V:YAG saturable absorber for flash-lamp and diode pumped solid state lasers

Jan Šulc[a], Helena Jelínková[a], Michal Němec[a]
Karel Nejezchleb[b], Václav Škoda[b]

[a]Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering
Břehová 7, 115 19 Prague 1, Czech Republic
[b]Crytur, Ltd. Turnov, Palackého 175, 511 01 Turnov, Czech Republic

ABSTRACT

V:YAG saturable absorber was used for efficient Q-switching and mode-locking of Nd:YAG and Nd:YAP flash-lamp or diode pumped lasers operating in 1.3 μm region. Crystals of Yttrium-Aluminum Garnet (YAG) doped with three-valence vanadium V^{3+} in tetrahedral position (V:YAG) were grown using of Czochralski method in reducing protective atmosphere. High purity oxides were used for crystal growth (Y_2O_3 (5N), Al_2O_3 (5N), V_2O_5 (4N)). Concentration of V_2O_5 in the melt reached up to 1 wt. %. Discs of the diameter 5 or 10 mm and of various thickness were machined from grown V:YAG crystals. The discs were both sides polished and AR coated so that minimum reflectivity at 1.08 and 1.34 microns was reached. The initial transmission of the saturable absorber was dependent on the sample's thickness and its annealing process. We report stability improvement of passively mode-locked (by these V:YAG crystals) Nd:YAP flash-lamp pumped lasers. The maximum output energy 53 mJ at wavelength 1340 nm was obtained for Nd:YAP flash-lamp pumped laser operating at repetition rate 5 Hz. Mode-locked train envelope width was measured to be 22 ns (FWHM). Individual pulses inside the train were shorter than 1 ns. Also results with composite Nd:YAG rod Q-switched by V:YAG crystal and with Nd:YAG/V:YAG monolith rod under CW longitudinal diode pumping was obtained and compared. These laser systems represent new powerfull sources in the near infrared region.

Keywords: V:YAG saturable absorber, Nd:YAP laser, passive Q-switching, passive mode-locking, monolith crystal

1. INTRODUCTION

In the past few years, the target of many investigations has been generation of radiation with the wavelength in the vicinity of 1.5 μm — so called "eye safe" radiation. These wavelengths can be generated using of Raman or parametric conversion in nonlinear crystals excited by the radiation $\sim 1.3\,\mu$m.[1, 2] Threshold intensity needed for the initialization of those nonlinear effects suppose the higher power it means that the primary laser could work in Q-switched or mode-locked regime with an active or passive Q-switch. The passive Q-switch — saturable absorbers — has some advantages in comparison with the active one: they are compact, inexpensive and easy-to-operate. In the past, they were mostly formed by dyes dissolved in various solvent. As the saturable dyes have to fulfill the requirement that they can absorb quanta of generated laser radiation resulting in bleaching, no such dyes are available for every type of laser. On the other hand if the absorbers with proper saturable absorption exist, mostly they have disadvantages of liquid substances — temperature and long-term instability.[3] Therefore solid-state materials possessing reliable saturable absorption, good chemical and physical properties are the object of constant interest of researchers. Many bulk passive Q-switched lasers use the Cr^{4+}:YAG as a saturable absorber.[4, 5] The saturable absorption of Cr^{4+} ions in the near infrared extends from 0.8 μm up

---

Further author information: (Send correspondence to J.Š.)
J.Š.: E-mail: sulc@troja.fjfi.cvut.cz, Tel.: +420 221 912 240, Fax: +420 221 912 252
H.J.: E-mail: hjelin@troja.fjfi.cvut.cz, Tel.: +420 221 912 243, Fax: +420 221 912 252
M.N.: E-mail: nemecm@troja.fjfi.cvut.cz, Tel.: +420 221 912 259, Fax: +420 221 912 252
K.N.: E-mail: nejezchleb@crytur.cz, Tel.: +420 481 319 511, Fax: +420 481 322 323
V.Š.: E-mail: skoda@crytur.cz, Tel.: +420 481 319 511, Fax: +420 481 322 323

to 1.2 μm, making it suitable for the 0.946 μm and 1.064 μm Nd^{3+} transitions. However, it is not suitable for longer wavelength transitions, such as 1.34 μm transitions of Nd^{3+} ions. More recently the use of quantum wells in semiconductor saturable absorber mirror (SESAM) has produced ultrashort pulses at longer wavelengths at 1.342 μm or 1.53 μm.[6,7] These SESAM devices however have relatively high loss, giving low pulse energies, and their low damage threshold limits their scalability.

As reliable Q-switch for 1.3 μm spectral region, solid state crystal V:YAG (Yttrium-Aluminum Garnet (YAG) doped with three-valence vanadium V^{3+}) has appeared.[8–14] This saturable absorber was studied in many arrangements: for switching of Nd:YAP, Nd:YAG, Nd:YVO_4 or Nd:KGW laser ($\lambda \sim 1.3\,\mu$m) with the flashlamp[14,15] or diode[16–20] pumping. In flash-lamp pumped systems, the maximum energy obtained with the train of mode locked pulses reported in those works were 4.5 mJ[14] for the combination Nd:YAG/V:YAG, and 8 mJ for the combination Nd:YAP/ V:YAG. In diode pumped laser systems, the maximum reported[20] average power, peak power, and pulse energy were 2.1 W (Nd:YVO_4/ V:YAG), 2.8 kW (Nd:YAP/ V:YAG) and 79 μJ (Nd:YAG/ V:YAG), respectively.

In our previous study[15] we have obtained as maximum 10 mJ and 27 mJ in 20 ns long (FWHM) train of pulses for Nd:YAP flash-lamp pumped oscillator, and oscillator-amplifier arrangements, respectively. In this paper we prolonged our study with the goal of obtaining the higher energy from the oscillator only.

