600-W lamp pumped CW Nd:YAG laser

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A lamp pumped CW Nd:YAG laser is presented in this paper for the requirement of industrial application. The main factors, which affect output power and beam quality of high power solid-state laser module, are theoretically analyzed. Total electro-optics efficiency of lamp pumped Nd:YAG crystal as high as 4.0% is obtained, and output power is higher than 647 W with beam parameter product 22 mm·mrad.

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High power CW Nd:YAG lasers, with reasonable beam quality, are competitive lasers for material processing applications. The solid-state lasers have several advantages compared with CO_2 lasers, which can be transmitted by fiber for flexible processing, the wavelength is relative shorter for material absorption, and the system is rather compact combined with robot. Especially, the lamp pumped laser system of processing with output power higher than 2 kW has great application value, which has been widely used in automobile industry and other industry for the good rate of performance to cost.

There are some requirements on high power solid-state Nd:YAG lasers for material processing[1]: (1) high extracting efficiency and high output power; (2) high beam quality, which can be transmitted through optical fiber (often 600-m fiber is used), (3) broad output power variation range, (4) long-term stability. It is difficult to fulfill all these requirements simultaneously; we can only partly meet them.

Currently, multirod resonator modules configuration is used to compose high power Nd:YAG laser[2]. The performance of high power Nd:YAG laser is determined by single rod laser module. The main factors, which affect output power and beam quality of single rod laser module, are analyzed theoretically and investigated experimentally in this paper. Total electro-optics efficiency of lamp pumped Nd:YAG crystal as high as 4.0% is achieved, and output power is higher than 647 W with beam parameter product 22 mm·mrad.

Lamp pumped solid-state Nd:YAG lasers have severel disadvantages for heat effect. They are: (1) the energy difference between pumping band and fluorescent energy level dissipating in the host crystal lattice by radiationless transition; (2) quantum efficiency of fluorescent process is less than 1, part of the photon energy dissipating in the host crystal lattice; (3) the pumping light out of absorbing spectrum regions transferring into heat. The heating and cooling of the laser medium will lead to uneven temperature distribution across the laser rod, this results in thermal lens and birefringence effects, which make beam quality bad, even decrease the output power.

As a laser rod is CW pumped homogeneously, cooling is provided by water circulation around the out side of the rod. There is an approximately radial thermal gradient in the rod, with the highest temperature in the center of it. The thermally induced refractive index varies parabolically with the radial coordinate, and the laser rod can be considered as a positive lens-like component. To the first order approximation, the rod can be described by the diopter D, as followings[3]

$$D_i = \frac{1}{f_i} = \frac{P_{\mathrm{p}}}{A}\frac{n_0}{K} \times \left(\frac{1}{2n_0}\frac{\mathrm{d}n}{\mathrm{d}t} + n_0^2\beta(C_r + C_\theta) + \frac{r_0\beta(n_0-1)}{l} \right), \quad (1)$$

where A is cross-sectional area of rod, P_{p} is pump power, $\mathrm{d}n/\mathrm{d}t$ is change of refractive index with temperature, C_r and C_θ are photoelastic coefficients, r_0 is radius of laser rod, the average value is obtained as

$$D = \frac{\alpha}{A}P_{\mathrm{p}}, \quad (2)$$

where $\alpha = \frac{1}{K}\left[\frac{\mathrm{d}n}{\mathrm{d}t} + \frac{1}{2}n_0^3\beta(C_r + C_\theta) + \frac{2n_0 r_0\beta(n_0-1)}{l}\right]$.

The relation between laser output power and the pump power can be expressed as[1]

$$P_{\mathrm{out}} = \eta_s(P_{\mathrm{p}} - P_{\mathrm{th}}), \quad (3)$$

η_s is efficiency of laser, P_{th} is threshold of pump power. From Eqs. (2) and (3), we can get the relation between the stable range of the diopter and the changing range of the output power

$$\Delta D = \frac{\alpha}{\eta_s A}\Delta P_{\mathrm{out}}. \quad (4)$$

From Eq. (4), we can find that improving the laser efficiency is favorable to decrease the stable range of the diopter (increasing the thermal focus), and acquiring high output power.

