Comparison of different side-pumping configurations for high power laser diode pumped solid-state laser

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Ray-tracing method is used to simulate the distribution of absorption in crystal rod for different side-pumping configuration. The distribution of pumping power and absorption efficiency is compared, and the numerical results are presented. The results show that the more uniform pumping and the higher absorption coefficient are obtained with a diffuse cavity. And the method of the slow axis of laser diode stack perpendicular to the axis of lasing gives the higher central pumping density.

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In the past few years, the study of high efficiency, high beam quality and diode pumped solid-state lasers (DPSSLs) has been concerned on. Comparing with the lamp pumped solid-state lasers, DPSSL has higher efficiency and more compact size. Two pumping schemes of end and side pumping are usually used in DPSSL. The end-pumping configuration is an efficient and simple method, and the high optical-to-optical efficiency has been proved[1]. However the end-pumping configuration has a disadvantage with regard to scalability. The side-pumping configuration is a scalable method, and the higher output power can be obtained. The higher optical-to-optical efficiency and beam quality are the objective for side pumping scheme. Numerous resonators have been demonstrated, including slab and rod system. A slab laser is highly efficient with the TEM_{00} mode, but it is more complicated than that of rod. Recently, the side pumping of rod-medium with a diffuse cavity has been implemented[2], and as high as 28% electrical efficiency was obtained[3]. For the high power DPSSL, designing a cavity with uniform pumping and high absorption efficiency of pump power becomes attractive. In this letter, we prefer to discuss the pumping power distribution by quasi-CW diode stack under the different pumping configurations. Furthermore, the effect of orientation of axis of diode-stacks to the axis of medium will be also studied. The numerical simulation results will be presented.

Figure 1 illustrates the cross-section views of the two pumping configurations. In Fig. 1(a), the laser rod is surrounded by a diffusive reflector, and cooled by water in a glass tube. The beams from diode-stack are transferred into the diffusive reflector through a glass wave-guide inserted into the ditch of the diffusive reflector. Figure 1(b) is same as (a) except for the diffusive reflector and the wave-guide. Both schemes are symmetrically pumped by three diode-stacks. Since when the diameter of the Nd:YAG rod is larger than 6 mm the uniformity will degrade for the absorption coefficient of 2.78 cm^{-1}[4], we choice the Nd:YAG rod with diameter of 5 mm in calculations. Though increasing the inner diameter of diffusive cavity will uniform the absorption distribution of pump radiation, the absorption efficiency will decrease. Here the inner diffusive cavity diameter of 12 mm is chosen. The Nd^{3+} doping concentrations of 0.5 at.-% and 1 at.-% in YAG crystal, which corresponding to effective absorption of 3.3 cm^{-1} and 6.5 cm^{-1} are calculated in the following simulation. The YAG crystal has cubic crystal structure and is isotropic to pump radiation. For an anisotropy crystal, the absorption coefficient is relative to polarization and direction of pump radiation.

In the following simulation, the fast axis and the slow axis of diode-stack[5] are assumed to be perpendicular to the axis of medium rod in the two pumping configuration, respectively. The illumination along the crystal rod is taken to be uniform, thus only a cross-section of power distribution is calculated. The emission profile can be treated approximately as Gaussian distribution of the degree θ[6]

$$P(\theta) = A\exp(-\theta^2/\theta_{1/2}^2), \tag{1}$$

where $\theta_{1/2}$ is the FWHM, A is a constant with a value of

$$A = \frac{P_0}{\int_{-\pi/2}^{\pi/2}\exp(-\theta^2/\theta_{1/2}^2)\mathrm{d}\theta},$$

P_0 is the radiation power of an unit length of the diode-stack. Each diode stack is consisted of five diode bars