In this paper we also report new results obtained with V:YAG Q-switched diode end-pumped laser. Composite Nd:YAG rod Q-switched by V:YAG crystal and with Nd:YAG/V:YAG monolith rod under CW longitudinal diode pumping was obtained and compared.

2. V:YAG PASSIVE SATURABLE ABSORBER

2.1. Material properties of V:YAG crystal

Matrix of pure garnet is optically neutral in the range of ultraviolet to far infrared, so that all optical effects of doped garnet are dependent on dopant properties and ligands field symmetry. Oxygen sub-lattice of garnet matrix is formed by dodecahedrons with the point symmetry D_2 and coordination number eight populated by Y^{3+} ions, octahedrons of the symmetry C_3 and coordination number six, populated by Al^{3+} and tetrahedrons of the symmetry S_4 and coordination number four, populated also by Al^{3+} ions. It was found, that vanadium ions V^{3+} substitute only Al^{3+} in octahedral and tetrahedral centers.[18]

Absorption bands at 430 nm and 600 nm are related to V^{3+} ion in octahedral position.[13] The tetrahedrally coordinated V^{3+} ion contributes to the peaks at 720 – 900 nm (max. 825 nm) and 0.9 – 1.5 μm (max. 1330 nm). Therefore tetrahedral coordination of the ions is important for passive Q-switch at 1.064 and 1.342 μm.[18] On the other hand, the fraction of V^{3+} ions in tetrahedral coordinated position of V:YAG crystals grown in iridium crucibles is less than 1 %. It was also found, that the post-growth thermal annealing in reducing atmosphere increases the concentration of optically active V^{3+} ions.[13] Major characteristics of V:YAG saturable absorber in comparison are summarized in Table 1. The dependence of V:YAG crystal absorption coefficient on the wavelength is in Figure 1.

Table 1. Summary of V:YAG characteristics

	V:YAG (at 1.34 μm)
Ground state absorption cross-section[9,18]	$\sigma_{gsa} = (7.2 \pm 2.6) \times 10^{-18}\,\mathrm{cm}^2$
Excited state absorption cross-section[9,18]	$\sigma_{esa} = (7.4 \pm 2.8) \times 10^{-19}\,\mathrm{cm}^2$
Recovery time[8,9,18]	$\tau_r = 5 - 22\,\mathrm{ns}$
Saturation intensity[11,20]	$I_{sat} = 10 - 30\,\mathrm{MW.cm}^{-2}$
Absorption coefficient[18,20]	$\alpha = 0.5 - 2.2\,\mathrm{cm}^{-1}$

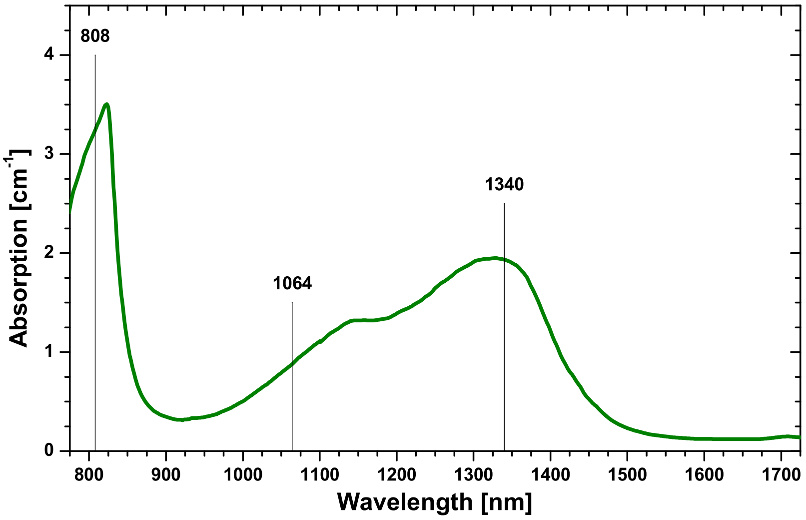

Figure 1. Measured dependence of used V:YAG crystals absorption coefficient on the wavelength.

3. EXPERIMENTAL ARRANGEMENT

3.1. Flash-lamp pumped Nd:YAP laser

Flashlamp pumped Nd:YAP crystal rod with 5 mm diameter and 90 mm long was used as laser active media. The both ends of the crystal were cut at angle 1° and were antireflection coated for both wavelength 1.08 and 1.34 μm. The 45 cm long optical cavity was composed of concave rear mirror M_1 ($r = -7$ m, a maximum reflectivity for the 1.34 μm and a minimum reflectivity for 1.08 μm) and a plane output mirror M_2 with the minimum reflection on the wavelength 1.08 μm. The output mirror reflectivity R_2 for the generated wavelength 1.34 μm was varied from 40 % up to 60 % to optimize energy E_{out} and duration $\Delta\tau$ of the output laser pulse (FWHM).

For flash-lamp pumped Nd:YAP laser switching discs of the diameter 10 mm and of the thickness 2.08 mm, 5.10 mm, 7.14 mm, and 8.0 mm were machined from V:YAG crystals. The initial transmission of used V:YAG crystal samples was 68 %, 38 %, 28 %, and 23 %. The discs were both sides polished and AR/AR coated so that a minimum reflectivity on 1.08 and 1.34 μm was reached. The studied V:YAG saturable absorber was placed near the rear mirror. The initial transmission of this crystal was also optimized with the regard to the output energy and length of generated train of pulses.

