y, Gd, La, and Lu, we can change the stimulated emission cross section, absorption cross sections, the absorption and emission bandwidths, the lasing wavelength, the level lifetimes, etc.

The $Nd: Gd_{0.5}La_{0.5}VO_4$ crystals [2] were the first mixed vanadates in which lasing was obtained. The width of the luminescence band of these crystals was 5.3 nm for σ-polarised light and 4.8 nm for π-polarised light.

Passive *Q*-switching in diode-pumped lasers and spectroscopic parameters of mixed $Nd:Gd_xY_{1-x}VO_4$ crystals were studied in [3, 4]. Passive mode locking with the help of a SESAM was demonstrated in a $Nd:Gd_{0.5}Y_{0.5}VO_4$ crystal [5]. The duration of laser pulses was 4 ps.

In this paper, we studied for the first time three passive mode-locking regimes in a diode-pumped $Nd:Gd_{0.7}Y_{0.3}VO_4$ mixed vanadate laser: active mode locking with an acousto-optic modulator (AOM), passive mode locking by the Kerr nonlinearity, and hybrid mode locking by using simultaneously an AOM and passive Kerr mode locking.

2. Spectroscopic studies

Researchers at the A.M. Prokhorov General Physics Institute, RAS have developed the unique technology for growing high-quality $GdVO_4$, YVO_4, and $Gd_xY_{1-x}VO_4$ crystals doped with various activators to produce the active elements for diode- and flashlamp-pumped lasers emitting in a broad spectral range. The technology was developed based on modern Crystal-2 and Crystal-3M industrial setups with inductive heating for crystal growing by the Czochralski method in the automatic regime.

The $Nd:Gd_{0.7}Y_{0.3}VO_4$ crystals (with the atomic Nd concentration of 0.5 %) of length 70 mm and cross section 15 mm × 15 mm were grown by the Czochralski method from an iridium crucible of diameter 60 mm. To avoid the interaction of the melt with the crucible, a protective weakly oxidising atmosphere was used. The crystal drawing and rotation rates during the crystal growth were 0.8 – 2 mm h^{-1} and 10 – 15 rpm, respectively. Crystalline $Nd:Gd_{0.7}Y_{0.3}VO_4$ boules with the atomic Nd concentration of 0.5 % have a

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Received 29 September 2006
Kvantovaya Elektronika **37** (4) 315 – 318 (2007)
Translated by M.N. Sapozhnikov

high optical quality over the entire length and therefore the complete volume of the boule was used to fabricate laser elements.

The spectral parameters of laser crystals were studied with a Shimadzu UV-3101PC spectrophotometer and a spectrometer based on an UV-90 autocollimation tube with a resolution of 0.1 nm mm^{-1}.

Our studies showed that the absorption bands of Nd^{3+} in mixed vanadates are only slightly broadened and in fact are not shifted compared with respect to the absorption bands of traditional $\mathrm{Nd:GdVO_4}$ and $\mathrm{Nd:YVO_4}$ crystals in the wavelength range 740 – 840 nm, which is used for pumping by laser diodes.

Figure 1 shows the luminescence spectra of neodymium-doped YAG, $\mathrm{GdVO_4}$, $\mathrm{YVO_4}$, and $\mathrm{Gd_{0.7}Y_{0.3}VO_4}$ crystals at the $^4\mathrm{F}_{3/2}-{}^4\mathrm{I}_{11/2}$ transition for the π-polarisation. One can see that the luminescence band of Nd^{3+} in the mixed vanadate is located between the luminescence bands of Nd^{3+} in $\mathrm{GdVO_4}$ and $\mathrm{YVO_4}$ and depends on the concentration ratio of Y and Gd in the crystal. By varying this ratio ($\mathrm{Gd}_x\mathrm{Y}_{1-x}$), the laser wavelength can be change from 1063 to 1064 nm.

