CHARACTERISTICS OF SOLID-STATE LASERS WITH PASSIVE Q-SWITCHING BY POLYMER SATURABLE ABSORBERS

V.I. BEZRODNYI,[1] A.A. ISHCHENKO,[2] A.M. NEGRIYKO,[1] A.O. YASKOVETS,[1] A.A. DEMIDOVICH,[3] M.B. DANAILOV,[3] V.A. ORLOVICH,[4] P. SHPAK[4]

[1]Institute of Physics, Nat. Acad. of Sci. of Ukraine
(46, Nauky Prosp., Kyiv 03028, Ukraine)

[2]Institute of Organic Chemistry, Nat. Acad. of Sci. of Ukraine
(5, Murmanska Str., Kyiv 02660, Ukraine)

[3]Laser Laboratory Sincrotrone-Trieste
(Strada Statale 14-km, 163.5, Trieste 34012, Italy)

[4]B.I. Stepanov Institute of Physics, Nat. Acad. of Sci. of Belarus
(68, Nezalezhnast Ave., Minsk 220072, Belarus)

PACS 42.55.Ah, 42.62.-b

The characteristics of miniaturized diode-pumped compact passively Q-switched Nd:YAG and Nd: YVO_4 lasers have been studied. Lasing at a wavelength of 1.064 μm with a pulse repetition rate of up to 25 kHz, a pulse duration of 2–5 ns, an average power of 130 mW, and a pump power of 3.5 W was realized with the use of a polymer Q-switch on the basis of polyurethane doped with the bis-(4-dimethylaminodithiobenzyl)-nickel dye. Diode-pumped solid-state mini lasers with passive Q-switching by sandwich-type modulators are efficient compact sources of short powerful light pulses with a high optical quality of the beam.

1. Introduction

Nonlinear optics, despite its half-century long history, continues to draw the steady attention of researchers as a direction of physics, which develops actively and fruitfully. Let us recall that, unlike classical optics, the optical properties of a medium – in particular, its absorption, refractive index, dispersion – depend on the light intensity at high intensities of a light flux typical of laser beams. The superposition principle becomes violated, so that the frequency of light oscillations can change in the course of the light propagation in a medium and so forth. Nonlinear effects of different nature are observed at the propagation of intensive light fluxes in solids, liquids, atomic and molecular gases, plasma.

Nonlinear optical effects form a basis for such elements to control the lasing parameters as optical harmonic generators, parametric oscillators, electro-optical and acousto-optical modulators, Q-switches. In particular, the passive Q-switching is often applied in compact solid-state lasers. Passive Q-switched lasers generate short powerful light pulses of the nanosecond duration. At the same time, they do not need complex electronic control systems and high voltages and, as a result, find numerous practical applications. For neodymium lasers operating at a wavelength of 1.064 μm, passive Q-switches (PQSs) on the basis of yttrium-aluminum garnet doped with chrome ions (Cr^{4+}:YAG) [1–3], PQSs on the basis of radiation-colored lithium fluoride [4], and semiconductor saturable absorber Q-switches [5, 6] are applied. Recently, an application of saturable absorption by graphene for Q-switching in a neodymium laser on the Nd:$GdVO_4$ crystal was reported [7]. Cheap and accessible for manufacturing under laboratory conditions are PQSs on organic dyes in polymeric matrices. In work [8], reticulated polyurethane was offered to be used as a matrix for PQS. Its hardening, unlike that in epoxy polymers, occurs under soft conditions, namely, at room temperature and in a neutral environment, which allows dyes of various classes to be introduced into it without a dye decomposition. PQSs on the basis of this polymer, which were fabricated in a triplex design of the sandwich type, provided an effective Q-switching in lamp-pumped lasers [8]. For diode-pumped lasers, the most widespread PQSs for today are PQSs with such matrices as cellulose acetate [9, 10] and polyvinylcarbazole [11]. At the same time, polyurethane-based PQSs of the sandwich type can be considered as promising systems for modulating the diode-pumped mini and micro lasers owing to their high radiation stability and high optical quality.