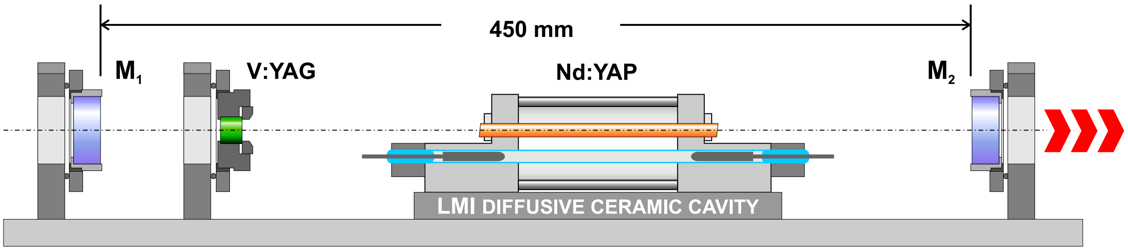

Figure 2. Flash-lamp pumped Nd:YAP laser system. Nd:YAP crystal (5 mm diameter and 90 mm long) pumped in LMI difusive reflection cavity by Xe-flash-lamp. M_1 – concave rear mirror ($r = -7$ m) with maximum reflectivity for the 1.34 μm and a minimum reflectivity for 1.08 μm; M_2 – plane output mirror with the minimum reflection on the wavelength 1.08 μm.

3.2. CW Diode pumped Nd:YAG laser – Nd:YAG composite rod

The active medium of first tested diode pumped laser was end-pumped composite Nd:YAG crystal. This YAG crystal consists of 8 mm long active part doped by Nd^{3+} ions (1 at. %) and of 4 mm long undoped part – see Figure 3. The diameter of this crystal was 5 mm. The outer frontal part of the laser crystal had broadband antireflection coatings (AR) for the 1064 nm wavelength. The undoped part was bounded to the pumping face of the crystal doped part. In our previous study[21] we have confirmed that using of such undoped part of laser rod enlarges the active material cooling surface and improves a laser active media thermal field uniformity and heatsink. Laser crystal was mounted in adjustable water-cooled cupreous ring. Temperature of cooling water was not a specially stabilized and it was moving in range from 12 to 14 °C.

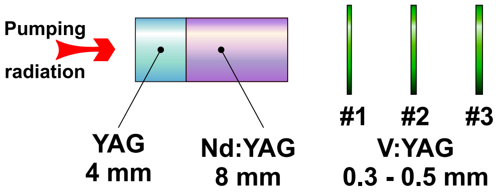

Figure 3. Active and passive crystals used in diode pumped Nd:YAG laser. Composite Nd:YAG crystal (undoped part 4 mm, Nd^{3+} doped part 8 mm) and separated passive saturable absorbers (#1, $d = 330\,\mu$m, $T_0 = 93\,\%$;#2, $d = 420\,\mu$m, $T_0 = 91\,\%$; #3, $d = 520\,\mu$m, $T_0 = 89\,\%$).

The pumping source used was a CW operating laser diode HLU20F400 (LIMO Laser Systems) emitting radiation at wavelength 808 nm with the maximum output power 20 W at the end of the fiber (fiber core diameter: 400 μm; numerical aperture: 0.22). The diode radiation was focused into the active Nd:YAG crystal by two achromatic doublet lenses with the focal length $f = 75$ mm. The measured diameter of pumping beam focus inside the crystal was 360 μm. The active part of laser crystal absorbed approximately 95 % of pumping radiation.

The 80 mm long resonator of the Nd:YAG laser was formed by a planar dielectric mirror R_1 with high transmission for the pumping radiation ($T > 98\,\%$ @ 808 nm) together with the high reflectance for the generated radiation ($R_1 = 100\,\%$ @ 1340 nm), and by a concave (100 mm or 146 mm) dielectric mirror R_2 serving as an output coupler – see Figure 4. As this coupler five various dielectric reflectors was proved: $R_2^{(1)} = 98\,\%$ @ 1340 nm, $r = 146$ mm; $R_2^{(2)} = 94\,\%$ @ 1340 nm, $r = 100$ mm; $R_2^{(3)} = 91\,\%$ @ 1340 nm, $r = 146$ mm; $R_2^{(4)} = 86\,\%$ @ 1340 nm, $r = 146$ mm; and $R_2^{(5)} = 82\,\%$ @ 1340 nm, $r = 146$ mm.

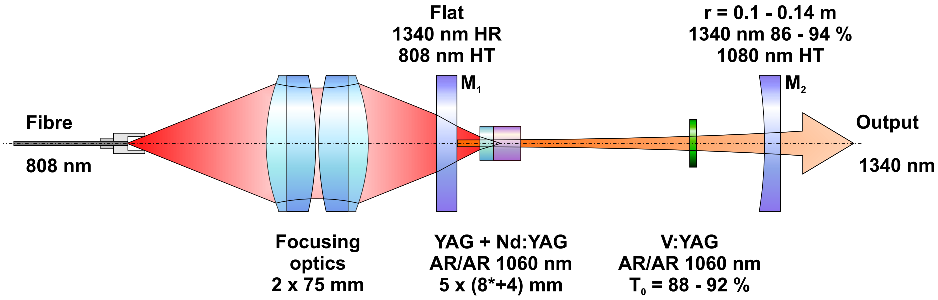

Figure 4. Longitudinaly diode pumped Nd:YAG laser system Q-switched by independent V:YAG crystal. M_1 – rear (pumping) resonator flat mirror, M_2 – curved output coupler.

For the Q-switching three samples of V:YAG crystals with different initial transmission were used. The diameter of used discs was 7 mm and the thickness was 320, 410 and 520 μm. Corresponding initial transmission of used V:YAG crystal samples was 93 %, 91 %, and 89 %. These discs were also both sides polished and AR/AR coated to obtain a minimum reflectivity on 1.08 and 1.34 μm. This crystals were fixed in adjustable air-cooled cupreous ring and placed in the laser resonator between laser crystal and output coupler – see Figure 4.

