

LASERS

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Efficient diode-side-pumped $Nd:YVO_4$ slab laser in different generation regimes

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***Abstract*. A diode-side-pumped $Nd:YVO_4$ slab laser with the grazing-incidence bounce geometry of the cavity is studied experimentally. Upon continuous pumping different lasing regimes are realised, namely, cw, passive and active Q-switching and passive mode-locking. The resonator parameters are optimised to achieve the maximum cw output power ($\sim$ 17 W) and high-quality beam ($M^2 \approx 1.3$).**

Keywords: *Nd:YVO$_4$ laser crystal, diode pumping, solid-state laser, cw lasing, Q-switching, mode locking.*

1. Introduction

At present, diode-pumped solid-state lasers based on yttrium vanadate crystals doped with Nd^{3+} ions ($Nd^{3+}:YVO_4$) are attracting interest around the world due to their promising properties [1 – 6]. One of the advantages of these lasers is a high efficiency which is achieved due to large cross sections of pump radiation absorption and large cross sections of stimulated emission in $Nd:YVO_4$ crystals. In most papers, such active elements are longitudinally pumped, which requires expensive diode bars with a fibre pigtail and/or complicated optical systems for producing the spatial structure of the pump beam in the laser rod.

Side pumping of $Nd:YVO_4$ slabs with radiation from diode bars makes it possible to simplify considerably the system of optical pumping and to separate spatially pump and laser channels. Several research teams from Canada, Great Britain and Germany have been recently studying diode-side-pumped $Nd:YVO_4$ lasers [7 – 9]. The major problem in producing these lasers is the necessity to match spatially the laser beam with the gain regions inside the active medium.

The aim of this paper is to study the possible optimisation of the parameters of the diode-side-pumped $Nd:YVO_4$ laser with the grazing incidence geometry of the laser beam in order to improve the lasing efficiency at a high beam quality. Apart from continuous lasing, passive and active Q switching as well as passive mode locking are investigated.

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2. Active element and pump geometry

The active element made of the $Nd:YVO_4$ crystal (with 1 % atomic concentration of Nd^{3+} ions) had the form of a $20 \times 5 \times 2$-mm parallelepiped cut in the direction of the crystallographic axis a (the c axis was perpendicular to the parallelepiped face of size 20×5 mm). The end faces of the crystal slab (5×2-mm faces) were skewed at an angle of 5° to prevent parasitic oscillations.

The $Nd:YVO_4$ laser was pumped by a Coherent diode bar with the output power up to 50 W at the wavelength of $\sim$ 807.5 nm, which was stabilised and tuned by varying the diode-bar temperature. A cylindrical lens with the focal distance of $\sim$ 12 mm was used to vertically focus the pump beam into the $Nd:YVO_4$ slab through the 2×20-mm face.

In the $Nd:YVO_4$ crystal (1 % of Nd^{3+}), the working laser transition between $^4F_{3/2}$ and $^4I_{1/2}$ levels, providing lasing at 1064 nm, has a large stimulated emission cross section (15.6×10^{-19} cm^2), and the transition between $^4F_{5/2}$ and $^4I_{9/2}$ levels has a large absorption cross section at the pump wavelength 807.5 nm (27×10^{-20} cm^2) [10], which allows laser systems with the differential efficiency of 68 % [11] to be manufactured by using this crystal. A high absorption coefficient at the pump wavelength ($\sim$ 30 cm^{-1}) results in a narrow gain region developing inside the crystal near the face through which pumping is performed. This fact makes side pumping most suitable for the lasers in which the beam experiences total internal reflection from this face.

The laser resonator was formed by two flat dielectric mirrors. One of the mirrors had the reflection coefficient of $\sim$ 99.9 % and the reflection coefficient of the other mirror varied from 4 % to 40 % (Fig. 1). The laser beam was focused by cylindrical lenses with the focal distance of $\sim$ 50 mm inside the active region near the face through

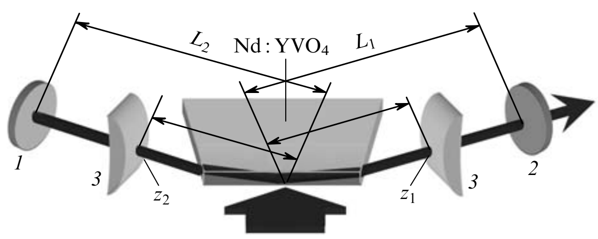

Figure 1. Scheme of a cw diode-side-pumped $Nd:YVO_4$ laser: (*1*) mirror with a reflection coefficient of $\sim$ 99.9 %; (*2*) a semitransparent output mirror; (*3*) cylindrical lenses with a focal distance of 50 mm.

which pumping was performed. This geometry of the resonator was used in all operation regimes: cw, Q-switching and mode locking.

