CHIN.PHYS.LETT. Vol. 25, No. 2 (2008) 521

# A High-Energy Good-Beam-Quality Krypton-Lamp-Pumped Nd:YAG Solid-State Laser with One Pump Cavity *

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(Received 5 December 2007)

*We investigate a high-energy good-beam-quality krypton-lamp-pumped pulsed Nd:YAG solid-state laser with one pump cavity. The symmetrical resonator laser is developed and is rated at 80 J with beam parameter product 12 mm mrad. The total system electro-optics efficiency of the lamp-pumped YAG laser is as high as 3.3% and the stability of output energy is ±2% with pulse width tunable between 0.1 ms and 10 ms. The experimental results are consistent with the theoretical analysis and simulation.*

*PACS: 42. 55. Rz, 42. 60. Da, 42. 60. Lh, 42. 60. Pk*

Lamp-pumped pulsed Nd:YAG solid-state lasers have many advantages such as high peak power, good beam quality, transmission through optical fibres, smaller cutting heat-affected zone and less recast. They have been applied extensively in industry processing. Nowadays, the best high average power pulsed laser made by Trumpf (Hass) in German is expensive to some countries, whose maximum output single pulsed energy is 90 J with beam quality 25 mm mrad and the laser beam can transmit through 600 m optical fibres. In China, it was reported that Huazhong University of Science and Technology has reached the average power 348 W in laboratory. Beijing Focus Laser Co. fetching in series of IQL YAG laser made by Quantel in France reached the highest single pulsed energy 45 J and the total electro-optics efficiency is less than 3% with very huge volume of the facility. In this Letter, we present a novel pulsed laser in theoretical analysis and experiments, whose maximum single pulsed energy is 80 J with beam quality of 12 mm mrad and the total electro-optical efficiency is as high as 3.3%.

Generally, a plane-plane resonator is used for high energy pulsed solid-state laser, and the stable area of the symmetric resonator is wider than that of the asymmetric resonator.[1] A symmetric plane-plane resonator with one rod inside is considered, and the configuration of the single-rod laser is shown in Fig. 1. The rod is equivalent to a thin lens with diopter $D = 1/f$ (Ref. [2]) ($f$ is thermal lens focal length), which is direct proportional to the pumping energy. The principal planes are constant in the first order and located at $h = L/2n$, in which $L$ is the geometric length of the rod and $n$ is its refraction index on the axis. The distances from HR mirror and AR mirror to principal lanes are $d_1$ and $d_2$, respectively. The optical element inside the resonator is characterized by its ABCD ray transfer matrix. By multiplying all these matrices for a trip, the transfer matrix $M$ at output coupling mirror can be obtained to be

$$M = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -D & 1 \end{bmatrix} \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix}.$$

Choosing $d_1 = d_2 = d$, we can obtain

$$M = \begin{bmatrix} 1 - dD & d(1 - dD) + d \\ -D & 1 - dD \end{bmatrix}, \quad (1)$$

where $D$ is diopter directly proportional to the input pumping energy, determined by[3]

$$D = \frac{E_{\text{in}} n_0}{FK} \Big( \frac{1}{2n_0} \frac{dn}{dt} + n_0^3 \beta C_{r,\theta} + \frac{r_0 \beta (n_0 - 1)}{n_0 l} \Big), \quad (2)$$

$$g_1 = A' - B'/R = A' - dD, \quad (3)$$

$$g_2 = D' - B'/R = A' - dD. \quad (4)$$

Thus $g_2 = g_1$. From Eqs. (3) and (4), when $g_2 = g_1 = 1$, we have $D = 0$; when $g_2 = g_1 = -1$, $D = 2/d$; when $g_2 = g_1 = 0$, $D = 1/d$.

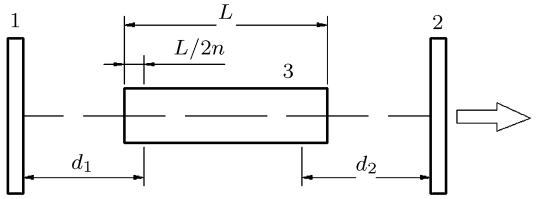



**Fig. 1.** Schematic diagram of the experimental setup of the laser including HR mirror 1, AR mirror 2, laser rod 3.

Industrial high energy pulsed Nd:YAG lasers usually operate in a large output energy range. There are several critical stable points needed to pass through with the increasing pumping energy. $A(1, 1)$, $B(0, 0)$ and $C(-1, -1)$ are these critical stable points which are presented in Fig. 2. At the beginning the resonator

*Supported by the National Natural Science Foundation of China under Grant No 604070090, and the Beijing Key Project for Technology under Grant No 954810900.