3.3. CW Diode pumped Nd:YAG/V:YAG monolith laser

For the construction of longitudinally diode pumped Q-switched Nd:YAG laser operating at wavelength 1340 nm a specially developed sandwich crystal was tested. This crystal combine in one piece cooling undoped part (undoped YAG crystal), active laser part (YAG crystal doped with Nd^{3+} ions) and saturable absorber (YAG crystal doped with V^{3+} ions) – see Figure 5. The undoped YAG and Nd^{3+} doped part of this crystal is exactly the same like in the previous case described in subsection 3.2, that means that the diameter of this crystal, the lengths of undoped, and the lengths of Nd^{3+} doped part was 5 mm, 4 mm, and 8 mm, respectively. The thickness of the V:YAG part was 530 μm and its initial transmission was approximately $T_0 \doteq 88\,\%$. This value was set up on the base of previous experiment results to be sure, that the system reach the threshold. The outer frontal part of the laser crystal had broadband antireflection coatings (AR) for the wavelength 1064 nm and 1340 nm. The undoped part was bounded to the pumping face of the crystal doped part.

This combination of active crystal and saturable absorber in one monolithic part allows us to realize more compact resonator. The shortest tested resonator, limited by the optics and crystal mount, was only 33 mm long – see Figure 6. The pumping laser diode, cooling system, and laser output couplers were the same like in previous case.

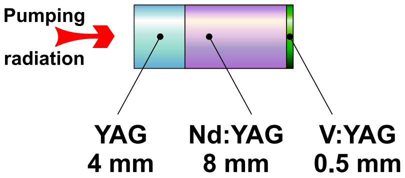

Figure 5. Nd:YAG/V:YAG monolith crystal used in diode end-pumped laser: undoped part 4 mm, Nd^{3+} doped part 8 mm and V^{3+} doped part 530 μm ($T_0 = 88\,\%$).

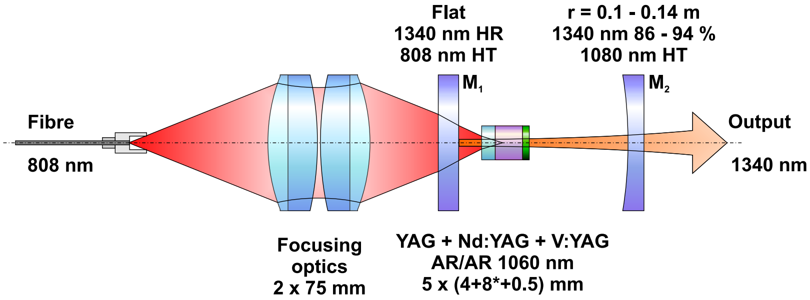

Figure 6. Longitudinaly diode pumped Q-switched laser based on Nd:YAG/V:YAG monolith crystal. M_1 – rear (pumping) resonator flat mirror, M_2 – curved output coupler.

3.4. Methods of characterization

The time characteristics were measured with the help of a fast vacuum photodiode. With this photodiode Tektronix oscilloscope TDS 3052B (500 MHz, 5 GS/s) or the S7-19 oscilloscope (7 GHz) were used. A computer-operated two channel Molectron JD 2000 Joulemeter with two thermal detectors (Gentec ED-200LA, voltage responsivity 1.87 V/J; Molectron J25, voltage responsivity 8.59 V/J) was used for the energy measurements. The output power was obtained by Molectron energy/power meter EMP 2000 with two Molectron *PowerMax* probes (PM10 and PM3). A spectrum of the generated radiation was investigated with the help of an IR wavelength meter (StellarNet EPP 2000).

4. EXPERIMENTAL RESULTS

4.1. Flash-lamp pumped Nd:YAP laser

Four V:YAG samples were investigated in order to maximize output power and to obtain the best pulse stability of flash-lamp pumped Nd:YAP mode-locked/Q-switched laser. The initial transmissions of available samples at 1.34 μm were $T_0 = 68\,\%$, $38\,\%$, $28\,\%$, and $23\,\%$. The lamp driving power was chosen for just-above-threshold operation in order to generate the single Q-switched/mode-locked pulse train. The dependence of the output energy and of the mode-locked pulse train duration on the initial transmission of the V:YAG saturable absorber was measured.

A full modulation was observed with three samples with initial transmission in the range of 28 – 68 %. The initial transmission of the fourth samples ($T_0 = 23\,\%$) was to low to obtained laser emission with used laser pump source. The highest energy for one generated train of pulses was reached for the initial V:YAG transmission $T_0 = 28\,\%$. For this initial transmission the output oscillator energy, and the corresponding pulse train duration was 53 mJ, and 17 ns, respectively. The train of pulses corresponding to $T_0 = 28\,\%$ is in Figure 7, left. For the measurement of the individual pulse duration in train the vacuum photodiode (CTU) and 7 GHz oscilloscope S7-19 with a CCD readout was used — Figure 7, right. The value measured is around 1 ns.