High power CW Nd:YAG laser usually operates in multimode. There is a corresponding relation between higher-order mode and basic mode for beam radius and divergence[4]

$$W_m = Mw_0, \quad (5)$$

$$\theta_m = M\theta_0, \quad (6)$$

where M is coefficient of higher-order mode.

$$W_m = Mw_{of} \le r_f, \quad (7)$$

where r_f is effective aperture of the rod, W_m and w_{of} are beam radius of higher-order mode and basic mode at the principal of the rod, respectively.

If M is the maximal coefficient of higher-order mode, from the expression (7), we can get that

$$M = \frac{r_f}{w_{of}}. \tag{8}$$

To the circular symmetrical cavity mirror, we can describe the beam quality as

$$\theta_m * W_m = M^2 \frac{\lambda}{\pi}. \tag{9}$$

From the expressions (7) and (9), we can get that

$$\frac{(\theta_m * W_m)_{\max}}{r_f^2} = \frac{\lambda}{\pi}\left(\frac{1}{w_{of}^2}\right)_{\min}. \tag{10}$$

To a symmetry parallel plane resonator configuration containing a single rod, as the diopter increasing, g^*-parameter moves along a straight-line in the g_1^*-g_2^* diagram. There is only one stable region. When the radius of basic mode is minimum, it is the one border of the stable region, and the other border of the stable region is the primary point of symmetrical parallel plane resonator, the width of stable region is

$$\Delta D_c = 2\frac{\lambda}{\pi w_{of}^2}. \tag{11}$$

So Eq. (10) can be described as

$$\frac{(\theta_m W_m)_{\max}}{r_f^2} = \frac{\Delta D_c}{2}. \tag{12}$$

Substitute Eq. (4) into Eq. (12), we can get

$$\frac{\Delta P_{\text{out,max}}}{(\theta_m W_m)_{\max}} = \frac{2\pi\eta_s}{\alpha}. \tag{13}$$

From the above equation, we can find that improving laser efficiency is favorable to decrease the product of beam parameter and improving the beam quality of the output laser. At the same time, the output power range of the laser and the beam quality is contrary for a certain laser. In order to improve the beam quality of the laser, we have to confine the range of the output power.

Based on the above analysis, output laser power and beam quality are dependent on the laser cavity efficiency. The efficiency of lamp pumped Nd:YAG laser is dependent on the factors, such as spectrum and efficiency of pumping lamp, the efficiencies of pump cavity and laser medium crystal, configuration of the resonator. Those factors of the laser components are synthetically considered as we design the laser. To the single rod high power laser, symmetrical parallel plane resonator is adopted and diffusive ceramic cavity is applied. Laser medium is ϕ 9 × 155 mm^2 with two krypton pumping lamps, whose size is ϕ 8 × 150 mm^2, and the maximal power of the power supply is 16 kW, as shown in Fig. 1.

The output power is recorded with the optimal reflectivity of output coupling mirror, the relation between pumping power and output laser power is presented in Fig. 2. The output laser power approximately increases linearly as increasing pumping power. When the pumping power is maximum, which is 16 kW, the output laser power is higher than 647 W. The output laser power increment decreases appreciably near 12-kW pumping power. It passes the critical point at the g_1^*-g_2^* diagram as increasing pumping power. For the difference of thermal lens between radial and tangential of the laser medium, there are two thermal lens transitting zero point of the g_1^*-g_2^* diagram sequentially, so there is a critical stable plateau region. The long-time stability of laser is also tested, as shown in Fig. 3, where the instability of output laser power is 2%. In the first 30 minutes, the output laser power decreased appreciably, then the laser was operated in thermal balance, and output laser power was kept constant in 4 hours.

The power density of output laser is measured with high power laser beam/focus quality diagnostic instrument[5], the results are presented in Fig. 4.