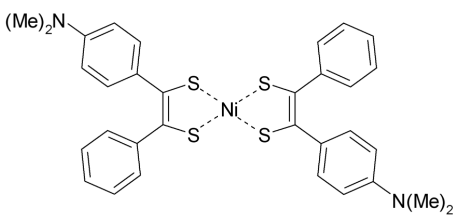
This work aimed at researching the passive Q-switching in mini lasers with a Q-switch of the sandwich type on the basis of colored polyurethane.

2. Experimental Researches of Passive Q-switched Mini Laser Characteristics

2.1. Experimental setup

In this work, we used solid-state PQSs on the basis of an organic dye dissolved in a polymeric matrix. Structurally, the PQS was fabricated in the form of a triplex (polymer sandwiched between two glass plates), the external working surfaces of which were antireflection-coated to a level of 0.2% in the spectral range of about 1.06 μm. The matrix refractive index could be controlled within a range from 1.48 to 1.52 by varying the concentration of polymer components. Therefore, reflection losses at the polymer–glass interface could be reduced almost to zero.

The polymer matrix was activated by doping it with a photostable dye bis-(4-dimethylaminodithiobenzyl)-nickel (BDN). The latter was prepared as a product of the reaction between 4-dimethylaminobenzoin and phosphorus pentasulfide in boiling dioxane with the admixture of a nickel chloride aqueous solution. The structural chemical formula of BDN dye looks like



This dye proved itself well in polymer PQSs in lamp-pumped pulsed lasers [11]. A polyurethane composition synthesized in the polycondensation reaction of diole with diisocyanate according to

$$n\text{HO–R–OH} + n\text{OCN-R}'\text{-NCO} \rightarrow$$

$$\rightarrow \text{-[-O-R-O-CO–NH-R}'\text{-NH-CO-]}n\text{-},$$

where n is the number of molecules, and R and R$'$ are aliphatic or aromatic carbohydrate groups, served as the polymeric matrix. The chosen polymer composition is a mesh elastomer, in which all the molecules are connected by chemical bonds of various nature. An important feature of polymers is the fact that organic dyes belonging to basic classes, which are used in the laser technique, can be dissolved in them without formation of dimers or more complex objects. Metalloorganic complexes (the BDN dye is one of them) can be easily introduced into the initial components of a chosen polyurethane polymer composition within a wide concentration interval (10^{-4}–10^{-7} mol per 1 g of polymer) without aggregation. We even managed to introduce polymethine dyes into this polymer [12, 13], although it is known that, for instance, in widely used polymethylmethacrylate, those dyes become almost completely decomposed even at the polymerization stage.