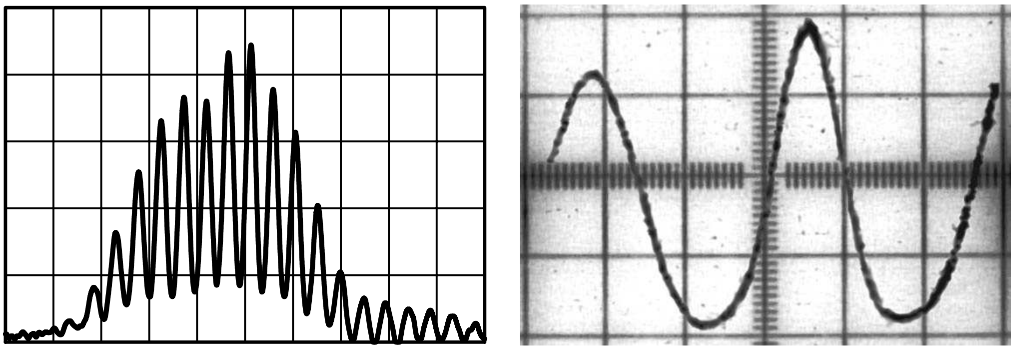

Figure 7. Flash-lamp pumped Nd:YAP laser modelocked by V:YAG absorber — train of pulses (left, 5 ns/div, 0.5 GHz) and single pulse (right, 1 ns/div, 7 GHz) temporal development. Resonator length 45 cm, V:YAG initial transmission $T_0 = 28\,\%$, output coupler reflectivity $R_{OC} = 60\,\%$.

4.2. CW Diode pumped Nd:YAG laser – Nd:YAG composite rod

In free-running regime (without passive Q-switch inside the resonator) constructed Nd:YAG laser was operating with all five available output couplers (R_{OC} = 82, 86, 91, 94, and 98 % – see subsection 3.2). From measured dependencies of generated output power at wavelength 1342 nm (pump power at 808 nm) it was found that optimum output coupler reflectivity is between 87 and 90 %. The maximum output power 1.6 W @ 1340 nm (absorbed pumping power 10 W) was reached in CW free-running regime with output coupler reflectivity 91 %. The differential efficiency was better than 20 %.

For Q-switching regime there were tested 15 possible combinations of the output coupler reflectivity (five output couplers) and passive Q-switch initial transmissions (3 V:YAG samples), but only for the eight combinations the laser emission was reached. For these cases following parameters of Nd:YAG laser output radiation in dependence on pumping power were measured: a mean output power, generated giant pulse width (FWHM), and repetition rate of generated pulses. From obtained values, single pulse energies and peak powers were calculated. Results are summarized in Table 2. Examples of generated Q-switched pulses are shown on Figure 8.

It was found, that the shortest pulses (21 ns) are generated when the saturable absorber with the lowest initial transmission (88 %) was used. This absorber was operating only together with the output coupler having the reflectivity 94 % and the corresponding peak mean power, single pulse energy and peak power were 215 mW, 64 μJ, and 3.1 kW, respectively. Longer but more powerful pulses were generated when the output coupler having close optimal reflectivity 91 % was used. The generated pulse lengths were 30 ns and 25 ns for V:YAG saturable absorbers with $T_0 = 93\,\%$, and $T_0 = 91\,\%$, respectively. In these cases, the higher mean power (525 mW for $T_0 = 93\,\%$, and 365 mW for $T_0 = 91\,\%$) was reached which corresponds to higher pulse energy (118 μJ for $T_0 = 93\,\%$, and 126 μJ for $T_0 = 91\,\%$) and higher peak power (4.3 kW for $T_0 = 93\,\%$, and 4.8 kW for $T_0 = 91\,\%$).

Table 2. CW diode pumped Nd:YAG laser parameters – Nd:YAG composite rod, separated V:YAG saturable absorber. Dependence of generated radiation parameters on the output coupler reflectivity R_{OC} and saturable absorber initial transmission T_0.

Mirror reflectivity R_{OC} [%]	**V:YAG transmission** T_0 [%]	**Mean power** P [mW]	**Pulse width** FWHM [ns]	**Pulse energy** E [μJ]	**Peak power** P_{peak} [kW]	**Pulse frequency** f [kHz]
98	93	188	36	64	1.7	16.0
98	91	186	28	68	2.4	7.8
94	93	308	37	22	0.6	14.0
94	91	270	26	53	2.0	7.1
94	**89**	215	**21**	64	3.1	5.6
91	**93**	**525**	30	**126**	**4.3**	11.0
91	**91**	**365**	**25**	**118**	**4.8**	5.3
86	93	306	31	84	2.7	4.9

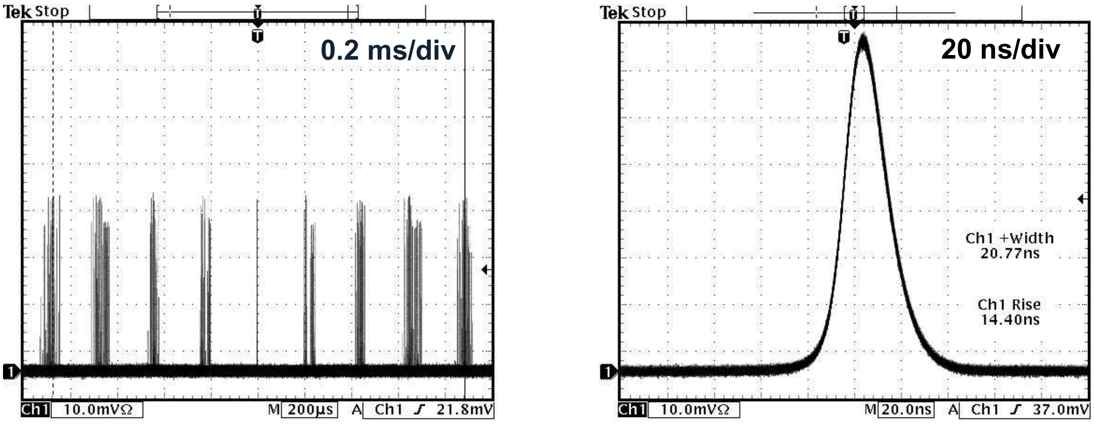

Figure 8. CW Diode pumped Nd:YAG laser parameters – Nd:YAG composite rod, separated V:YAG saturable absorber. Time structure of generated radiation in large scale and in detail. Output coupler reflectivity 94 %, V:YAG initial transmission $T_0 = 89\,\%$, resonator length 80 mm.

