Mode matching of LD end-pumped 946-nm Nd:YAG laser

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Mode matching of the pump beam with laser modes in laser diode (LD) end-pumped solid-state laser was experimentally studied. Considering both the mode-match degree and laser threshold, the effective absorbed pump power in Nd:YAG was calculated. Based on the criteria, a 946-nm laser resonant cavity was designed and a 473-nm blue-light solid-state laser was efficiently assembled by means of intracavity frequency doubling.

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With the improvement of technology and technique of semiconductor, it is an important method to produce small and medium-sized solid-state laser by using LD end-pumping. The mode matching of the pump beam with laser modes in solid-state laser influences the conversion efficiency and output mode greatly. Some theoretical models have been given in many papers[1−4]. In this paper, effective absorbed pump power in Nd:YAG was calculated based on relationship between the two mode-match degree and laser threshold of two modes, and the maximum effective absorbed pump power was considered the criteria to improve pump efficiency. On the basis of the criteria, a 946-nm laser cavity was designed, and by the way of intracavity double frequency, accomplishing an assembly of an high efficiency 473-nm blue light lasers.

Figure 1 shows that pump beam is absorbed by laser crystal for different focus position of pump beam. When laser crystal is end-pumped, the absorption of the pump beam changes with the focus position of pump beam in the laser medium.

When focus point of the pump beam goes into the incident surface, the radius of beam on the surface is large with power density. The loss of pump power brings the reduction of the radius of gain region.

When the focus point of the pump beam is close to the incident surface, the larger power density produces larger beam intensity after the medium. Therefore, the average diameter in the gain region becomes bigger.

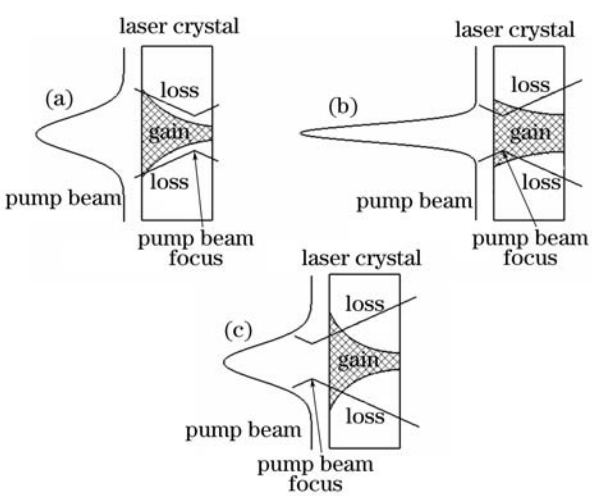

Fig. 1. Pump beam is absorbed by laser crystal for different focus positions of pump beam.

Similarly, when the focus point of pump beam appears before the incident surface of crystal, smaller power density results in fewer intensity of beam after the medium, thus the average diameter becomes smaller.

So it is important for producing high-efficient laser that the suitable crystal length is taken and the pump beam focus position is adjusted according to the pump power and the doping concentration with which the gain and the loss are well balanced for laser oscillation.

The threshold of the quasi-three-level laser is[5]

$$P_{\mathrm{th}}[1-\exp(-\alpha L)] = \frac{\pi h\nu_{\mathrm{p}}}{2f_{\mathrm{b}}\eta_{\mathrm{p}}\tau}(\omega_0^2+\omega_{\mathrm{p}}^2) \times \left(\frac{\delta}{2\sigma}+f_{\mathrm{a}}N_0L\right), \quad (1)$$

where α is the absorption coefficient, ω_{p}, ω_0 stand for the waist diameters of pump beam and laser, L represents the length of gain medium. The spot radius of pump beam and laser inside crystal can be thought to be approximately equal to ω_{p}, and ω_0 for the working length in crystal is commonly very short in the way of end-pumping. P_{th} is the threshold pump power, $h\nu_{\mathrm{p}}$ is the pump photon energy, and η_{p} is the pump quantum efficiency, the number of ions in the upper laser level is created by each absorbed photon. τ is the lifetime of upper laser manifold, σ is the stimulated emission cross section, δ is the round-trip loss. f_{a} and f_{b} are the fractional population in the upper and lower levels.

