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Investigation on passively Q-switched Nd:YAG slab laser pumped by 2D quasi cw diode laser stack

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The paper presents results of investigations on generation of Nd:YAG triangle slab laser pumped by 2D diode array. The pump beam shape quality with respect to pump/mode overlap efficiency was investigated both theoretically and experimentally. Two cavity schemes with and without pump forming optics were verified in free running and passively Q-switching modes. Slope efficiency of 45% and output energy of 24 mJ for incident 60 mJ of pump energy were achieved in free running mode. Applying Cr^{4+}:YAG crystal as passive Q-switch, the output energy of 5 mJ and 0.5 MW peak power were obtained in the optimised resonator.

Keywords: diode pumped lasers, passive Q-switching, slab laser.

1. Introduction

The development of efficient quasi-cw diode arrays and stacks in the early 90's made possible intensive research on several types of moderate and high-energy diode pumped lasers [1–11]. The main advantages of such type lasers comparing to lamp pumped ones, are higher repetition rates (~100 Hz), much lower heat load, and much higher wall plug efficiency. Thus, such lasers have found application in space research [9] as well in new generation of lasers for inertial confinement fusion [11]. The 1D diode arrays emitting typically 100 W per 1 cm of width were firstly applied in practice in the designs of compact 1 mJ class Q-switched laser [1–10] applied in several areas as range finding, pulse generators, etc. It was found in numerous works that for such a type of pump unit the efficiency of end pumping scheme is comparable or favourable in some cases to side pumping one. However, the best results, with respect to output energy maximisation in fundamental mode, were obtained in a side pumped cavity with active medium of a slab shape [9,10].

Applying 100 W quasi-cw pump unit we have obtained about 1 mJ in electro-optic Q-switched end pumped Nd:YVO_4 laser working in single spatial and longitudinal mode [5] and more than 2 mJ for side pumped single bounce triangle Nd:YAG slab laser [10]. Increase in the output energy up to 5–10 mJ in the same compact size cavity has required application of 2D diode stacks or several, separated pump units. For the simplest 2D diode stack (with emitting area of 10×1 mm^2) the end pumped as well as side pumped cavity is feasible. The main task of this work is theoretical analysis as well as experimental verification of such types of pumping schemes aiming at elaboration of efficient Q-switched generator of 5 mJ class.

In Section 2, numerical analysis of pumping schemes for 1D and 2D diode stacks is presented. In Section 3, the pumping unit as well as free running mode generation for three different cavities are examined. In Section 4, investigations of passive Q-switching for the best case (i.e., cavity consisting of side pumped triangle Nd:YAG slab and Cr^{4+}:YAG saturable absorber) are presented, and in the last section the conclusions are derived.

2. Optimisation of a pumping scheme

According to the well-established formula (e.g. Refs. 12 and 13), the output power P_{out} and the threshold P_{thr} are given by

$$P_{out} \propto \eta_{ovl}\eta_{abs}(P_p - P_{thr}), \tag{1}$$

$$P_{thr} \propto \frac{I_{sat}}{\eta_{abs}} V_{efc}, \tag{2}$$

where η_{abs} is the absorption efficiency given by

$$\eta_{abs} = 1 - \exp(-\alpha_{avg} L), \tag{3}$$

α_{avg} is the averaged absorption coefficient of a pump beam, L is the length of active medium, η_{ovl} is the overlapping efficiency given by

$$\eta_{ovl} = \frac{\left(\int S_l G_p dV\right)^2}{\int S_l^2 G_p dV}, \tag{4}$$

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V_{efc} is the effective mode volume given by

$$V_{efc} = \frac{1}{\int S_l G_p dV}, \qquad (5)$$

$I_{sat} = h\nu/\sigma\tau$ is the saturation power density, h is the Planck's constant, ν is the laser frequency, σ is the emission cross section, τ is the laser upper level lifetime, S_l is the normalised 3D laser mode intensity distribution, and G_p is the normalised 3D gain distribution. We assume, that gain distribution is proportional to the absorbed pump density and laser mode intensity distribution corresponds to a symmetrical Gaussian beam with the given waist radius W_o. For simplicity of the analysis (well proofed for Rayleigh range of cavity much longer than pump volume size) we assume that the mode distribution does not change along optical axis inside a pump volume. Thus, we have two additional input data, the absorption coefficient α_{avg} and the mode waist radius W_o.