3. Cw lasing

To achieve the maximum cw output power, we optimised different laser parameters: the position of the diode bar and lens focusing its radiation, the temperature of the diode bar and laser crystal, the angle of incidence of the laser beam on the crystal face, the position of the cylindrical lenses in the resonator, the reflection coefficient of the output mirror.

We found that the incidence angle of the laser beam on the active element plays an important role. The optical gain in the active medium depends on it (Fig. 2). The crystal characteristics (its dimensions, the skew angle of the end faces, temperature) as well as the power and location of the pump beam inside the active element determine the optimal angle of incidence. The experimentally found dependence of the laser output power on the incidence angle of the laser beam on the $Nd:YVO_4$ slab showed that the optimal angle (with respect to the face through which pumping is performed) was $\sim 22.7°$ (the length of the pump region is $L \approx 1.5$ cm, the crystal temperature is ~ 13 °C and the pump power is ~ 31 W).

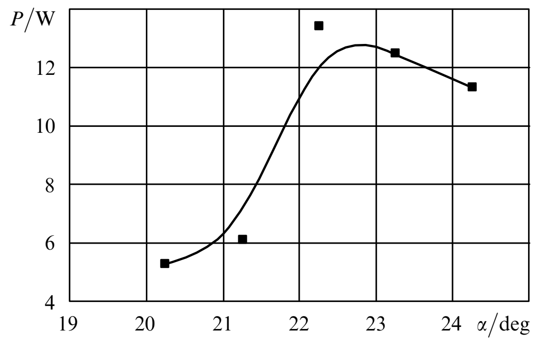

Figure 2. Dependence of the laser output power P on the angle of incidence α of the laser beam with respect to the face through which pumping is performed; the length of the pump region is 1.5 cm.

The position of the cylindrical lenses focusing the laser beam into the crystal had a noticeable effect on the lasing parameters (Fig. 3). These lenses form the waist of the amplified laser beam in the active element and their optimal position allows one to achieve the maximum extraction of the stored population inversion of the working laser transition.

One of the main resonator parameters affecting the output power is the reflection coefficient of the output mirror. In the experiments we used a set of dielectric mirrors with reflectances $R = 4\,\%$, $9\,\%$, $19\,\%$, $24\,\%$, $31\,\%$, $36\,\%$ and $40\,\%$ (the output surface of the mirror had an antireflection coating at 1064 ± 20 nm). The use of the output mirror with $R = 9\,\%$ provided the largest output power. In this case, the lasing threshold was greater than that for output mirrors with a higher reflection coefficient; however, the slope efficiency also increased, which allowed the output power to be increased up to ~ 17 W with the efficiency of the optical pump energy conversion to the output energy being as high as ~ 43.5 % (Fig. 4).

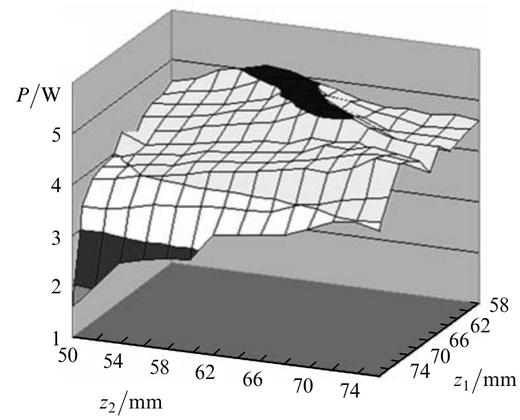

Figure 3. Dependence of the laser output power P on the position of cylindrical lenses with respect to the active element (coordinates z_1 and z_2 are measured from the middle of the crystal face).

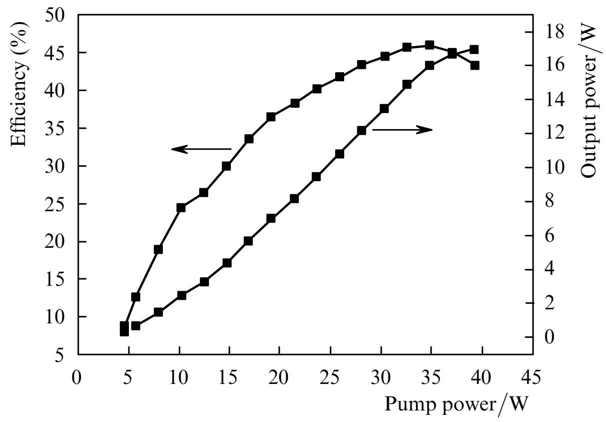

Figure 4. Dependences of the output power and the conversion efficiency of pump radiation into laser radiation on the pump power at the $\sim 9\,\%$ reflectance of the output mirror.