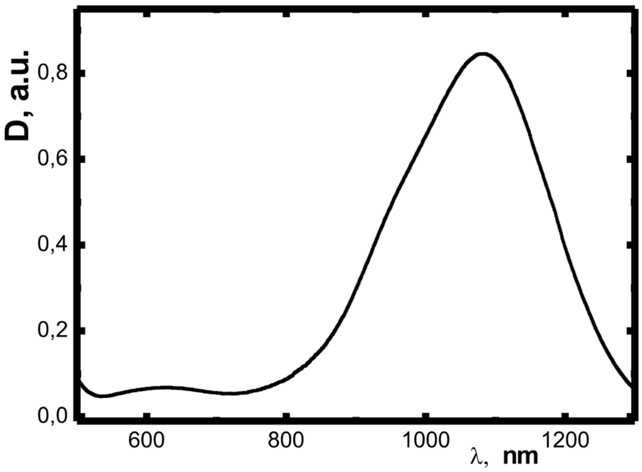


Fig. 1. Absorption spectrum of BDN dye in a polyurethane matrix

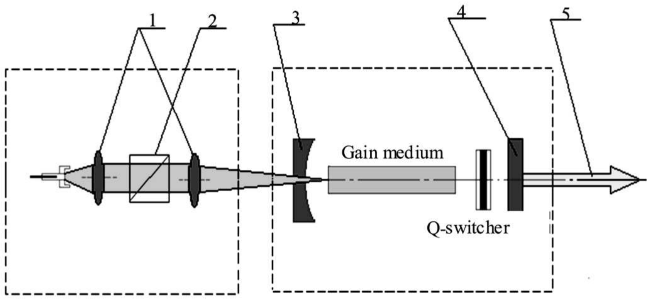


Fig. 2. Experimental setup for a laser with passive Q-switching and longitudinal pumping: (*1*) collimating objective lenses, (*2*) modulation unit, (*3*) totally reflecting mirror, (*4*) exit mirror, (*5*) output laser beam

The scheme of the experimental laser setup is shown in Fig. 2. A diode laser with a wavelength of 808 nm, which was supplied with an LDS-80 electronic block to provide both continuous-wave and pulsed operation modes, served as a pump source. Pump radiation was directed using a optical fiber with a core diameter of 200 μm to the modulation block, which governed the pulse-periodic pump mode, the polarization transmission regulator al-

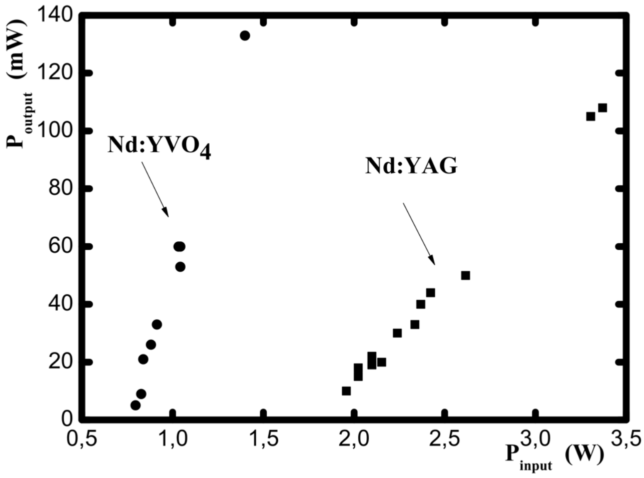


Fig. 3. Average power of generation by Nd:YVO$_4$ and Nd:YAG passive Q-switched mini lasers

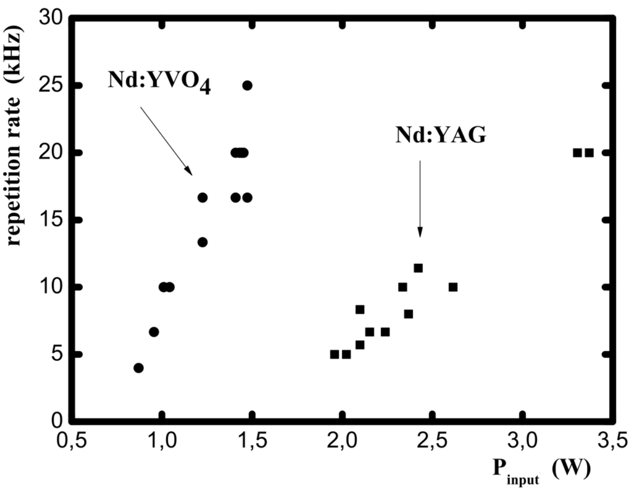


Fig. 4. Repetition frequency of output pulses for Q-switched mini lasers

lowing a pump reduction without shifting the beam in space. Collimators formed a pump beam 280 μm in diameter in the active medium.