For end pumping scheme and axially symmetric distribution of G_p and S_l, the integrals in Eqs. (4) and (5) can be solved analytically leading to well-known Laporta's model [13]. However, in our case only numerical results are available.

We have limited the scope of analysis only to 2D stack consisting of 3 bars with vertical pitch of 0.4 mm and horizontal width of 10 mm (SDL 3251-A3). We intend to estimate the threshold and overlap efficiency in dependence on cavity and pump volume parameters for two cases:

- pump volume of 2D bar with optics of waist size 2×1 mm^2 and divergence half angles 0.6×0.6 rad,
- pump volume of 2D bar without optics of waist size 10×1 mm^2 and divergence half angles 0.1×0.6 rad

Moreover, for comparison the properties of 1D bar with or without optics were estimated. For 1D bar with beam forming optics we assume the waist size 2×1 mm^2 and divergence half angles as 0.6×0.6 rad.

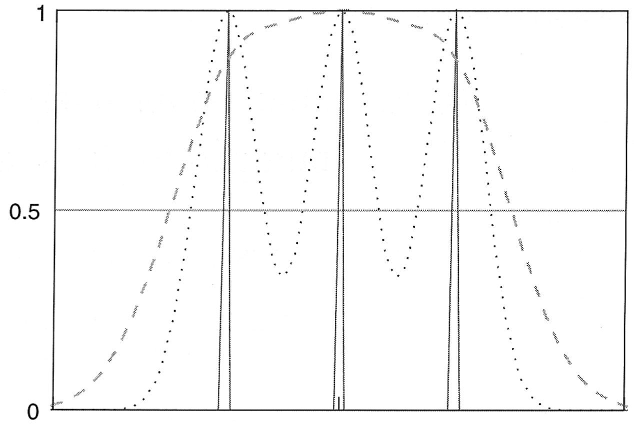

Fig. 2. Normalised pump intensity of 2D diode array in vertical section at the distances 0, 1, 2 mm, respectively, from the slab basis.

Before starting, let us consider in detail the geometry of side pumped slab by means of 2D diode stack (Fig. 1). Due to Brewster cut input faces of slab and total internal reflection on slab basis, laser mode beam has asymmetrical shape inside a pump volume with aspect ratio defined on slab basis as high as 3. Thus, such a pumping scheme configuration is well matched to asymmetrical pump beams typical for 1D or 2D high power pump units. Let us notice that due to high refractive index of the active medium and noncoherent adding of three beams the pump divergence in the vertical axis (perpendicular to figure plane) decreases, thus we have natural limitation of pump size in vertical plane enabling efficient pumping in this section (Fig. 2). Moreover, applying the beam-forming optics [Fig. 3], pump beam can be quite efficiently confined also in the horizontal plane.

The main task in pumping scheme calculations is the choice of proper laser mode geometry for the given parameters of pump unit, with respect to maximisation of the output power. As it was shown in Figs. 4 and 5, the threshold and overlapping efficiency increase with a waist radius W_o,