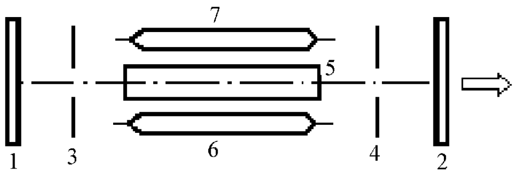

Fig. 1. Principal set-up of the laser. 1 and 2: cavity mirrors; 3 and 4: diaphragms; 5: laser rod; 6 and 7: pump lamps.

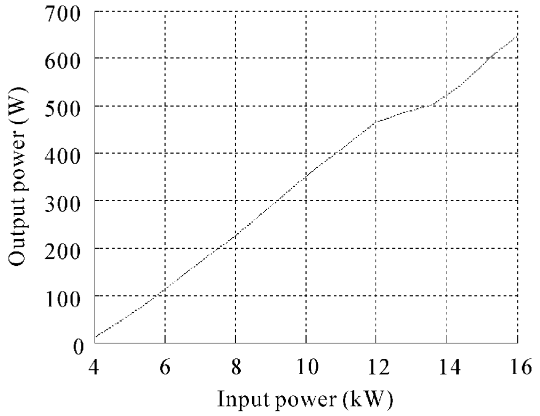

Fig. 2. Experimentally measured laser output power versus electrical input power.

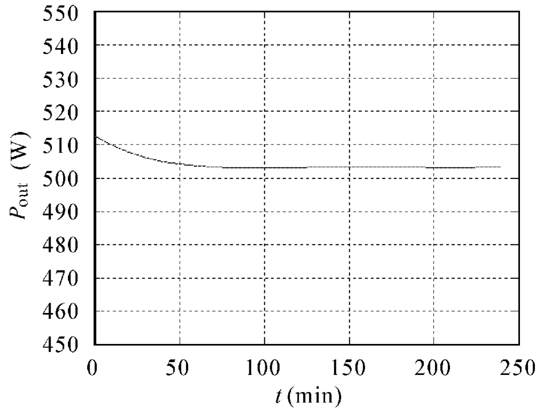

Fig. 3. Experimentally tested laser output power stability, output power versus time.

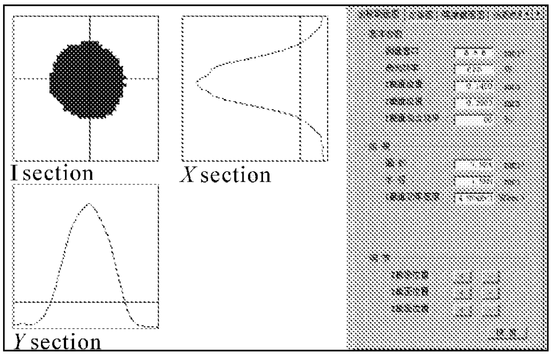

Fig. 4. Intensity distribution of output laser beam. The measuring area is 6×6 mm^2; position of X section: 0.1450 mm; position of Y section: 0.3983 mm. The laser power is 600 W; 86% of the power is contained in the X section. The effective area is 7.924 mm^2, with the radius of 1.568 mm. Power density of the I section is 4.884×10^3 W/cm^2.

Because the beam waist of the output laser beam is at the output coupling mirror, we can focus the output laser beam with a lens and measure the beam quality by the method of trepanning[6], namely, with high power laser beam quality diagnostic instrument, two beam radii after a focus lens at 86% laser intensity were measured, the position is at the beam waist and the point of the focus length. The corresponding distance was also measured. Based on these data, we calculated the beam quality of laser as 22 mm·mrad.

The total electro-optic transfer efficiency is considered for lamp pumped solid-state laser. By measuring the highest input electronic power and the corresponding output laser power with high beam quality, the total electro-optic transfer efficiency calculated is 4.0%.

It is indicated by the experiments, high power and high beam quality output by improving the efficiency of lamp pumped laser were acquired. The output power is higher than 647 W with beam quality of 22 mm·mrad, and total electro-optic transfer efficiency is 4.0%. It provides the base for the research of industrialized solid-state laser system with output laser power higher than 2 kW.

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