The most widespread diode-pumped lasers that emit in the infra-red range at a wavelength of 1.06 μm, are those based on neodymium-doped yttrium aluminum garnet (Nd:YAG) and yttrium vanadate (Nd:YVO$_4$). In both those crystals, the Nd absorption spectrum reveals a wide absorption band at a wavelength of about 808 nm, which coincides with the radiation-emission wavelength of the semiconductor pump laser. The absorption band in the Nd:YVO$_4$ crystal is six times as wide as that in the Nd:YAG crystal. This circumstance weakens requirements set to the thermal stability of the radiation spectrum emitted by a pump laser on Nd:YVO$_4$. In addition, the absorption coefficient for the Nd:YVO$_4$ crystal is approximately four times higher than that for the Nd:YAG one at identical neodymium concentrations [14].

In this work, both the Nd:YVO$_4$ and Nd:YAG lasers were studied. Their active elements were cylindrical (8 mm in length and 3 mm in diameter) and with parallel (the angular misalignment of not more than $10''$) working surfaces. The latter were antireflection-coated for wavelengths of 808 and 1064 nm.

The average power of laser radiation was measured by a Laser Star Powermeter. The pulse duration was measured with the use of a four-channel TDS-7104 Digital Phosphor Oscilloscope with a transmission band of 1 GHz and an ET 3500F photo diode with a transmission band of 12 GHz. The laser radiation profile was determined with a CCD camera.

2.2. Experimental results and discussion

We studied the characteristics of a mini laser operating in the passive Q-switching mode, provided the longitudinal diode pumping with Nd:YAG and Nd:YVO$_4$ active elements. To reduce the thermal loading on the active elements, the pulsed pump mode was used. The pump pulse duration was 5 ms at a repetition frequency of 20 Hz. The mini laser resonator 10 mm in length was created by a totally reflecting mirror 150 mm in radius and a plane exit mirror with a reflection of 70% at the lasing wavelength.

Figure 3 demonstrates the dependences of the averaged output power of mini lasers on Nd:YAG and Nd:YVO$_4$ with a PQS that had an initial transmittance of 62%. Using the same passive Q-switch, the dependence of the pulse repetition frequency on the pump power was studied (Fig. 4). The pulse repetition frequency was measured within the time interval of a pump pulse (i.e. within 5 ms). The pulse duration was determined at various pump levels (see Fig. 5 for the Nd:YAG laser and Fig. 6 for the Nd:YVO$_4$ one). In the former case (the garnet-based laser), the pulse duration varied from 3 to 5 ns and was practically independent of the pump power. The pulse duration for the vanadate-based mini laser was 2.2 ns. The stability of the pulse duration in both lasers was not studied purposely. However, we may assert that it was much better for the Nd:YVO$_4$ laser. In this research, we did not aimed at optimizing the output parameters for the diode-pumped mini laser.

Unlike film PQSs on dyes [9–11], Q-switches of the sandwich type can operate at higher average powers owing to the better heat removal from the working zone. By