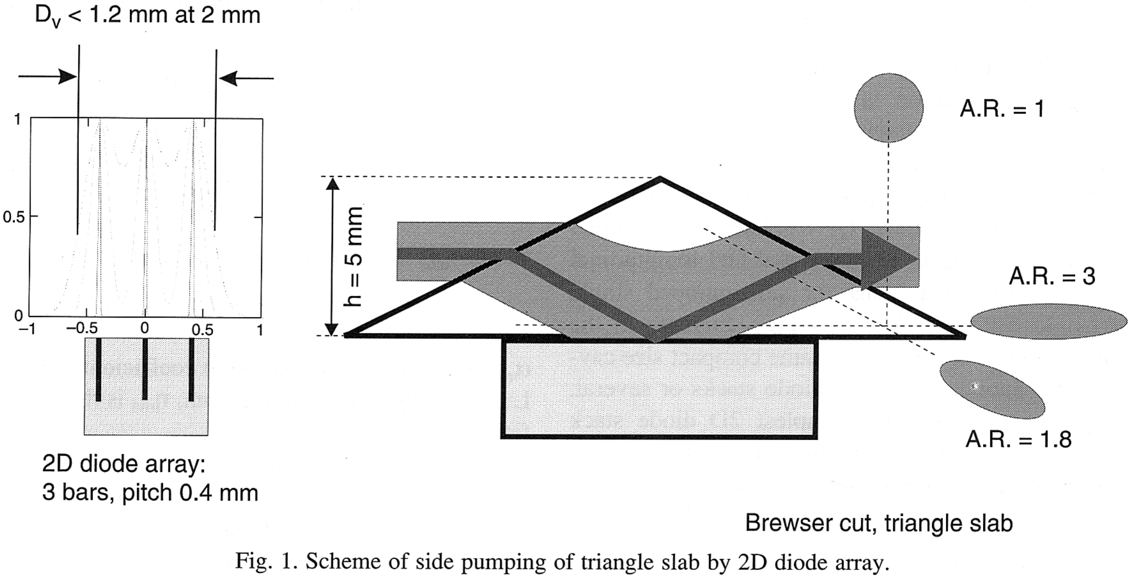

Fig. 1. Scheme of side pumping of triangle slab by 2D diode array.

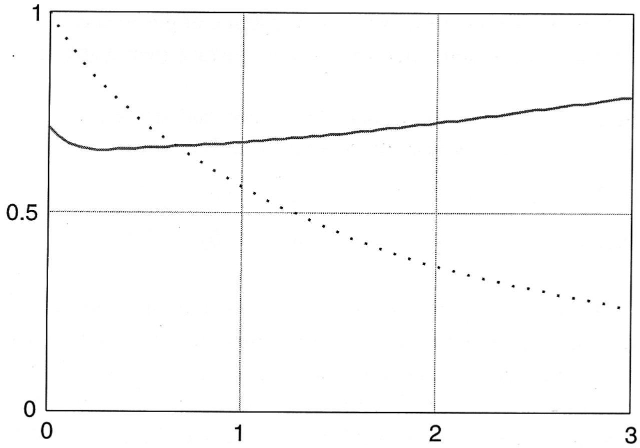

Fig. 3. Pump beam half width in dependence on distance to slab basis for beam forming optics case – continuous curve, absorbed pump power density – dashed curve.

thus, for the given pump power we should find the compromise between these two contrary effects. To be close to our previous experience with 1D diode bar [5,10], we have calculated the expected output energy dependence on pump energy (Fig. 6) for two pump units (1D diode bar of energy of 20 mJ with optics and 2D diode stack of maximum energy of 60 mJ). As you can see in Fig. 6, the output energy for 2D pump is 2.5 times higher than output energy determined for 1D pump despite two times higher threshold and lower overlapping efficiency. It means, that pumping scheme applying 2D stacks in slab geometry can be quite efficient. The above presented results of numerical analysis were confirmed in the experiments carried out for free running mode (Section 3) as well for passive Q-switching (Section 4).