4.3. CW Diode pumped Nd:YAG/V:YAG monolith laser

On the base of previous experiments, a special crystal monolith based on YAG combining in one block undoped cooling part, Nd^{3+} doped active laser crystal, and V^{3+} passive saturable Q-switch, was designed and realized (Figure 5). The initial transmission of used saturable absorber was set to 88 %. This crystal was tested with all possible output couplers (R_{OC} = 94 %, 91 %, 86 %, and 82 %) except of output coupler with reflectivity 98 % to prevent dielectric coatings damage. Constructed longitudinally diode CW pumped laser was operating with all these mirrors. More compact system allows us to use shorter laser resonator – three different lengths were tested: 54 mm, 42 mm, and 33 mm. Like in previous case, following parameters of Nd:YAG laser output radiation in dependence on pumping power were measured: a mean output power, generated giant pulse width (FWHM), and repetition rate of generated pulses. From obtained values, single pulse energies and peak powers were calculated. Results are summarized in Table 3. Examples of generated Q-switched pulses are shown on Figure 9.

From results it follows, that in case of this compact laser more stable CW Q-switched output at wavelength 1340 nm was obtained. Generated pulse lengths were in range between 11 na 20 ns and depends mainly on resonator lengths – it did not changed significantly with pumping power and with output coupler reflectivity. Duration of shortest pulses obtained with resonator length 33 mm was only 11 ns. Maximum obtained mean power, peak power, and pulse energy at wavelength 1340 nm was 0.7 W, 6.1 kW, and 97 μJ, respectively.

Table 3. CW diode pumped Nd:YAG laser parameters – Nd:YAG/V:YAG monolith rod. Dependence of generated radiation parameters on the output coupler reflectivity R_{OC} and resonator length L.

Output coupler R_{OC}	**Resonator length** L [mm]	**Mean power** P [mW]	**Pulse width** FWHM [ns]	**Peak power** P_{peak} [kW]	**Pulse energy** E [μJ]	**Pulse frequency** f [kHz]
94 %	54	360	19.6 ± 0.7	4.3	78	4.6
91 %	54	570	19.3 ± 0.4	4.8	96	5.9
86 %	**54**	500	19.7 ± 0.3	5.0	**97**	5.2
82 %	54	510	19.6 ± 1.5	4.7	90	5.7
91 %	**42**	**700**	14.7 ± 0.5	4.6	67	10.4
82 %	42	580	14.4 ± 0.6	4.9	68	8.5
82 %	33	500	12.0 ± 0.5	4.9	58	8.6
82 %	**33**	430	**11.0 ± 0.4**	**6.1**	67	6.4

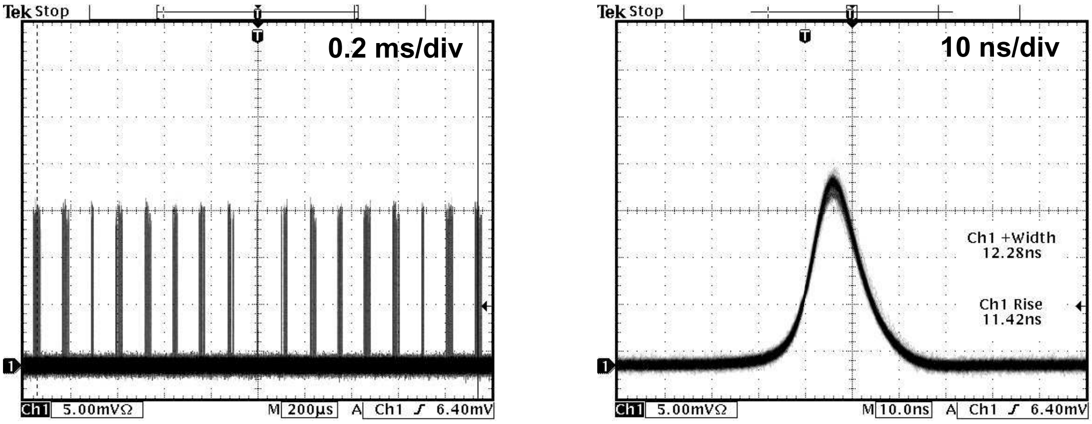

Figure 9. CW diode pumped Nd:YAG laser parameters – Nd:YAG/V:YAG monolith rod. Time structure of generated radiation in large scale and in detail. Output coupler reflectivity 82 %, V:YAG initial transmission 88 %, resonator length 33 mm.

5. DISCUSSION

5.1. Flash-lamp pumped Nd:YAP laser

The laser oscillator optimal performance of the flash-lamp pumped Nd:YAP laser Q-switched/mode-locked by V:YAG saturable absorber was found by varying the initial saturable absorber transmission and the resonator length. The highest energy for one generated train of pulses was reached for the initial V:YAG transmission $T_0 = 28\,\%$. The output oscillator energy was 53 mJ, the corresponding pulse train duration was 17 ns. The length of single pulse in train was around 1 ns (FWHM).

5.2. Diode pumped Nd:YAG lasers

V:YAG saturable absorber was also tested for Q-switching of diode end-pumped Nd:YAG laser with short cavity. Two similar configurations, mainly differing in active crystal and saturable absorber position, were tested and compared.

In the first configuration as an active medium the composite Nd:YAG crystal was used. This crystal consists of YAG undoped cooling part and Nd^{3+} ion doped gain part – Figure 3). Used V:YAG saturable absorber was placed in the laser resonator separately in its own holder – see Figure 4.