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works at point $A$, where $D = 0$. With the increasing pumping energy, $D$ grows to $1/d$, the resonator works at point $B$. For the input maximum electric energy $E_{\rm in}$, $D$ reaches $2/d$, the resonator works at point $C$ which has the maximum outputs energy.

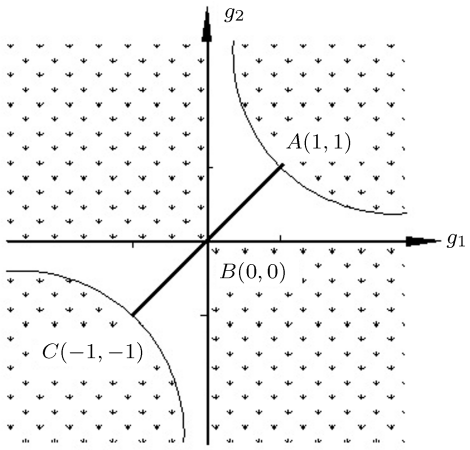



**Fig. 2.** Stability diagram of an optical resonator; shadowed areas indicate the regions of unstable operation.

For the long pulsed width laser, the maximum output energy can be expressed by[4]

$$E_{\rm out,max} = \left(\sqrt{\eta_{\rm excit} E_{\rm in}} - \sqrt{F J_s t_0 |\ln V|}\right)^2. \quad (7)$$

and the output energy range of the laser and the beam quality are contrarily expressed by[5]

$$\frac{\Delta E_{\rm out,max}}{(\theta_m \omega_m)_{\rm max}} = \frac{2\pi\eta t_0}{\alpha}, \quad (8)$$

$$\alpha = \frac{1}{K}\left[\frac{dn}{dt} + \frac{1}{2} n_0^3 \beta (C_r + C_\theta) + \frac{2 n_0 r_0 \beta (n_0 - 1)}{l}\right],$$

where $V$ is the loss factor of the cavity, $F$ is laser medium cross area, $J_s$ is the saturation intensity, $t_0$ is the pulse period, $E_{\rm in}$ is pumped energy, $\eta$ is the laser efficiency.

In order to obtain high output laser energy and improve the beam quality of the laser, we can confine the range of the output energy. In the pumping high energy segment, the change of the diopter is small as pumping energy increasing. Thus we can sufficiently use the segment diopter by designing the relevant distance between the principal plane of the rod and mirrors. For example, when the diopter of laser changing from $1/d$ to $2/d$, the laser only moves across one critical stable point at $g_i = 0$, see Eq. (6). Then it is easy for us to let the laser operate stably and to obtain high energy output. Thereby the laser reaches good beam quality and high energy output as better as possible by compromising the range of the output energy.

Based on the above analysis, we can realize that the output laser energy, output energy range and beam quality are dependent on the resonator configuration, resonator parameters and matching of the diopter. For the single rod high energy laser, a symmetrical parallel plane resonator with an output-coupling mirror is adopted and the distances $d_1$ and $d_2$ are equal. The distance $d$ is designed for considering three factors: $1/d < D < 2/d$, output laser beam quality and output energy. The laser module uses the components, namely, the module cavity is a mirror-reflecting metal cavity, and the laser medium of the module is a reflection reducing coated Nd:YAG laser rod in dimensions $\phi 7\,{\rm mm} \times 165\,{\rm mm}$, which was pumped by double krypton flashlamps (Kr:Xe=9:1, $\phi$ $9\,{\rm mm} \times 150\,{\rm mm}$). The flashlamp was provided by a laser power supply rated up to 2400 J. The laser head was water cooled by a double-cycle chiller, with a constant temperature of $25^\circ{\rm C}(\pm 0.5^\circ{\rm C})$ in the experiment.