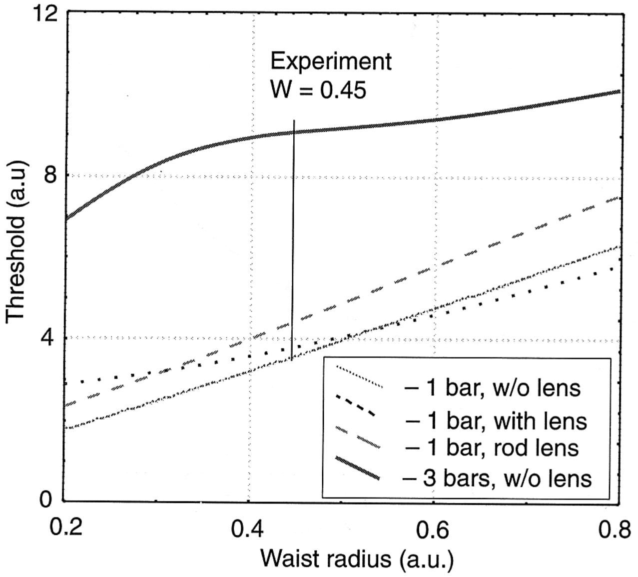

Fig. 4. Threshold power in dependence on waist radius of laser mode for four different pump units.

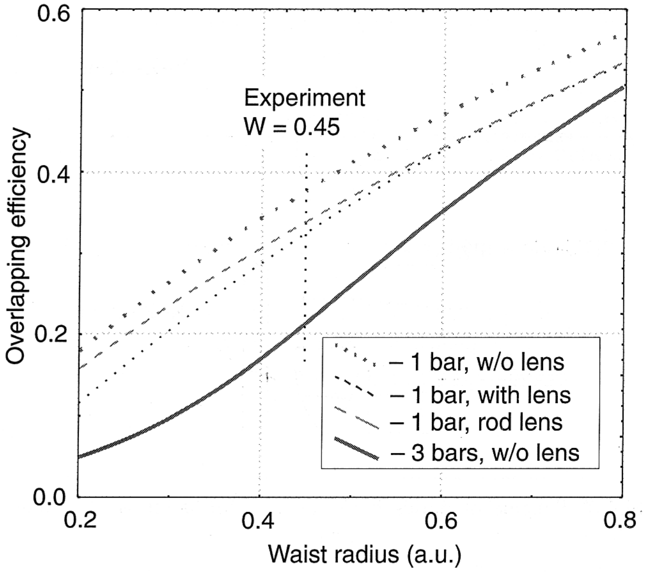

Fig. 5. Overlapping efficiency in dependence on waist radius of laser mode for four different pump units.

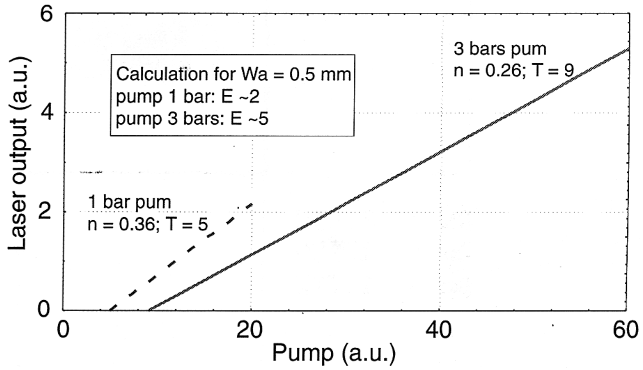

Fig. 6. Output energy vs. pump energy for laser mode waist radii $W_0 = 0.5$ mm, 1D pump with optics – dashed line, 2D diode array without optics – continuous line.

3. Free running experiments

3.1. Pump unit characterisation

We have realised in preliminary analysis, that the radiation of 2D diode stack with emitting area of 10×1 mm^2 can be focused to the area of 3×1 mm^2 determined mainly by much larger beam product in the junction plane. Because such caustics sizes are comparable to the sizes of pump volume typical for 1D diode bar used in the previous works [5,10], the end pumping as well as side pumping schemes are feasible for such a pump source. We have designed, manufactured and characterised the special asymmetrical optical system performing such a task (Fig. 7). Applying quasi-geometrical method [14,15] the intensity distribution in a pump volume was calculated, Figs. 8(a) and 8(b). The results of theoretical estimations of pump sizes in the waist were confirmed in experiments, Figs. 9(a) and 9(b).