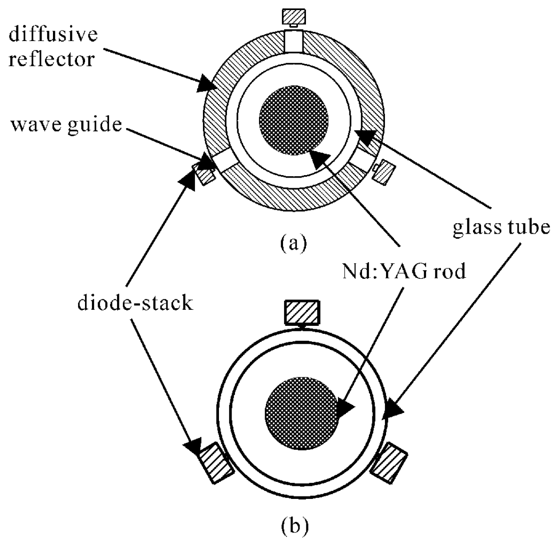

Fig. 1. Configurations of side-pumping. (a) With diffusive optical cavity; (b) without diffusive optical cavity.

with 0.5-mm distance between stacks. The radiation FWHWs of fast axis and slow axis were taken as 38° and 10°, respectively. Ray-tracing method[7] was used to analyzed the distribution of pumping power. Radiation direction of each ray is generated with Monte Carlo method. The diffused cavity is taken as Lambertian reflector with a reflectance of 95%. Each ray is reflected randomly according to the Lambert law. The cross-section of the crystal rod is divided into 90000 zones by the 250 divisions in the radial direction and 360 divisions in the angular direction. When a ray passes the zone (i,j) with a distance of Δd, the absorbed power $P_{\rm abs}(i,j)$ can be expressed as

$$P_{\rm abs}(i,j) = P_0(i,j)[1-\exp(-\alpha\Delta d)], \tag{2}$$

where α is the absorption coefficient of the crystal, $P_0(i,j)$ is the pump power before the ray passing through the zone.

At first, the pumping power distributions of the configuration without the diffusive reflector are calculated. The results are shown in Fig. 2. The pumping power is more uniform in the rod with low absorption coefficient than that with high absorption coefficient when the fast axis of diode-stack is perpendicular to the axis of rod. While the absorption efficiency is low due to the incomplete absorption of pumping power in the rod. When the slow axis is perpendicular to the axis of rod, the absorption efficiency is higher than the case of Figs. 2(a) and (b). The center distribution is quit better in the rod with low-doped concentration as shown in Fig. 2(d). On the contrary, when the fast axis is perpendicular to the axis of rod, the edge illumination is higher than that of the center, particularly in the rod with high concentration.

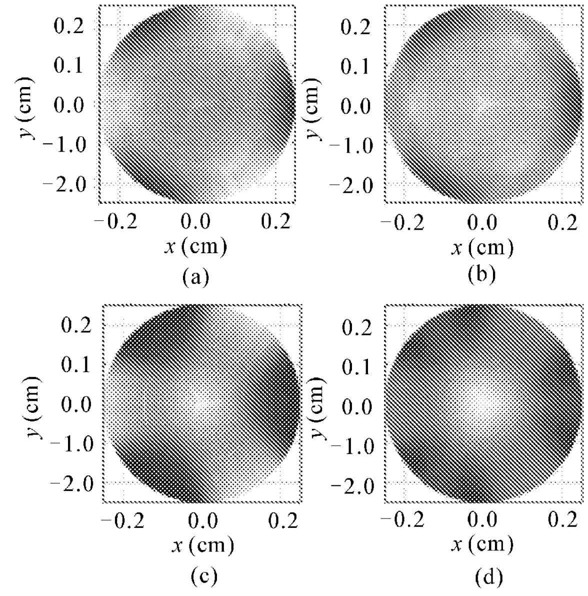

Fig. 2. Absorbed power distribution in crystal calculated from the scheme without diffusive optical cavity. (a) The fast axis of diode perpendicular to the axis of rod with the absorption coefficient of 6.5 cm^{-1}; and (b) α = 3.3 cm^{-1}; (c) the slow axis of diode perpendicular to the axis of rod with the absorption coefficient of 6.5 cm^{-1}; and (d) α = 3.3 cm^{-1}.

Figure 3 is the results of configuration with diffusive reflector. The absorption efficiency and uniformity are improved greatly, especially when the slow axis of diode-stacks is perpendicular to the axis of the crystal rod as showed in Figs. 3(a) and (b). Same as the case in Fig. 2, when the slow axis of diode-stacks is perpendicular to the axis of the rod, the absorption efficiency is higher than that of fast axis being perpendicular to the axis of rod. With the rod of low concentration, the absorption efficiency is improved because the non-absorbed pumping power is reflected into rod again, and the uniformity is also improved comparing to the case without diffusive cavity.