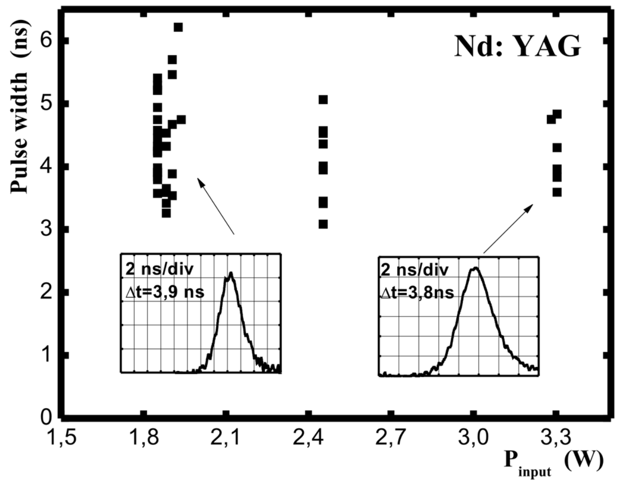


Fig. 5. The shape of giant pulse of a Nd:YAG mini laser and its reproducibility

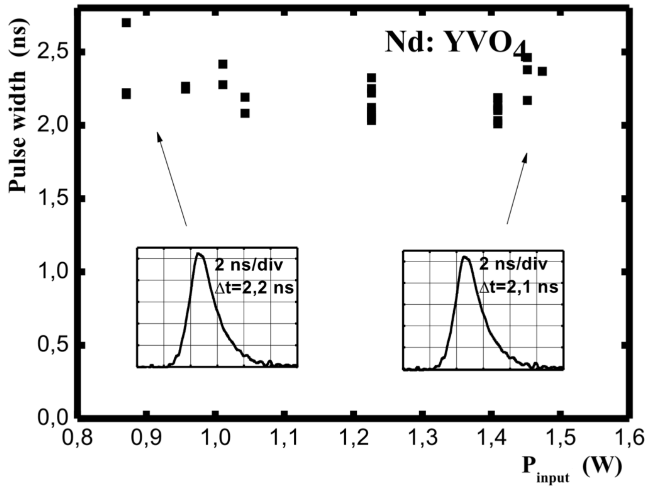


Fig. 6. The shape of giant pulse of a Nd:YVO_4 mini laser and its reproducibility

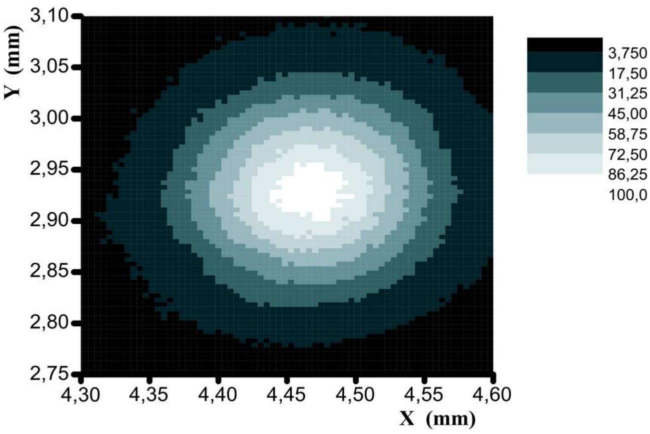


Fig. 7. Spatial structure of a radiation beam in the plane of a passive laser Q-switch

its optical quality, the sandwich-type PQS is not worse than other components of the resonator (mirrors, the active element), which provides the generation of high-quality laser radiation and the laser operation in the single-transverse mode.

As is seen from the results of power characteristic researches, the Nd:YVO_4 mini laser is more efficient that the Nd:YAG one. The generation threshold was approximately 2.5 times lower, when using the vanadate, than that for the garnet-based laser. Within the studied range of the pump power up to 3.5 W, the output laser power grew linearly with increase in this parameter for the active elements of both types. The repetition frequency of output pulses also depended linearly on the pump power (Fig. 4), which evidenced a reliable work of the sandwich-type PQS at reached lasing powers.

The spatial profile of mini laser radiation (Fig. 7), which was obtained using a CCD camera and approximated with the use of the Gauss method, testifies to a symmetric distribution of energy in the laser beam, the transverse cross-section of which grows with the pump power.

3. Conclusions

Passive Q-switching in diode-pumped mini lasers with the sandwich type polymer Q-switch on the basis of colored by BDN dye polyurethane made it possible to generate short intensive nanosecond pulses. At a resonator length of 18 mm and an initial transmittance of PQS equal to 62% , we obtained an output power of 120 mW for the laser with the Nd:YAG active element and 130 mW for the laser with the Nd:YAG one. The repetition rates for those active elements were 20 and 25 kHz, respectively. The pulse duration varied from 2 to 5 ns. Short pulses give rise to a high peak power, which allows compact diode-pumped lasers with passive modulation using sandwich-type Q-switches on the basis of dye-activated polyurethane to be applied in nonlinear optics and various applied problems.