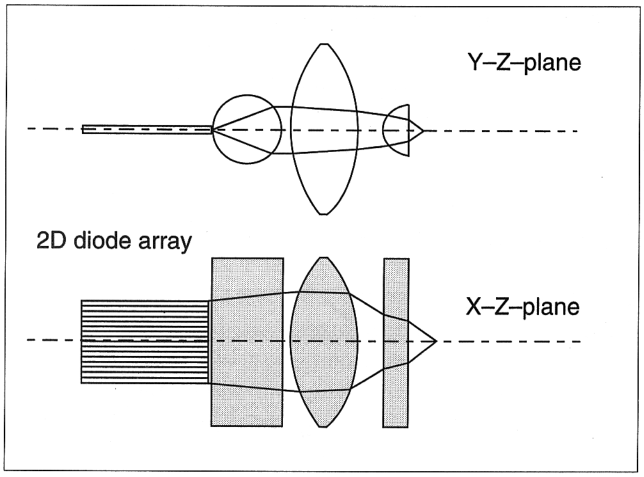

Fig. 7. Scheme of optics for beam transformation of 2D-diode array.

Firstly, we have measured divergence angle in the junction plane in dependence on a diode current (see Table 1).

Table 1. Results of horizontal divergence half angle measurements of laser diode array SDL 3251–A3.

Diode current (A)	60	80	100	120
Divergence half angle (mrad)	90	107	115	126

As it is presented in Table 1, the horizontal divergence angle increases with diode current, thus the estimated width of a pump beam in the waist was 3.1×1.2 mm^2. As we can see in Figs. 9(a) and (b), the waist sizes are 4×1 mm^2 for maximum current, thus such pump unit can be used in the end pumping scheme for rods with a diameter > 4 mm. The caustics sizes are larger than expected, caused mainly by the underestimated increase of divergence with a diode current.

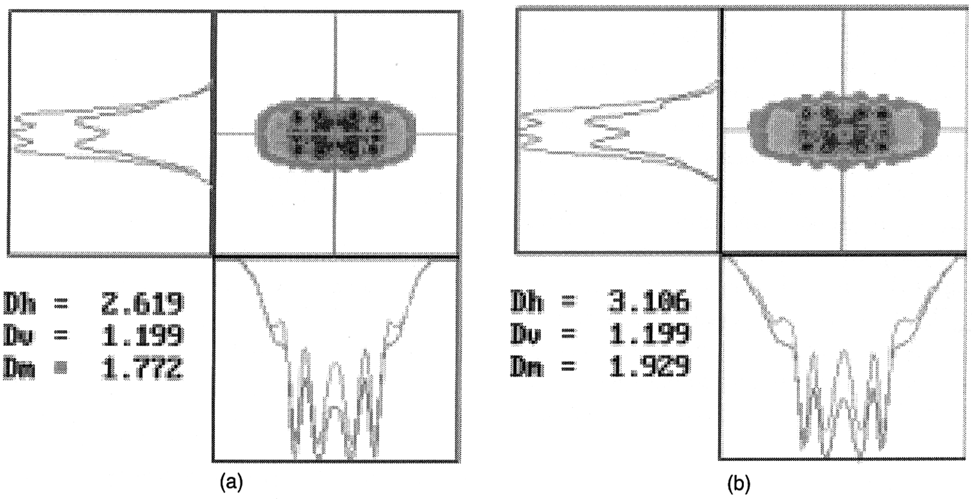

Fig. 8. Pump distribution in waist plane for horizontal divergence half angle 60 mrad (a) and 125 mrad (b); results of calculations.