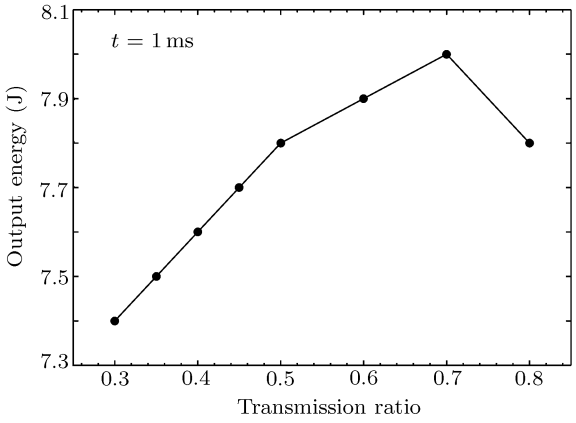



**Fig. 3.** Output energy versus transmission ratio.

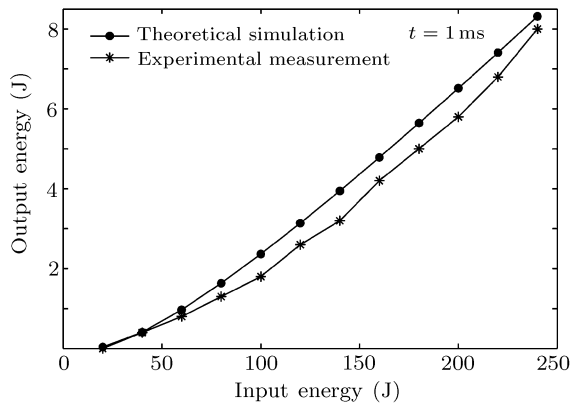



**Fig. 4.** Theoretical simulation and experimentally measured output energy versus input energy.

We recorded the output energy with the resonator cavity length 800 mm and optimal reflectivity $T = 70\%$ of the output coupling mirror. Figure 3 presents the maximum output energy versus transmission ratio with $t = 1\,{\rm ms}$, $E_{\rm in} = 240\,{\rm J}$, and the relation between the pumping energy and the output laser energy is presented in Fig. 4. The output laser energy increases approximately linearly with the increas-

ing pumping energy. When $t = 1\,\text{ms}$, $t_0 = 20\,\text{ms}$, $E_{\text{in}} = 240\,\text{J}$, the output energy is 8 J, presented in Fig. 4(b), which are very close to the theory simulating results presented in Fig. 4(a). According to Eq. (7) and classical parameters:[6] $\eta_{\text{excite}} = 0.06$, $V = 0.95$, $J_s = 1620\,\text{W/cm}^2$, $F = 0.5\,\text{cm}^2$ (diameter 8 mm), $t_0 = 20\,\text{ms}$, the relationship between the output energy and input energy is simulated, and the simulating maximum output energy is 8.3 J (Fig. 4(a)). When the pumping energy reaches the maximum (2400 J), the output energy is 80 J (Fig. 5). The long-time stability of output laser energy is ±2% for 12 h.

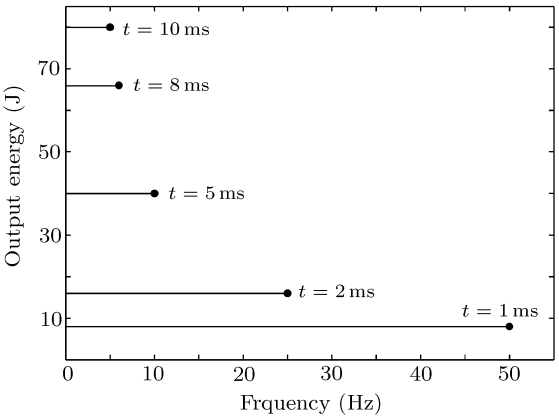



**Fig. 5.** Output energy versus pulse frequency with different pulse widths.

Because the beam waist of the output laser beam is at the position of the output-coupling mirror, we measured the beam quality of the laser with a photosensitive image paper.[7] The spot radius was 3.9 mm near the output-coupling mirror and 6.9 mm at 1m away from the mirror (Fig. 6) with $E_{\text{in}} = 240\,\text{J}$, $t_0 = 20\,\text{ms}$, $t = 1\,\text{ms}$. Then the beam quality was calculated conservatively and the maximum beam parameter product was 12 mm mrad. It is important that the laser beam can be coupled into a 400 $\mu$m optical fibre easily.

The total electro-optic transfer efficiency is considered for lamp-pumped pulsed solid-state laser by measuring the highest input energy and the corresponding output laser energy with compromised good beam quality, the total electro-optic transfer efficiency calculated is 3.3%.

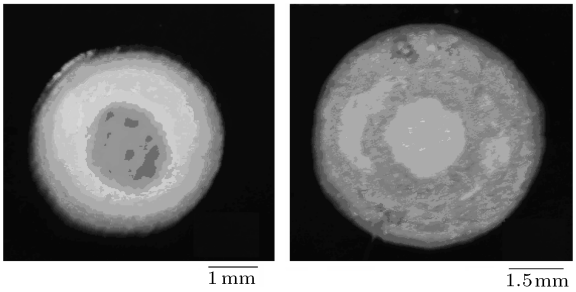



**Fig. 6.** Spots at the positions near the output mirror and 1 m away from the mirror.

In summary, we have experimentally obtained the maximum single pulsed output energy 80 J with one pump cavity, good beam quality of 12 mm mrad, total electro-optic transfer efficiency 3.3%, operation stability ±2% with the operation time more than 12 h. The laser is suitable for industrial processing and breaks the foreign high energy pulsed industrial laser monopolization to our country.

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