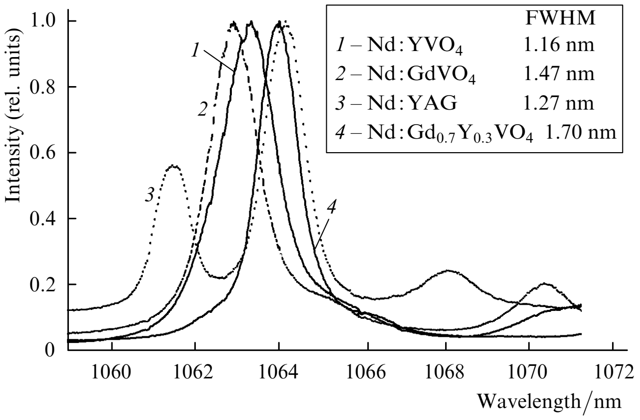

Figure 1. Luminescence spectra of neodymium-doped $\mathrm{GdVO_4}$, $\mathrm{YVO_4}$, $\mathrm{Nd:Gd_{0.7}Y_{0.3}VO_4}$, and YAG laser crystals at the $^4\mathrm{F}_{3/2}-{}^4\mathrm{I}_{11/2}$ transition.

We used in our experiments a $\mathrm{Nd:Gd_{0.7}Y_{0.3}VO_4}$ mixed vanadate crystal, which had the luminescence bandwidth of 1.7 nm and produced lasing at 1063.3 nm.

3. Continuous-wave lasing regime

To estimate the quality of active laser elements based on $\mathrm{Nd:Gd_{0.7}Y_{0.3}VO_4}$ mixed vanadate crystals at the $^4\mathrm{F}_{3/2}-{}^4\mathrm{I}_{11/2}$ transition, we performed cw lasing experiments by using a short flat resonator.

A laser $\mathrm{Nd:Gd_{0.7}Y_{0.3}VO_4}$ crystal of size 4 mm × 4 mm × 6 mm with the Nd concentration of 0.5% was cut along the *a* axis. A dielectric mirror M1 was deposited directly on one of the surfaces of the crystal and had a high reflectance ($R > 99.9\,\%$) at a wavelength of 1064 nm and a high transmission ($T > 90\,\%$) at a pump wavelength of 808 nm. The second side of the active element had an AR coating for a wavelength of 1064 nm. A plane output mirror had the transmission $T = 8\,\%$ at 1064 nm. The total length of the resonator was 15 mm. Active elements were pumped by a LIMO HLU25F200 linear laser diode array with a fibre pigtail (the numerical aperture $\mathrm{NA} = 0.22$ and the core diameter was 200 μm) emitting up to 25 W at a wavelength of 808 nm. The pump radiation was focused by a system of objectives which provided the diameter of the waist spot in the crystal from 150 to 400 μm. Active elements were mounted with the help of an indium foil in copper blocks cooled with Peltier elements or a water flow.

Figure 2 shows the dependence of the output power of the laser on the absorbed pump power. The lasing threshold was 510 mW. The maximum output power of 8.2 W was obtained for the absorbed power equal to 15 W. The slope lasing efficiency achieved 71 % for the total efficiency equal to 56 %. Note that these lasing parameters are at the level of the best results obtained for Nd:YAG, $\mathrm{Nd:GdVO_4}$, and $\mathrm{Nd:YVO_4}$ crystals.

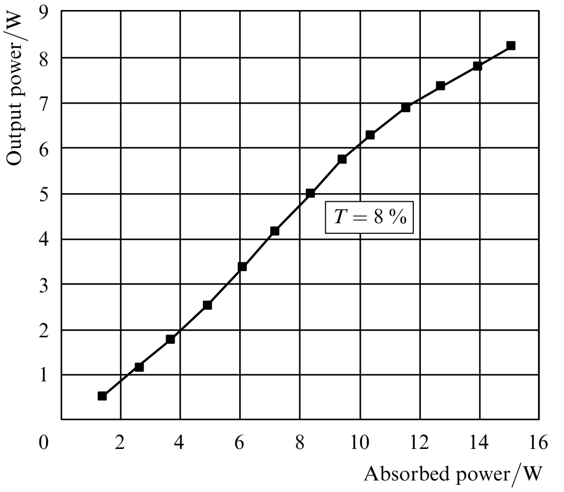

Figure 2. Dependence of the output power of the $\mathrm{Nd:Gd_{0.7}Y_{0.3}VO_4}$ laser at the $^4\mathrm{F}_{3/2}-{}^4\mathrm{I}_{11/2}$ transition at 1063.3 nm on the absorbed pump power.