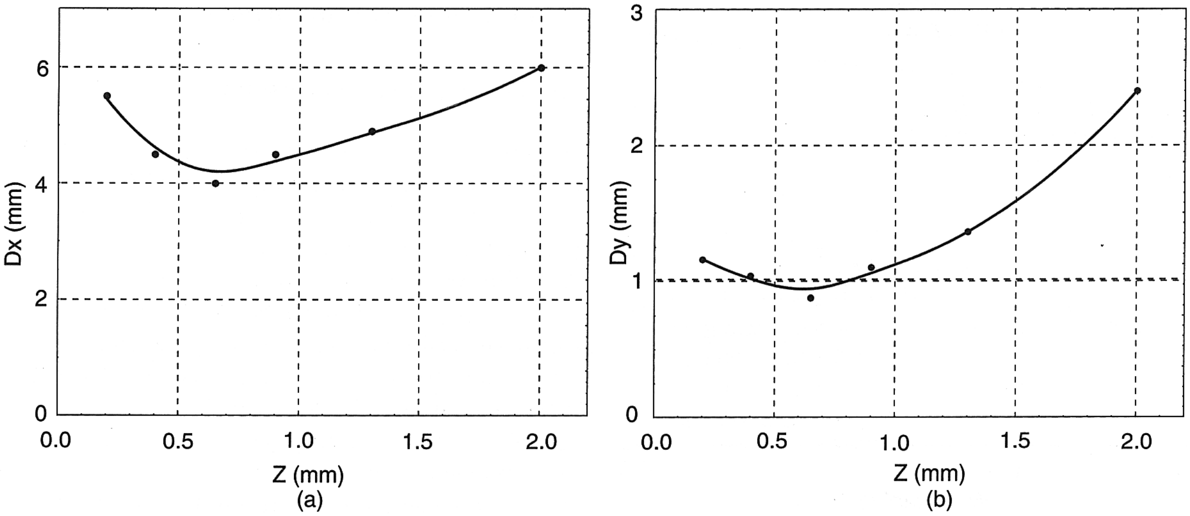

Fig. 9. Caustics width in horizontal section (a) and vertical section (b) in dependence on distance from the last surface of optics; results of measurements for diode current 120 A.

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3.2. Investigations of Nd:YAG slab laser in free running mode

In preliminary experiments of free running mode we have checked end pumped and slab-side pumped configurations (Fig. 10). Because the results obtained for end-pumped cavity were considerably worse, we have focused on side pumped configuration in further investigations only. The beam forming optics confines pump beam in the horizontal plane more than 2 times, resulting in lower threshold. However, the available pump energy decreases to about 80% of incident pump radiation due to high curvatures of optical surfaces and not optimal AR coatings. The free running characteristics are shown in Figs. 11 and 12 for a cavity with beam forming optics and for a cavity without optics, respectively.

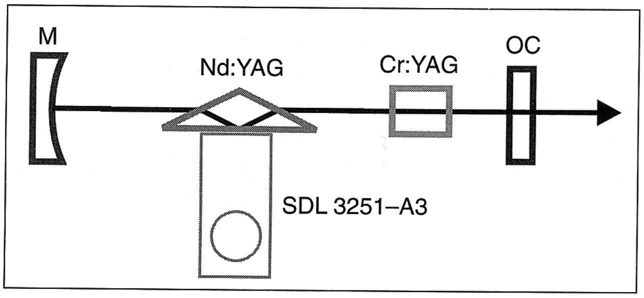

Fig. 10. Scheme of Nd:YAG slab laser side pumped by 2D diode stack with beam forming optics.