If P_{th} is differentiated with respect to L and minimized, the optimal crystal length under the minimum incident threshold power is obtained as

$$\frac{f_{\mathrm{a}}N_0\sigma}{\alpha} = \frac{\exp(-\alpha L)}{1-\exp(-\alpha L)}(f_{\mathrm{a}}N_0\sigma L+\delta/2). \quad (2)$$

The efficient absorption power is the power absorbed by laser crystal and by which the laser is created with the pump power P, absorption coefficient α and crystal length L,

$$P_{\mathrm{E}} = (P-P_{\mathrm{th}})[1-\exp(-\alpha L)]. \quad (3)$$

Substituting Eqs. (1) and (2) into Eq. (3), one obtains

$$P_{\mathrm{E}} = P[1-\exp(-\alpha L)] - \frac{\pi h\nu_{\mathrm{p}}}{2f_{\mathrm{b}}\eta_{\mathrm{p}}\tau}(\omega_0^2+\omega_{\mathrm{p}}^2) \times \left(\frac{\delta}{2\sigma}+f_{\mathrm{a}}N_0L\right). \quad (4)$$

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Considering the mode matching of pump beam and the laser modes, we need to make the pump beam ω_p equal to ω_0 of laser. If P_E is differentiated with respect to L and minimized, the optimum crystal length of laser is obtained. So the laser cavity can be designed for optimum crystal length with different pump powers,

$$P\alpha\exp(-\alpha L)=\frac{\pi f_a N_0 h\nu_p}{2 f_b \eta_p \tau}(\omega_0^2+\omega_p^2)[\exp(\alpha L+1)]. \quad (5)$$

In the experiment, the laser cavities are plane concave. The plan cavity is formed with multi-layer film placed on the laser crystal end, which can be written as

$$\omega_0=\sqrt[4]{\lambda^2 L(R-L)\pi^2}, \quad (6)$$

where λ is the laser wavelength, R is the radius of concave mirror, and L is the oscillation cavity length. Assuming R = 30 mm, L = 20 mm with stable oscillation, one obtains ω_0 = 66 μm. When the twist radius of oscillating beam, ω_0, is chosen, the radius of pump beam, ω_p, should match with ω_0 to make the pump energy efficiently couple into the laser modes. Let $\omega_p = \omega_0$, then we get the twist radius of pump beam, ω_p = 66 μm.

The emission area of the normal pump source, laser diode (LD) is 150×1 (μm) and emission angle is 10×10 (deg.). If the emission beam was concentrated by cylinder lens in the fast axial direction, it is easy to make the emission angle be 10×10 (deg.). The coupling lenses are used to couple the pump beam into crystal. Changing the object-image distance, the emission area is reduced from 1/2 to 1/3. Because of the aberration of cylinder lens and coupling lens, the size of the coupling focus point is adjusted to be 125×115 μm approximately square, and the divergence angle to be 18×18 (deg.), thus it guarantees the pump energy efficiently to couple into the laser mode, with which the pump efficiency is enhanced greatly.

According to above-mentioned analysis, for the Nd:YAG with 1% dopant concentration, the parameters adopted in the course of calculating are $N_0 = 1.5\times10^{20}$, α = 7.5 cm^{-1}, $\sigma = 4.0\times10^{-20}$ cm^2, τ = 230 μm, ω_0, ω_p = 66 μm, f_a = 0.0074, f_b = 0.6, λ_p = 808.5 nm and T = 300 K. Considering the suppression of beam at 1064 nm and intracavity doubling to produce blue light of 473 nm, the requirement of coating in the experiment is as follows: The base of the input cavity is Nd:YAG with coatings of $R < 20\%$ @ 1064 nm, HR>99.5% @ 946 nm, AR<10% @ 808.5 nm; the base of the output cavity is K9 with coatings of $R < 30\%$ @ 1064 nm, HR>99.5% @ 946 nm; in addition, the other surface of Nd:YAG is coated with $R < 0.5\%$ @ 946 and 473 nm.

According to above description, in one round-trip the oscillating beam passed through the surface about six times with each loss less than 0.5%, and the total loss less than 3%, taken as 2%. So the relationship between the threshold power and the crystal length can be gotten as shown in Fig. 2, it shows that the lowest threshold power appears when the crystal length is about 2 mm.