In the second configuration specially prepared Nd:YAG/V:YAG monolith crystal was tested as the active medium. This crystal interconnect the Nd:YAG laser gain medium, YAG undoped cooling part and V:YAG saturable absorber in one compact piece – Figure 5).

The first configuration (separated gain medium and saturable absorber) allow us to change simply the initial transmission of used saturable absorber and to optimize the laser configuration. Several suitable conbinations of saturable absorber initial transmissions and output coupler reflections were found. For resonator length of 80 mm (limited by mounting elements), the shortest obtained pulses were 21 ns long (FWHM) (the output coupler reflectivity and V:YAG initial transmission was $R_{OC} = 94\,\%$, and $T_0 = 89\,\%$, respectively). In this case, mean power, peak power, and pulse energy was 215 mW, 3.1 kW, and 64 μJ, respectively. The highest mean power (525 mW) and pulse energy (126 μJ), but longer pulses (30 ns) were obtained for $R_{OC} = 91\,\%$ and $T_0 = 93\,\%$. The highest peak power (4.8 kW) reached in this configuration was obtained for $R_{OC} = 91\,\%$, and $T_0 = 91\,\%$.

The second configuration of diode pumped laser system, based on Nd:YAG/V:YAG monolith crystal, allowed us to use shorter external resonator (up to 33 mm), but low level signal transmission of saturable absorber was fixed to value $T_0 = 88\,\%$. This value (as was explained in subsection 3.3) was set on the base of results obtained in experiment made with separated V:YAG saturable absorbers. This initial transmission is a little bit lower than the lowest value of tested separated V:YAG crystal ($T_0 = 89\,\%$). While the laser Q-switched by this separated V:YAG absorber was operating together with output coupler with reflectivity $R_{OC} = 94\,\%$ only, the Nd:YAG/V:YAG monolith crystal was operated in the laser resonator designed with all tested output couplers ($R_{OC} = 82 - 94\,\%$). The generated pulse parameters depends mainly on resonator length and it did not changed significantly with pumping power and with output coupler reflectivity. These parameters affect mainly the mean power and the pulse repetition rate. Duration of shortest pulses obtained with resonator lengths 33 mm was only 11 ns. Maximum obtained mean power, peak power, and pulse energy at wavelength 1340 nm was 0.7 W, 6.1 kW, and 97 μJ, respectively.

6. CONCLUSION

Passive Q-switching provides a successful and compact means of generating short, high-intensity laser pulses. V:YAG crystals grown in reducing atmosphere have higher concentration of V^{3+} tetrahedrally coordinated ions, that effect in more intense absorption bands and lower parasitic nonsaturable losses in comparison to V:YAG crystals grown in iridium crucibles. Various samples of the saturable absorbers were grown and experimental observations were given with the goal of finding the optimal laser system configuration.

It could be summarized that the laser oscillator optimal performances were found for flashlamp as well as diode pumped laser Q-switched by V:YAG saturable absorber. From the point of the applications both systems are useful. The highest energy – 50 mJ – in Nd:YAP flashlamp pumped laser oscillator obtained with the transmission $T_0 = 28\,\%$ of V:YAG could be useful in the system of Raman laser which can generate eye safe 1.5 μm wavelength.

Diode pumped laser can be used in the future for the technological laser systems. Comparing the the Nd:YAG/V:YAG monolith system with the same but "non-contact" configuration case (when the saturable absorber is separately from the active medium) some significant advantages of monolith arrangement for all future applications are seen:

- Simplest Q-switched laser system construction and adjustment, shorter laser resonator ⇒ more compact laser system, smaller sensitiveness to all mechanical disturbance, rugged and low-maintenance system, generation of shorter pulses.
- Contact of V:YAG saturable absorber with the rest of the monolith crystal inherently increase its cooling and improve thermal stability of all system ⇒ higher temporal stability of generated radiation (mean power and pulse frequency stability, pulse-to-pulse stability.)
- The simple arrangement of laser active-passive medium (the connection of two originally independent optical elements) result in the reduction of the inside resonator losses ⇒ lower obtained threshold, possibility of using the output mirror with lower reflection, higher power done by shorter length of generated pulse.
- Other improvement of monolith scheme can be expected in the case when the resonator mirrors will be implemented directly on the crystal faces ⇒ microchip laser based system.

ACKNOWLEDGMENTS

This research has been supported by the Czech Ministry of Education – Grant No. 210000022, and by the Czech Ministry of Industry and Trade – Project No.: FF–P/125.