Note that lasing was observed even in the absence of the output mirror ($R = 0$). In this case, because of the high gain in the active medium, it is necessary to remove the parasitic feedback appearing due to radiation scattering from laser elements. This can be achieved by removing optical elements from the beam path and/or using an optical Faraday isolator. However, the experiments showed that these measures cannot prevent lasing while highly-efficient lasing with a good beam quality can be explained by the formation of a dynamic grating in the active medium induced by the interference field of counterpropagating light waves and providing a positive feedback in the system. The possibility of this type of 'self-starting' lasing was discussed in papers devoted to the study of laser systems with a loop cavity [12–14].

Experiments on laser generation at different cavity parameters showed a high stability of the laser output power with the power fluctuation not exceeding 3 %. The emission spectrum consisted of a set of longitudinal modes whose number depended on the pump power excess over the threshold. For all the pump powers in a cavity with non-symmetric arms ($L_1 \neq L_2$), the spatial beam structure corresponded to that of the fundamental transverse mode (the M^2 factor measured by the slit method in accordance with ISO standard 11146 [15] was 1.3) (Fig. 5).

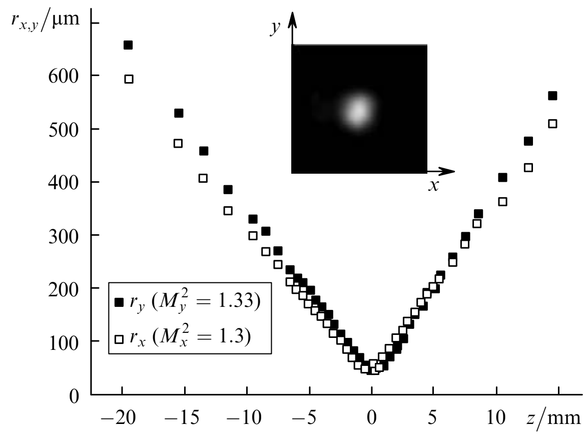

Figure 5. Experimentally measured radii of the beam caustic (near the focal waist of a 15-cm-focus lens) in the plane of incidence of the laser beam on the crystal face (r_x) and in the orthogonal plane (r_y) for 6-W laser output power used for calculating the M^2 factor. The z axis coincides with the beam axis. The caustic radius is minimal at $z = 0$. The inset shows the photograph of the beam focal spot being measured.

4. *Q*-switched lasing

4.1 Active *Q* switching

To realise the active Q-switching regime, we used a quartz acousto-optic modulator, which was placed in the left arm of the cavity (the arm with a highly reflecting mirror) (Fig. 1). The output mirror with the reflection coefficient of 40 % was used to increase the peak power and decrease the pulse duration. In this case, the average power of repetitively pulsed radiation was 16.9 W for the diode pump power of ~ 42 W. The laser pulse duration was ~ 10 ns for the pulse repetition rate of ~ 10 kHz. When the pulse repetition rate grew (to 100 kHz), the pulse duration increased (to 15 ns). The instability of the laser pulse amplitude did not exceed 10 % (Fig. 6).

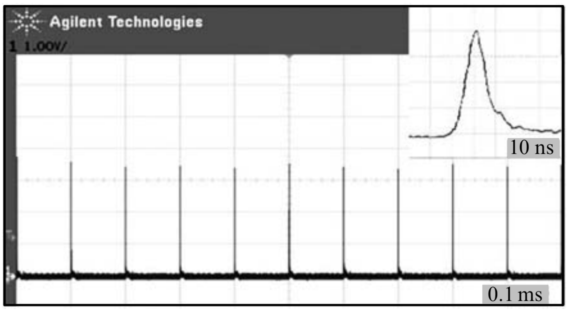

Figure 6. Oscillograms of laser pulses in the active Q-switching regime.

4.2 Passive *Q* switching

To realise the passive Q-switching regime, we used a saturable absorber in the form of a 4-cm-long LiF : F_2^- crystal of diameter 1 cm which had the following parameters: the absorption cross section was 1.7×10^{-17} cm^2 at 1064 nm and the relaxation time was 90 ns [16].

The parameters of the resonator assembled according to the scheme in Fig. 1 were as follows: $L_1 = 10.5$ cm, $L_2 =$ 15 cm, $R = 90$ %. The saturable absorber (the initial transmittance of ~ 33 %) was placed in the arm with a highly reflecting mirror at a distance of 11 cm from the active element. This cavity permitted us to achieve a pulse duration of ~ 20 ns and the peak power of ~ 400 W at the pulse repetition rate of ~ 120 kHz (Fig. 7).