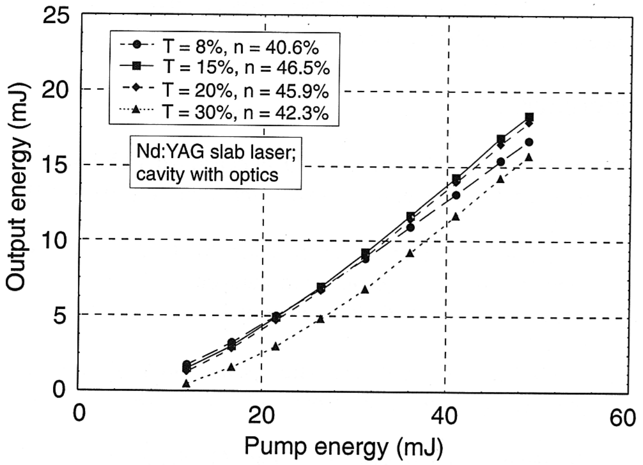

Fig. 11. Output energy vs. pump energy; free running experiments for Nd:YAG slab laser cavity with pump beam forming optics.

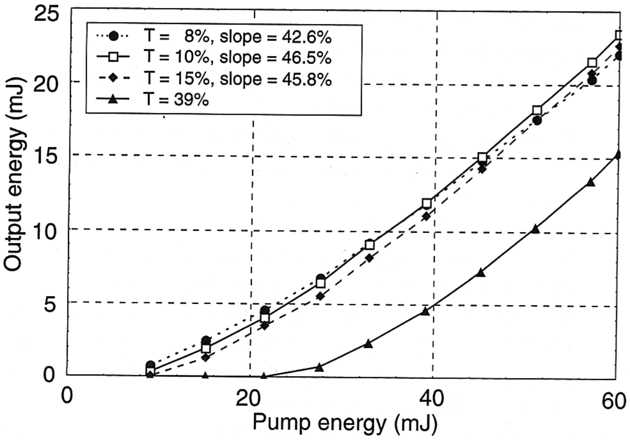

Fig. 12. Output energy vs. pump energy; free running experiments for Nd:YAG slab laser cavity without pump beam forming optics.

4. Investigations of passive Q-switching

To achieve the maximum output energy in Q-switching mode the optimisation procedure was applied [16–18]. It led for the given (determined in free running experiments) small signal gain level to the optimal values of output coupler (OC) and passive Q-switch initial losses. The best results were obtained for cavity of a length 120 mm with rear mirror of 2 m radius of curvature with passive Q-switch made of Cr^{4+}:YAG crystal. The results of experiments (with data of OC and passive Q-switch transmissions) were compared with theoretical optimisations in Table 2. Smooth pulses of pulse duration of 10–12 ns were observed

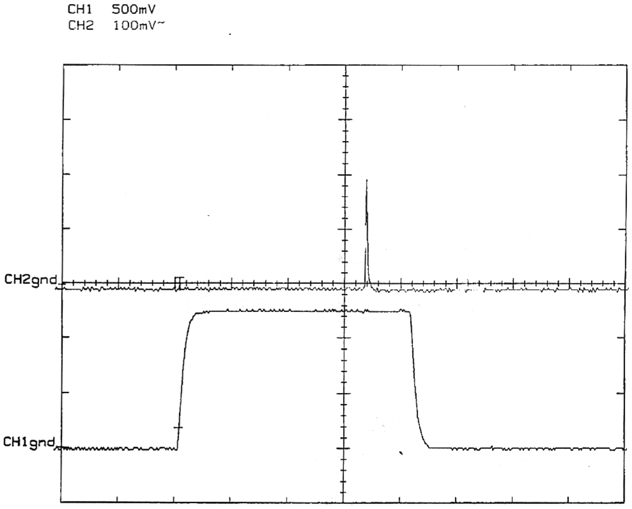

Fig. 13. Oscillogram of pump and Q-switched pulses.

