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Optimized analysis of the slab configuration in diode-pumped quasi-three-level solid-state lasers

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Abstract: Based on the condition of the maximized laser gain, the laser gain, the optimal optical crystal length and width of quasi-three-level solid-state slab lasers, which variate with pump power, are analyzed and optimized. At the same time we found that the the concentration of doping medium and the width of the slabs satisfied a certain relation under the condition of diode-side-pumped mode in lower pump power. The laser gain, the optical length and width of the slabs are optimized and simulated when pump power changes from 0 to 2 kW. These results can also be applied to the design for other quasi-three-level solid-state lasers.

Key words: diode pumping; quasi-three-level; solid-state laser; slab geometry.
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二极管泵浦准三能级板条固体激光器的优化设计

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摘 要: 基于最大激光增益条件,分析和优化了二极管泵浦准三能级Yb:YAG固体板条激光器的激光增益、板条的最佳光学长度和最佳宽度参数。结果表明:在低功率侧面泵浦条件下,板条增益介质的掺杂浓度和板条宽度满足一定的关系,这为研究该类激光器提供了一条有效途径,其结果可应用于其他准三能级固体激光器设计。

关键词: 二极管泵浦;准三能级;固体激光器;板条结构

1 Introduction

Quasi-three-level solid-state lasers, specially the ytterbium-doped lasers are of the great attractiveness due to the higher quantum efficiency and the lower thermal load[1-2]. Lower heat generation is a key issue to high-efficiency and high-power laser output. Therefore, a variety of geometries of Yb:YAG lasers have been demonstrated, such as microchip designs[3], wave-guides[4-5], fiber[6], and nonplanar ring structures[7] for low power output; rod lasers[8-13] in end-pumped and side-pumped configurations, thin disc geometries[14] for high peak and average powers. However, all of these designs are limited in the output powers of ~1 kW. The laser slab geometry[15-16] is an important configuration for the solid-state lasers to scale lasers of high peak and average powers, since the slab configuration has the lower thermal lens effect and thermal beam distortions. Recently, a novel zigzag slab design that uses pumping along the slab's edges was proposed[17]. Moreover, the oscillator modeling predicted that

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output powers beyond 1kW and up to 100 kW could be achieved. Optimizing the performance of such slab lasers depends on understanding and analyzing how laser charac-teristics such as small signal gain, slope efficiency, and threshold are affected by the spatial distribution and mode overlap of the laser and pump fields, and reabsorption loss. At the same time it is important how to correctly choose and determine the characteristic parameters of laser media such as dopant concentration, diameter and length of rod geometry; dimension and Brewste-cut angle of the slab configuration according to criteria. An optimum crystal rod length that minimizes the threshold in term of incident pump power in longitudinally TEM_{00} Gaussian beam pumping was proposed by Risk[18]. The optimal optical length of the laser rod for the maximal laser output intensity in diode-end-pumped was obtained by Lim[19]. The optimum laser rod diameter for maximum output energy in a solid-state neody-mium laser trans versely pumped with multiple laser diode array was reported[20].

The applications of the quasi-three-level solid-state lasers in high-energy laser weapons are described in Ref. [21]. Lower thermal loading and thermal distribution of Yb : YAG laser is demon-strated by Ref. [13].

In this paper, assuming that pump light distribution is symmetric top-hat function, laser beam distribution function is Gaussian shape and considering the space-dependent population rate of quasi-three level solid-state laser, based on the maximized laser gain condition, we have analyzed and optimized the laser gain, the optimal optical crystal length and width of quasi-three-level solid-state slab lasers in diode-edge-pumped geometry.

2 Theoretical analysis

Proceeding from the space-dependent rate equations, if the depletion of the ground-state population and the spatial hole burning effect are neglected, we derived the expression of the laser gain coefficient $g(x,y,z)$ associated with the spatial distribution of pump light and laser mode as

$$g(x,y,z)=\frac{(f_1+f_2)\sigma\tau Rr(x,y,z)-\sigma N_1^0}{1+(f_1+f_2)\tau\left[\frac{c\sigma}{n}\Phi\varphi(x,y,z)\right]} \tag{1}$$

for small signal gain coefficient $g_0(x,y,z)$,

$$g_0(x,y,z)=(f_1+f_2)\sigma\tau Rr(x,y,z)-\sigma N_1^0 \tag{2}$$

where, $r(x,y,z)$ and $\varphi(x,y,z)$ are the normalized spatial distribution functions of pump light and laser mode respectively, τ is the lifetime of the upper laser level, σ is the peak emission cross section, Φ is the total photon number in the cavity, N_1^0 is the doping concentration of the lower laser level, c is optical velocity and n is refractive index, f_2 and f_1 are the fractional population in the upper and the lower laser levels respectively. The pump rate R at which ions are excited into the upper laser manifold during the pump process is given by $R=\eta_q\eta_a P_p/h\nu_p$, where P_P is the incident pump power, η_q and η_a are the pump quantum efficiency and the absorbed efficiency respectively, $h\nu_p$ is the pump photon energy.