The uniformity of the output parameters of the laser over the cross section of active elements demonstrates a high quality of $\mathrm{Nd:Gd_{0.7}Y_{0.3}VO_4}$ mixed vanadate laser crystals used in experiments.

4. Mode-locking regime

We studied active and passive mode locking in a longitudinally pumped laser with a Z-shaped resonator, as in [6] (Fig. 3).

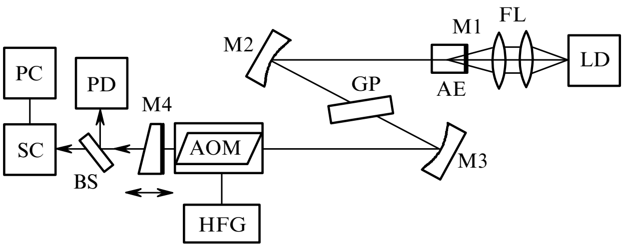

Figure 3. Experimental scheme of the mode-locked laser. AE: active element; LD: pump laser diode array; FL: focusing lenses; M1 – M4: resonator mirrors; GP: SF57 glass plate; AOM: acousto-optic modulator; HFG: thermally stabilised high-frequency generator; BS: beamsplitter; SC: streak camera; PC: personal computer; PD: photodetector.

The active element was placed near a highly reflecting mirror through which pumping was performed. The pump radiation was focused into a spot of radius ~ 100 μm on the active element. A Kerr lens was formed by using a 5-mm thick SF57 Schott glass plate (with the nonlinear refractive index $n_2 = 2.6 \times 10^{-15}$ cm^2 W^{-1}), which was placed between spherical mirrors at the Brewster angle to the resonator axis. To exclude the etalon effect, all the faces of intracavity optical elements were either oriented at the Brewster angle or wedge-like substrates were used.

The active element was similar to that described above, but its second surface was inclined at an angle of 1.5° and had the antireflection coating ($R \approx 0.02\,\%$). The Z-shaped resonator consisted of dielectric mirror M1 deposited on the input end of the active element, two spherical mirrors M2 and M3 (with the radius of curvature 100 mm), and wedge-shaped (with the wedge angle 1.5°) output mirror M4 ($T = 5\,\%$). The distances between mirrors M1 and M2, M2 and M3, and M3 and M4 were 380, 108, and 549 mm, respectively. Mirrors M2 and M3 were turned through ~ 16° to compensate for the astigmatism of spherical mirrors.

A ML-202 acousto-optic modulator (AOM) had Brewster faces and was located near output mirror M4. The AOM was thermally stabilised by means of a Peltier microcooler with an accuracy of 0.1 °C. The modulation frequency of the AOM was 70 MHz, corresponding to the geometrical length of the resonator equal to 1037 mm (the optical length was 1071 mm), and the pulse repetition rate was 140 MHz. The high-frequency signal power was varied from 1.5 to 8 W.

The emission of a laser pulse train was detected with a fast avalanche LFD-2 photodiode and a TDS3052 Tektronix oscilloscope (with a passband of 500 MHz). The duration of laser pulses was measured with a streak camera with a resolution of 0.7 ps (GPI Photoelectronics Dept. Mod. PN-01/s20).

Active mode locking was studied by removing the SF57 plate from the waist between spherical mirrors and by using it only to compensate for astigmatism. The resonator length was matched to the AOM frequency with the help of a precision adjusting unit. When the resonator length was detuned from the optimal value by more than 2 – 3 mm, only cw lasing was obtained. As the mismatch was reduced, the spike *Q*-switching mode was first developed and then mode locking appeared on these spikes and a system of several stochastic pulse trains was observed. The resonator length was adjusted by the minimal pulse duration. The stable generation of picosecond pulses was observed in the mismatch range 50 – 70 μm. The minimum pulse duration observed in our active mode-locking experiments with an acousto-optic modulator was 9.4 ps. The average power achieved in this case was 640 mW.