REFERENCES

1. J. T. Murray, R. C. Powell, N. Peyghambarian, D. Smith, W. Austin, and R. A. Stolzenberg, "Generation of 1.5 μm radiation through intracavity solid state raman shifting in $Ba(NO_3)_2$ nonlinear crystals," *Optics Letters* **20**, pp. 1017–1019, May 1995.
2. Z. Mierczyk, "Investigation of saturable absorber for "eye-safe" giant-pulse laser systems," *Optics and Optoelectronics, Theory, Devices and Applications* **2**, pp. 1033–1036, 1998.
3. M. Jelínek, H. Jelínková, and J. Kubelka, "Q-switching and mode-locking Nd:YAP laser 1.34 μm with BDN II," *Czech Journal of Physics B* **38**, p. 119, 1988.
4. Y. Shimony, Y. Kalisky, and B. H. T. Chai, "Quantitative studies of Cr^{4+}:YAG as a saturable absorber for Nd:YAG laser," *Optical Materials* **4**, pp. 547–551, Mar. 1995.
5. Y. Shimony, Z. Burshtein, A. B.-A. Baranga, Y. Kalisky, and M. Strauss, "Repetitive Q-switching of a CW Nd:YAG laser using Cr^{4+}:YAG saturable absorbers," *IEEE Journal of Quantum Electronics* **32**, pp. 305–310, Feb. 1996.
6. R. Fluck, B. Braun, E. Gini, H. Melchior, and U. Keller, "Passively Q-switched 1.34-μm Nd:YVO_4 microchip laser with semiconductor saturable-absorber mirrors," *Optics Letters* **22**, pp. 991–993, July 1997.
7. S. C. Zeller, L. Krainer, G. J. Spühler, K. J. Weingarten, R. Paschotta, and U. Keller, "Passively mode-locked 40-GHz Er:Yb:glass laser," *Applied Physics B: Lasers and Optics* **76**, pp. 787–788, 2003.
8. V. P. Mikhailov, N. V. Kuleshov, N. I. Zhavoronkov, P. V. Prokoshin, and K. V. Yumashev, "Optical absorption and nonlinear transmission of tetrahedral V^{3+} (d^2) in yttrium aluminium garnet," *Optical Materials* **2**, pp. 267–272, Oct. 1993.
9. V. S. Sidorov, E. N. Korobelnikova, S. A. Potylitsina, and S. K. Timoshenko, "Optical transmission spectra of yttrium aluminum garnet doubly doped with iron group elements," *Inorganic Materials* **33**(6), pp. 6330–6635, 1995.
10. K. V. Yumashev, N. V. Kuleshov, A. M. Malyarevich, P. V. Prokoshin, V. G. Shcherbitsky, N. N. Posnov, V. P. Mikhailov, and V. A. Sandulenko, "Ultrafast dynamics of excited-state absorption in V^{3+}:YAG crystal," *Journal of Applied Physics* **80**, pp. 4782–4784, Oct. 1996.
11. S. Kuck, P. Jander, and G. Huber, "Spectroscopy of tetraedrally coordinated V^{3+} on oxide crystals," in *OSA TOPS on Advances Solid State Lasers*, *Proceedings of OSA* **19**, pp. 509–513, 1998.

12. Z. Frukacz, Z. Mierczyk, and D. A. Pawlak, "YAG:V^{3+} single crystals growth and their selected properties," in *International Conference on Solid State Crystals '98: Single Crystal Growth, Characterization, and Applications*, A. Majchrowski and J. Zielinski, eds., *Proceedings of SPIE* **3724**, pp. 329–333, Mar. 1999.
13. Z. Mierczyk and Z. Frukacz, "YAG:V^{3+} — new passive Q-switch for lasers generating radiation within near infrared range," *Opto-Electronics Review* **1**(8), pp. 67–74, 2000.
14. V. B. Sigachev, T. T. Basiev, M. E. Doroshenko, V. V. Osiko, and A. G. Papashvili, "1.3 μm neodymium laser passively Q-switched with Nd^{2+}:SrF_2 and V^{3+}:YAG crystals and Raman shifting to eye-safe region," in *Advanced Solid-State lasers*, B. H. T. Chai and S. A. Payn, eds., *Proceedings of OSA* **24**, pp. 454–459, 1995.
15. H. Jelínková, P. Černý, J. Šulc, J. K. Jabczynski, K. Kopczynski, W. Zendzian, Z. Mierczyk, and M. Miyagi, "Passively mode-locked/Q-switched Nd:YAP 1.34-μm/1.08-μm laser with efficient hollow-waveguide radiation delivery," *Optical Engineering* **41**(8), pp. 1976–1982, 2002.
16. A. Agnesi, A. Guandalini, G. Reali, J. K. Jabczyński, K. Kopczyński, and Z. Mierczyk, "Diode pumped Nd:YVO_4 laser at 1.34 μm Q-switched and mode-locked by a V^{3+}:YAG saturable absorber," *Optics Communications* **194**, pp. 429–433, July 2001.
17. V. P. Mikhailov, N. I. Zhavoronkov, N. V. Kuleshov, V. A. Sandulenko, K. V. Yumashev, and P. V. Prokoshin, "Mode-locking of near infrared laser with V^{3+}:YAG crystal as a saturable absorber," in *Advanced Solid-State lasers*, A. A. Pinto and T. Y. Fan, eds., *Proceedings of OSA* **15**, pp. 354–358, 1993.
18. A. M. Malyarevich, I. A. Denisov, K. V. Yumaschev, V. P. Mikhailov, R. S. Conroy, and B. D. Sinclair, "V:YAG — a new passive Q-switch for diode-pumped solid state lasers," *Applied Physics B: Lasers and Optics* **67**, pp. 555–558, Nov. 1998.
19. A. S. Grabtchikov, A. N. Kuzmin, V. A. Lisinetskii, V. A. Orlovich, A. A. Demidovich, K. V. Yumashev, N. V. Kuleshov, H. J. Eichler, and M. B. Danailov, "Passively Q-switched 1.35 μm diode pumped Nd:KGW laser with V:YAG saturable absorber," *Optical Materials* **16**, pp. 349–352, Apr. 2001.
20. J. K. Jabczyński, K. Kopczyński, Z. M. A. Agnesi, A. Guandalini, and G. Reali, "Application of V^{3+}:YAG crystals for Q-switching and mode-locking of 1.3-μm diode-pumped neodymium lasers," *Optical Engineering* **40**, pp. 2802–2811, Dec. 2001.
21. J. Šulc, H. Jelínková, V. Kubeček, M. Jelínek, K. Nejezchleb, and K. Blažek, "Thermal properties of Nd:YAG-composite active media in diode-pumped laser," *Laser Physics, Modern trends in laser physics* **13**(10), pp. 1284–1289, 2003.