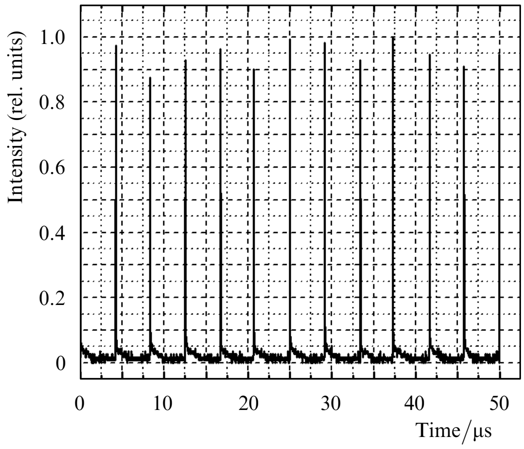

Figure 7. Oscillograms of a train of laser pulses in the Q-switching regime for a high-Q cavity.

5. Mode-locked regime

In papers known to us, passive mode locking in Nd : YVO_4 lasers was realised by using semiconductor saturable mirrors SESAM [17 – 19]. In this paper, we used an organic saturable absorber (polymethine dye No. 4965-u in a polyurethane matrix [20]), which was placed between two glass plates. The absorber had the following parameters: the absorption cross section was 8.6×10^{-16} cm^2 at 1064 nm, the relaxation time was 20 ± 2 ps [20]. The parameters of the laser resonator assembled according to the scheme in Fig. 1 were as follows: $L_1 = 55$ cm, $L_2 = 49$ cm. A longer cavity allowed us to increase the repetition interval between output pulses, which made their detection simpler. The reflection coefficient of the output mirror was increased to 90 %, which allowed us to stabilise the pulse amplitude whose variations did not exceed 5 % (Fig. 8). The pulse repetition interval measured in the experiment agreed with the theoretical estimate $T_{\rm theor} = 2L/c \approx 6.9$ ns.

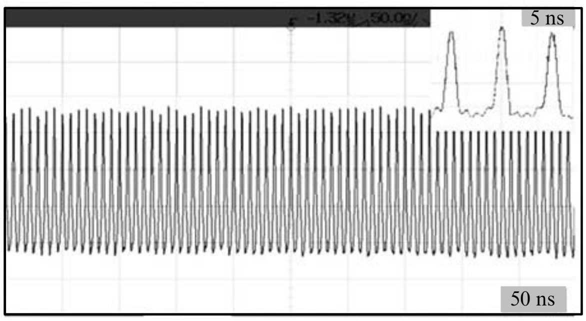

Figure 8. Oscillograms of laser pulses in the passive mode-locked regime at the 90 % reflectance of the output mirror.

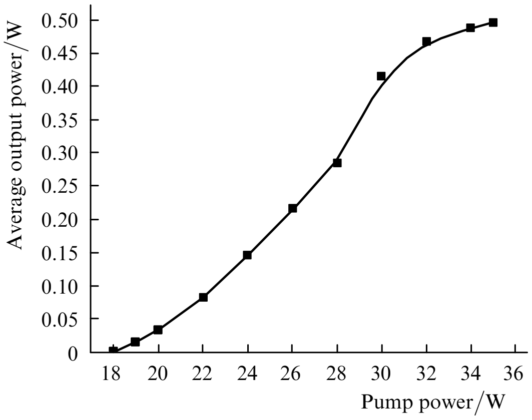

Figure 9. Dependence of the average output power of the passively mode-locked laser on the pump power at the 90% reflectance of the output mirror.

The pulse duration measured by the correlation method (by using second-harmonic generation in a $LiIO_3$ plate [21]) was $\sim 10 - 20$ ps. The average output power achieved 0.5 W (Fig. 9).

6. Conclusions

We have studied different generation regimes of a solid-state diode-side-pumped $Nd:YVO_4$ laser: cw lasing, active and passive Q-switching regimes and the passive mode-locked regime. The dependence of laser output parameters on the cavity parameters has been investigated. Optimisation of the laser parameters has allowed us to achieve a high conversion efficiency of the optical pump energy to the laser radiation energy, which was close to 50 % in the cw regime.

In the active Q-switching regime the laser generated 10–15 ns pulses at a pulse repetition rate of 10–100 kHz, and in the passive Q-switching regime – $\sim$ 20-ns pulses at a pulse repetition rate of $\sim$ 120 kHz. Passive mode locking has been realised for the first time in diode-pumped $Nd:YVO_4$ lasers by using an organic dye in a polymer matrix.

Thus, we have demonstrated the possibility of producing small-size solid-state lasers by using side diode pumping in the scheme with the grazing incidence of the laser beam. These lasers can operate both in the cw and pulsed regimes with a high slope efficiency. These lasers can find wide applications.

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