We also obtained passive mode locking by the Kerr nonlinearity. This regime was achieved by adjusting properly the distance between spherical mirrors M2 and M3 and the position of the SF57 plate between them. Two regions of stable emission of picosecond pulses were observed depending on the distance between mirrors M2 and M3. In this case, the optimal position of the SF57 plate was within 52 ± 1 mm from mirror M2. Passive mode locking appeared without any additional actions. When the positions of optical elements were optimised, first the cw lasing regime passed to the regular spike regime, then mode locking appeared on these spikes [7], which was followed by stable mode locking. The long-term stability of passive mode locking by the Kerr nonlinearity depended on the stability of a pump source. The duration of laser pulses measured in this regime was about 2 ps for an average power of 310 mW.

The operation of the Nd:$Gd_{0.7}Y_{0.3}VO_4$ laser was stabilised by using hybrid mode locking with the help of an acousto-optic modulator and a Kerr lens. In this regime, the expansion of the Kerr nonlinearity region was observed (by the position of the SF57 plate and the distance between mirrors M2 and M3), which simplified somewhat the laser adjustment and allowed us to obtain the shortest laser pulses.

At 3-W pump power, a stable train of laser pulses with the minimal duration down to 1.7 ps and an average output power of 340 mW was observed. Figure 4 shows the streak-camera sweep of such a pulse. The spectral width of the laser pulse was about 0.9 nm. The time-bandwidth product $\Delta\nu$ of the pulse by its duration Δt ($\Delta t\Delta\nu = 0.46$) virtually coincides in this case with the minimal possible value for a Gaussian emission pulse [$(\Delta t\Delta\nu)_{\min} = 0.44$] and is close to the minimal possible value for a pulse of the shape sech^2 [$(\Delta t\Delta\nu)_{\min} = 0.32$], which indicates that the laser pulse has no frequency chirp, and the compensation of the group velocity dispersion is not required.

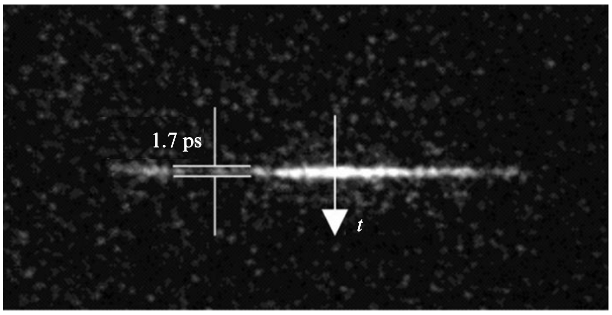

Figure 4. Streak-camera sweep of a laser pulse.

5. Conclusions

We have shown in this paper that Nd^{3+}:$Gd_xY_{1-x}VO_4$ mixed vanadate crystals are promising as active media for diode-pumped picosecond lasers. The high-optical quality Nd:$Gd_{0.7}Y_{0.3}VO_4$ crystals (with the Nd atomic concentration of 0.5 %) were grown and their spectral parameters were studied. The maximum cw output power of 8.2 W was achieved upon 15-W pumping. The slope efficiency was 71% (the total efficiency was 56 %), the lasing threshold being 510 mW. Different mode-locking regimes have been investigated: active mode locking, passive mode locking with a Kerr lens and hybrid mode locking. Stable picosecond laser pulses of duration 9.4 ps and average power 640 mW have been generated upon active mode locking. The minimum duration of laser pulses equal to 1.7 ps at an average output power of 340 mW was achieved upon hybrid mode locking. By optimising the ratio of the Gd and Y concentrations (Gd_xY_{1-x}) in mixed vanadate crystals, even shorter laser pulses can be generated.

Acknowledgements. This work was partially supported by the Russian Foundation for Basic Research (Grant No. 05-

02-17330) and the Swiss National Science Foundation (Grant No. IB7420-110873/1). The authors thank N.A. Vorob'ev and V.I. Lozovoi for their help in measurements of pulse durations and A.A. Ivanov for useful discussions.

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