PACS numbers: 42.55.Px; 42.60.Jf
DOI: 10.1070/QE2009v039n11ABEH014058

Beam structure of a diode-side-pumped $Nd:YVO_4$ slab laser

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***Abstract*. The beam spatial structure of a diode-side-pumped $Nd:YVO_4$ slab laser with grazing-incidence bounce geometry is studied. It is found how the mode structure changes with changing the cavity parameters in the cw and active *Q*-switching regimes. The parameters that allow one to improve the output beam quality retaining high output laser power are found.**

Keywords: *$Nd:YVO_4$ laser crystal, diode pumping, solid-state laser, laser beam spatial structure.*

1. Introduction

Among solid-state active media, the $Nd:YVO_4$ crystal is distinguished by a high absorption cross section at 807.5 nm and a large gain cross section for the laser transition. Such properties allow one to use this crystal to create highly efficient (with a high pump conversion efficiency) laser systems. The $Nd:YVO_4$ lasers are designed using two fundamentally different schemes, namely, with longitudinal pumping of rods and transverse pumping of slabs, which, as a rule, are used for elements with low and high concentrations of Nd^{3+}, respectively. To use longitudinal pumping of laser rods, it is necessary to create a system separating the pump and laser radiation. At the same time, transverse pumping allows one to design simpler and compact schemes due to a smaller number of used optical elements.

The diode-side-pumped $Nd:YVO_4$ slab lasers can operate in different regimes: cw, *Q*-switching, and mode-locking [1]; however, the problem of the laser beam mode structure, which arises in all these cases, has not been seriously considered until now.

The specific cavity geometry of diode-side-pumped $Nd:YVO_4$ slab lasers allows formation of specific spatial modes (different from the modes of axisymmetric cavities). The aim of this work is to study the mode structure of a diode-side-pumped $Nd:YVO_4$ slab laser (grazing-incidence bounce geometry) and determine the conditions of generation of a high-quality laser beam.

*Reported at the Conference 'Laser Optics 2008', St. Petersburg, Russia.

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Received 2 February 2009; revision received 6 May 2009
Kvantovaya Elektronika **39** (11) 1047 – 1049 (2009)
Translated by M.N. Basieva

2. Scheme of the experimental setup

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

The $Nd:YVO_4$ crystal was pumped by a Coherent laser diode bar at a wavelength of 807.5 nm (which was stabilised and tuned by varying the temperature) with cw power up to 50 W. The pump beam was vertically focused by a cylindrical lens with a focal distance of ~ 12 mm into the $Nd:YVO_4$ slab near the 2×20-mm face.

The laser transition between the $^4F_{3/2}$ and $^4I_{1/2}$ levels, which is responsible for lasing of $Nd:YVO_4$ at the 1064-nm wavelength (at the given Nd^{3+} concentration), has the gain cross section of 15.6×10^{-19} cm^2, while the absorption cross section of the transition between the $^4F_{5/2}$ and $^4I_{9/2}$ levels is 27×10^{-20} cm^2 [2]. The high pump absorption coefficient (~ 30 cm^{-1}) leads to the formation of a narrow gain region inside the crystal along the pumped face.

The laser cavity was formed by two plane dielectric mirrors: a highly reflecting mirror with the reflection coefficient $R \approx 99.9$ % and a semitransparent mirror with the reflection coefficient $R \approx 24\%$ (Fig. 1). The laser beam was focused by cylindrical lenses with a focal length of ~ 50 mm into the active region near the pumped face surface.

We studied the dependence of the laser beam transverse structure on the pump power and cavity parameters: arm lengths, positions of collimating lenses, and the angle of incidence of the laser beam on the pumped face of the active slab. As a result of our optimisation, we found a region of

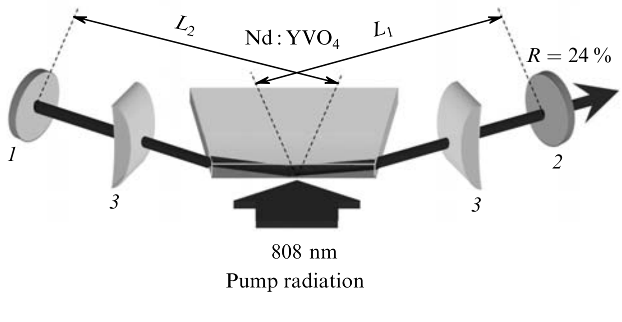

Figure 1. Scheme of a cw diode-side-pumped $Nd:YVO_4$ laser: (*1*) mirror with the reflection coefficient $R > 99.9$ %; (*2*) semitransparent output mirror; (*3*) cylindrical lenses ($F = 50$ mm).

parameters at which the considered scheme can generate a high-quality beam with a high efficiency of conversion of pump energy to laser radiation.