The absorption efficiencies in all cases are calculated and listed in Table 1.

From Table 1 we can find that in the cases of Figs. 3(a) and (b), the absorption efficiencies are almost the same while the absorption distributions differ greatly. We also calculated the pump power distributions with different absorption coefficient of 2.5, 4.5 and 5.5 cm^{-1}. Considering both the absorption efficiency and uniformity, the laser using a Nd:YAG rod with an absorption coefficient of 3.3 cm^{-1} will give better performance.

The optimum output power[8] can be given by

$$P_{\rm opt} = \eta_E\eta_T\eta_a\eta_u\eta_B P_p, \tag{3}$$

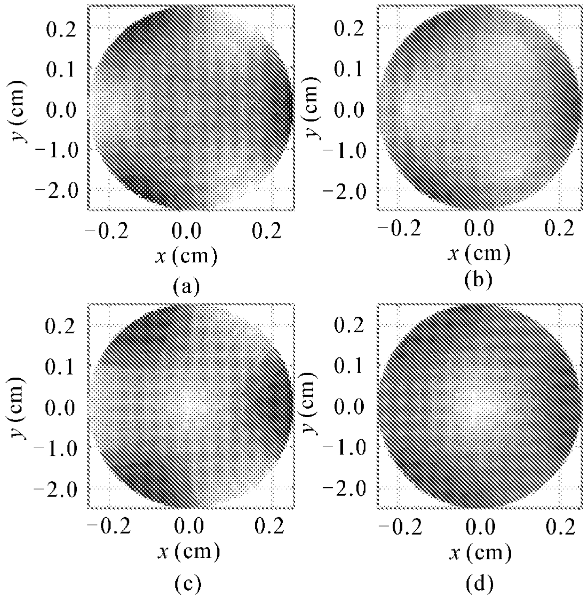

Fig. 3. Absorbed power distribution in crystal calculated from the scheme with diffusive optical cavity. (a) The fast axis of diode perpendicular to the axis of rod with the absorption coefficient of α = 6.5 cm^{-1}; and (b) α = 3.3 cm^{-1}; (c) the slow axis of diode perpendicular to the axis of rod with the absorption coefficient of α = 6.5 cm^{-1}; and (d) α = 3.3 cm^{-1}.

Table 1. Absorption Efficiency of Each Situation in Figs. 2 and 3

Fig. 2	Situations	(a)	(b)	(c)	(d)
	Absorption Efficiency (%)	76	66	96	83
Fig. 3	Situations	(a)	(b)	(c)	(d)
	Absorption Efficiency (%)	85	84	98	92

where P_p is pump power, and η_T is the radiation transfer efficiency defined as the ratio of the pump radiation transferred into gain medium and the total pump radiation. η_E represents the extraction efficiency and given by

$$\eta_E = (1 - \sqrt{L/2g_0 l})^2, \tag{4}$$

where L is the dissipative loss, $g_0 l$ is the single pass small signal gain of the system. η_a and η_u are the absorption efficiency and the upper state efficiency, respectively. η_B is the beam overlap efficiency and given as

$$\eta_B = \frac{2\omega_B^2}{\omega_g^2 + \omega_B^2}, \tag{5}$$

where ω_B and ω_g are the spot size for the gain and beam profiles, respectively. From Eqs. (4) and (5), it can be seen that under a certain cavity condition, the output power is determined not only by the pumping power, and also by the pump uniformity.

For the example of Fig. 3(b), η_B is approximate 0.8, the laser medium length is assumed 6 cm and each diode stack has power of 300 W, then η_E is 0.76 if L is assumed as 0.03, and the laser power can be as high as 318 W for the 20% output coupler in theory. As shown in the example, laser system with diffused cavity and optimum absorption coefficient of gain medium can output better beam quality and higher power.

In this letter, we analyzed the distribution of absorbed pump power in the rod medium with different pumping configurations using ray-tracing method. Results show that the higher and more uniform pumping can be obtained in the scheme with the diffusive cavity. Considering both the uniformity and the absorption efficiency, the configuration with the diffusive cavity and the fast axis of rod being perpendicular to the axis of rod is recommended for the high power laser system.

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