In the experiment, the length of Nd:YAG is 2 mm, and the threshold pump power of 946 nm reaches 300 mW. The LiB_3O_5 (LBO) adopted is produced by fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences. The both ends of the crystal are coated with AR @ 946 and 473 nm, in the way of critical matching ($\theta = 12.6°$, $\varphi = 90°$), and the relationship between the beam power and pump power could be obtained as Fig. 3

It is attached much attention that the length of pump beam changes with operating current in the course of changing the power of pumped source LD. The absorption band width of Nd:YAG could only be in 1 nm, and the central length of pump beam should be controlled at 808.5 nm in the way of changing the substrate temperature of LD as changing the current of the LD. Only like that, the relationship between the pump power and laser power could be reflected really. Otherwise the currents of LD and pump power increase while the output power go down. The main reason for that is the change of LD current, which makes the central wavelength far away from 808.5 nm.

In order to describe experimentally the matching relationship between the pump beam and oscillating beam,

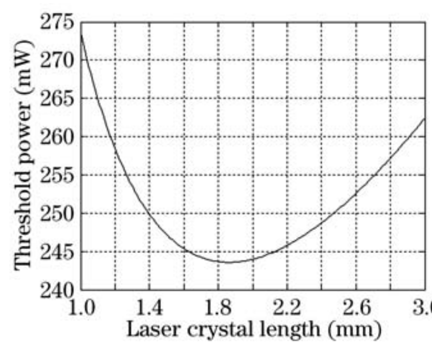

Fig. 2. Relationship between threshold power and crystal length.

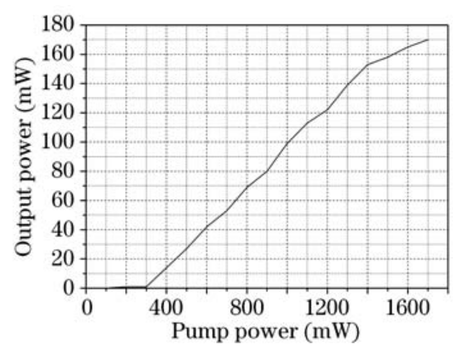

Fig. 3. Relationship between blue laser power of 473nm and pump power.

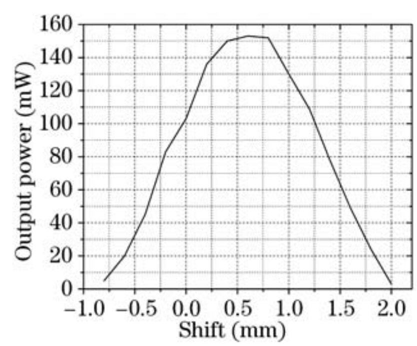

Fig. 4. Output power versus shifting of incident beam.

the radius $\omega_{\mathrm{p}}(z)$ of pump beam is regulated by adjusting the focus position of coupling beam in crystal,

$$\omega_{\mathrm{p}}(z) = \omega_{\mathrm{p0}} + |l - z| \times \theta_{\mathrm{p}}, \quad (7)$$

where l stands for the distance to the incident surface of crystal in the direction of through-light. When the pump power is 1.4 W, we adjust the value of l which bring the change of output power as shown in Fig. 4. It can be seen that in the crystal there is an optimal position for pump beam, which make it match well with oscillating beam, therefore higher conversion efficiency can be obtained.

The experimental result indicates that the threshold of output laser is 300 mW, approximating to the value in theory. When the pump power is 1.4 W, the output power of 473 nm reaches 153 mW, with 10.9% of the conversion efficiency and 13.9% of incremental efficiency. Observed from the far field, the mode of output laser of 473 nm is TEM00. With continuous monitoring and metering of power meter about two hours, the stability of output power can be described within 2%. We can see from Fig. 3 that there is inflexion at 1.4 W pump power, and the slope begins to decline. It could attribute to the mismatching of parameters of the laser with the value taken in design, owing to absorption saturation or the cavity parameters change resulted from thermal effect of crystal.

Proper design of LD coupling system will make the radius of the pump beam close to that of oscillating beam, and there will be a optimal position of pump beam in the crystal, then better matching of pump beam with the oscillating beam could be obtained to improve conversion efficiency. The method of designing and the entire developing in this paper could serve as the reference designing the same kind of lasers.

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