3. Discussion of results

When creating laser systems with transverse pumping of active elements with high concentrations of Nd^{3+}, one must take into account that, due to a large absorption cross section, the pumped region is quite narrow, adjacent to the pumped face. Therefore, in this case it seems preferable to use schemes with grazing incidence of the laser beam with its total internal reflection from the pumped face, which provides the most efficient extraction of the population inversion [3–5]. In particular, the possibility of creating a $Nd:YVO_4$ laser with an extremely high pump power conversion efficiency (up to 68 %) was demonstrated in [6]. However, such a high efficiency was achieved at a relatively low quality of the laser beam. The problem of laser beam quality relates to a rather wide gain region in the $Nd:YVO_4$ slab, which favours the generation of high-order transverse modes.

Previously [1] we found that the laser beam quality and the pump conversion efficiency strongly depend on the angle of incidence of the laser beam on the active element. The angle of incidence determines the gain length and the transverse dimension of the amplified mode, thus determining the optical gain in the laser medium and the diffraction losses of the laser beam. The experimentally found dependences of the output laser power on the angle of incidence of the laser beam on the $Nd:YVO_4$ slab [1] showed that the optimal angle of incidence needed to achieve a high beam quality with a high conversion efficiency is $\sim 22.7^{\circ}$ (at the pump region length $L \approx 1.5$ cm, the crystal temperature $\sim 13\,^{\circ}$C, and the pump power ~ 19 W). The subsequent investigations were performed with this angle of incidence.

For cavities with $L_1 = 13$ cm and $L_2 = 20$ cm, we observed the following dependence of the transverse beam structure on the pump power. At low pump powers, the laser beam was single-mode (TEM_{00}); with increasing the pump power, we observed lasing at higher transverse modes; and, at pump power exceeding 30W, the power of the multimode laser radiation decreased due to a local increase in temperature in the active crystal (Fig. 2). The optimal pump power to obtain a high-quality beam (under conditions of limited heat removal from the crystal) ranged from 15 to 19 W.

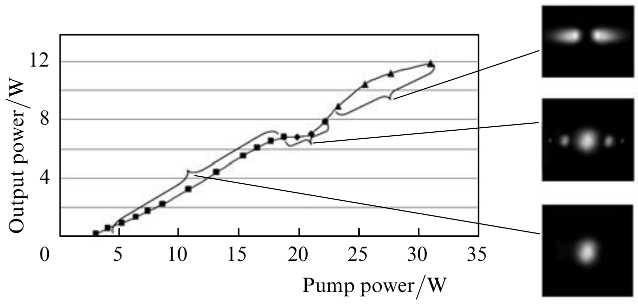

Figure 2. Dependence of the output power and beam structure on the pump power for a cavity with the arm lengths $L_1 = 13$ cm and $L_2 = 20$ cm.

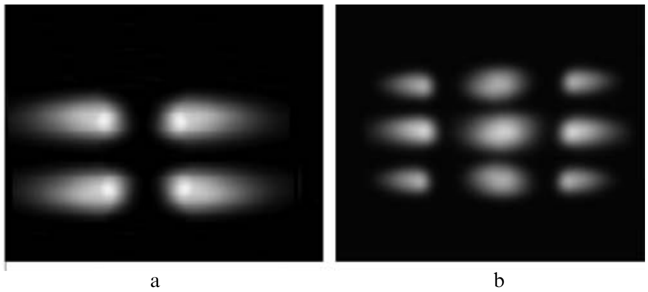

Figure 3. Laser beam structures with nonzero vertical indices obtained by varying the positions of collimating lenses.