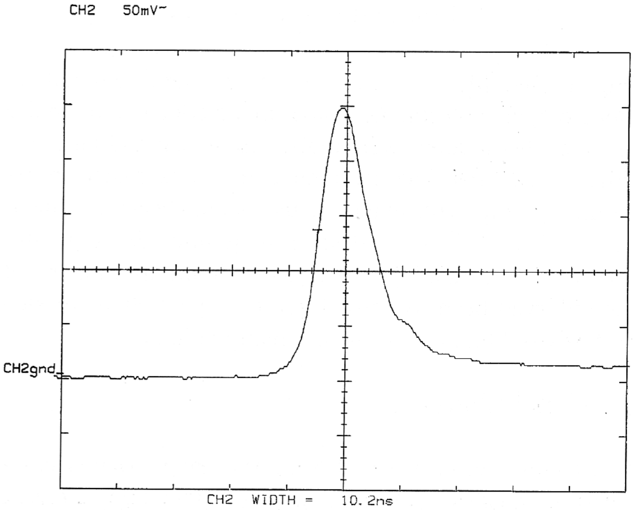

Fig. 14. Oscilloscope trace of Q-switched pulse shape.

Table 2. Results of passive Q-switch modelling and experiments; β is the ratio of excited state absorption cross section to ground state absorption cross section.

Pump energy E_p (mJ)	Round trip small signal gain $2g_{0l}$	Initial transmission of Q-switch T_{ini}	OC transmission T_{OC}	Pulse energy E_{out} (mJ)	
55	2.3	0.425	0.44	5.8	Model $\beta = 0.1$
60	2.5	0.406	0.46	6.2	
51	2.1	0.62	0.3	4.2	Experiment
55	2.3	0.57	0.3	5.3	

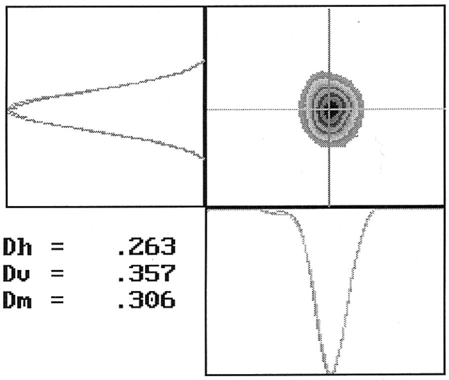

Fig. 15. Near field intensity distribution of output beam of Q-switched slab laser w/o optics.

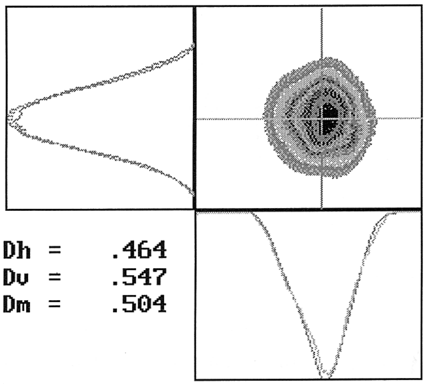

Fig. 16. Far field intensity distribution of output beam of Q-switched slab laser w/o optics.

(Fig. 13 and 14) as a rule, evidencing single longitudinal mode output. To estimate spatial mode contents, the pulse intensity distributions were registered in near and far fields (Figs 15 and 16). The divergence angles estimated in experiments (Fig. 16), evidence the output beam in fundamental mode (M^2 ~1.1), despite the multimode output observed in free running experiments. Some asymmetry of the observed beam is caused due to imperfections of slab surfaces and highly asymmetric pump volume.

5. Conclusions

Satisfactory performance of Nd:YAG triangle slab laser directly pumped by 2D diode array of 10×1 mm^2 emitting area was shown theoretically and verified in experiments. The output energy of above 24 mJ with 46% slope efficiency in free running mode was achieved in a cavity without beam forming optics. Applying passive Q-switch made of Cr^{4+}:YAG crystal the pulses with energy of above 5 mJ in 10-ns pulse duration were achieved. The evidenced output beam in fundamental mode is caused by an effect of the Gaussian diaphragm of passive Q-switch. Slightly ellipticity of intensity distributions in far field was caused by aberrations of slab surfaces.

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