The work was sponsored in the framework of the projects No. 1.4.1. V/137 and 1.4.1. VTs/139 of the National Academy of Sciences of Ukraine, and the Ukrainian-Belarusian project F29.1/021 of the State fund for fundamental researches in Ukraine. A.O.Ya. expresses his gratitude to the Secondary-Network Scientific Centres of Central European Initiative at Minsk

(Belarus) and Trieste (the Abdus Salam International Centre for Theoretical Physics, Italy) for their support.

1. C. Li, J. Song, D. Shen, J. Xu, and K. Ueda, Opt. Commun. **186**, 245 (2000).
2. N. Lai, M. Brunel, F. Bretenaker, and A. Floch, Appl. Phys. Lett. **79**, 1073 (2001).
3. C. Zuo, J. He, H. Huang, B. Zhang, Z. Jia, and C. Dong, Opt. Laser Technol. **41**, 17 (2009).
4. J.A. Morris and C.R. Pollock, Opt. Lett. **15**, 440 (1990).
5. R. Fluck, R. Häring, R. Paschotta, E. Gini, H. Melchior, and U. Keller, Appl. Phys. Lett. **72**, 3273 (1998).
6. G.J. Spühler, S. Reffert, M. Haiml, M. Moser, and U. Keller, Appl. Phys. Lett. **78**, 2733 (2001).
7. X. Li, J. Xu, Y. Wu, J. He, and X. Hao, Opt. Express **19**, 9950 (2011).
8. V.I. Bezrodnyi, L.V. Vovk, N.A. Derevyanko, A.A. Ishchenko, L.V. Karabanova, and I.L. Mushkalo, Kvant. Elektron. **22**, 245 (1995).
9. A. Zenteno, H. Po, and N.M. Cho, Opt. Lett. **15**, 115 (1990).
10. R. Salas-Montiel, L. Bastard, G. Grosa, and J. Broquin, Mater. Sci. Eng. B **149**, 181 (2008).
11. A. Inoue, J. Hayashi, T. Komikado, and S. Umegaki, Opt. Lett. **32**, 2807 (2007).
12. V.I. Bezrodnyi and A.A. Ishchenko, Opt. Laser Technol. **34**, 7 (2002).
13. V.I. Bezrodnyi, N.A. Derevyanko, A.A. Ishchenko, and Yu.L. Slominskii, Quant. Electron. **25**, 823 (1995).
14. K. Waichman and Y. Kalisky, Opt. Mater. **19**, 149 (2002).

Received 14.09.11.
Translated from Ukrainian by O.I. Voitenko

ХАРАКТЕРИСТИКИ ТВЕРДОТІЛЬНИХ МІНІЛАЗЕРІВ З ПАСИВНОЮ МОДУЛЯЦІЄЮ ДОБРОТНОСТІ НЕЛІНІЙНО-ПОГЛИНАЮЧИМИ ПОЛІМЕРНИМИ ЗАТВОРАМИ

В.І. Безродний, О.О. Іщенко, А.М. Негрійко, А.О. Ясковець, А.А. Демидович, М.Б. Данаілов, В.А. Орлович, П. Шпак

Р е з ю м е

Досліджено характеристики мініатюрних компактних лазерів на Nd:YAG та Nd:YVO_4 з діодною накачкою у режимі пасивної модуляції добротності. З використанням полімерного лазерного затвора на основі поліуретану, забарвленого барвником біс-4-діметиламінодітіобензил нікелю, реалізована генерація на довжині хвилі 1,064 мкм з частотою слідування імпульсів до 25 кГц, тривалістю 2–5 нс та потужністю до 130 мВт при накачці до 3,5 Вт. Твердотільні мінілазери з діодною накачкою і пасивною модуляцією добротності затворами сендвічевого типу є ефективними компактними джерелами коротких потужних імпульсів з високою оптичною якістю пучка.