The vertical mode of the beam was changed by varying the positions of collimating lenses with respect to the crystal. The laser scheme was positioned horizontally. The length and width of the pump region also were larger than the height. The vertical size of the laser beam in the crystal increased with increasing the distance between the cylindrical lenses and the crystal, which decreased the area of overlap of the beam with the inversion region but simultaneously decreased the diffraction losses for high vertical modes. Varying the positions of collimating lenses, we obtained generation of TE_{11} and TE_{22} modes at pump powers of 24–26 (Fig. 3a) and 20–23 W (Fig. 3b), respectively.

To realise an active Q-switching regime, we placed an acousto-optic modulator (AOM) in the cavity arm with the 100 % mirror. The introduction of the AOM decreased the average power by no more than 2 %. The pulse duration was 10 ns at a repetition rate of 100 kHz and a pump power of 15–20 W.

We also studied a laser with an elongated output arm of the cavity, which allowed easier introduction of the AOM into the scheme [6]. Based on the optimisation of the output power in the fundamental mode, we chose the arm lengths $L_1 = 41$ cm and $L_3 = 22$ cm and the output mirror reflection coefficient $R = 19\,\%$. For this cavity scheme, the dependence of the laser beam transverse structure on the pump power differed from the dependence described above: in the pump power regions of 17.7–24.5 and 35.4–40 W, no less than 94 % of the output power was contained in the TEM_{00} mode (Fig. 4). The maximum power (13.1 W) of a high-quality beam was obtained at a pump power of 39.5 W

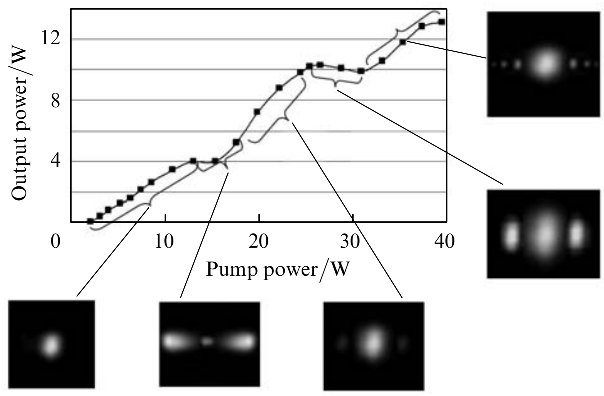

Figure 4. Dependence of the output power and beam structure on the pump power for a cavity with the arm lengths $L_1 = 41$ cm and $L_2 = 22$ cm.

(the pump conversion efficiency was 33 %). The maximum efficiency of conversion of pump power to a high-quality laser beam was achieved at a pump power of $\sim$ 25.5 W and was as high as 40 %, the output power being $\sim$ 10.2 W.

The dependence of the laser output power on the pump power has dips: one for the first described cavity (at a pump power of 19 – 24 W) and two for the second cavity (at pump powers of 13 – 17 and 26.6 – 33 W) (see Figs 2 and 4). These dips on the power dependences correspond to deterioration of the laser beam quality. This strongly nonlinear power dependence and variations in the beam quality can be explained by changes in the cavity stability due to changes in the induced thermal lens [4]. It should be noted that it is possible to obtain a high-quality beam when the pump power (and the output laser power) are higher than the pump power corresponding to the generation of a low-quality beam in the region of a dip.

The active Q-switching regime was also studied with an AOM introduced in the output arm. At the pulse repetition rate of 100 kHz, the average output power in the Q-switching regime was no more than 2 % lower than in the cw regime, the pulse duration being 10 ns. At the optimal alignment of the AOM, the laser beam quality was the same as in the case of the cw regime.

4. Conclusions

We have studied the dependence of the beam spatial structure of a diode-side-pumped Nd : YVO_4 slab laser on the system parameters: the lengths of cavity arms, the positions of collimating lenses, the angle of incidence of the laser beam on the active element, and the pump power. We found the regions of parameters that allow one to increase the output laser power retaining a high quality of the beam in both cw and active Q-switching regimes. The maximum power of a high-quality beam reached 13 W (with the pump power conversion efficiency of 33 %), while the maximum efficiency ($\sim$ 40 %) was achieved at an output power of 10.2 W.

Acknowledgements. This work was partly supported by the Russian Foundation for Basic Research (Grant Nos 07-02-92184 NTsNI_a and 08-02-99050-r ofi) and the programme 'Nonlinear optical methods and materials for creating new-generation laser systems' of Physical Sciences Department of the Russian Academy of Sciences.

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