For quasi-three level Yb-doping solid-state lasers, diode-edge-pumped slab geometry is a favorite scheme. Therefore, we will focus on the optimization of diode-edge-pumped quasi-three-level Yb : YAG slab geometry. In practical laser design the choice of the parameters of laser medium such as doping concentration, dimension of length and width, and thickness for slab geometry are very important. So we define the product $(N_{tot}L)$ of the doping concentration and laser crystal length as the optical crystal length, which is used to modify the laser properties.

3 Simulation and optimization design

Here we assume that the pump beam is the top-hat and uniformity pump distribution at diode-edge-pumped slab geometry. The pump distribution function is given by

$$r_p(x,y,z)=\frac{\alpha}{S_e\eta_a}\exp(-\alpha x) \tag{3}$$

where $S_e=DL$ is the area of the slab pump edge, L is the thickness, D is the slab length, the absorption efficiency $\eta_a=1-\exp(-\alpha W)$, W is the slab width, $\alpha=N_{tot}\sigma_a$ is the effective absorption coefficient.

Substituting Eq. (3) into Eq. (2) and then integrating with respect to x, y, z along three directions of the slab, we get the expression of the single pass gain as

$$g_0=\left((f_1+f_2)\tau\eta_q\eta_a\frac{P_p/S_e}{W\mathrm{h}\nu_p}-f_1N_{tot}\right)L\sigma \tag{4}$$

For the convenience of analysis, we intrude a parameter of the optical crystal width $N_{tot}W$ to modify the slab geometry. The maximal product of the gain and the slab width will be got by differentiating Eq. (4) with respect to $N_{tot}W$ and make the differential equation zero. We get the maximal product of the gain and the slab width as

$$(g_0W)_{max}=\frac{(f_1+f_2)\tau\eta_qP_p/S_e}{\mathrm{h}\nu_p}\left\{1-\exp\left[\ln\left(\frac{f_1\mathrm{h}\nu_p}{(f_1+f_2)\tau\sigma_a\eta_qP_p/S_e}\right)\right]\right\}+\frac{f_1}{\sigma_a}\ln\left[\frac{f_1\mathrm{h}\nu_p}{(f_1+f_2)\tau\sigma_a\eta_qP_p/S_e}\right]L\sigma \tag{5}$$

And the optimal optical width ($N_{tot}W$) of the slab satisfies the following equation

$$(N_{tot}W)_{opt}=-\frac{1}{\sigma_a}\ln\left[\frac{f_1\mathrm{h}\nu_p}{(f_1+f_2)\tau\sigma_a\eta_qP_p/S_e}\right] \tag{6}$$

In calculation, we chose $f_1=0.046$, $f_2=0.772$, $\sigma_a=0.77\times10^{-20}\,\mathrm{cm}^2$, $\tau=0.951$ ms, $\mathrm{h}\nu_p=2.097\times10^{-19}$ J, and assumed unity quantum efficiency $\eta_q=1.0$. The pump power changes from 0 to 2 kW, the thickness of the edge-pumped slab is chosen as 600 μm, 800 μm and 1 000 μm. The maximal product of the single pass gain and the width of the slab related to pump power is calculated and shown in Fig. 1.

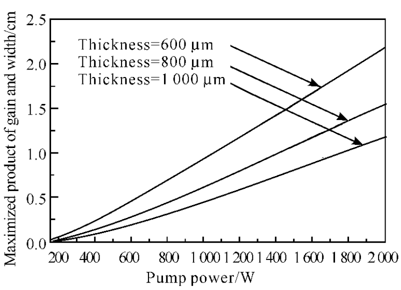

Fig. 1 The maximized product of the gain and the width versus pump power

The optimal optical width ($N_{tot}W$) of the slab versus pump power at different slab thickness is given in Fig. 2.

From Fig. 2 we find the optimal optical length is negative at low pump power, the corresponding values are 370 W for thickness of 600 μm, 496 W for thickness of 800 μm, and 620 W for thickness of 1 000 μm. For 1 at. % doped

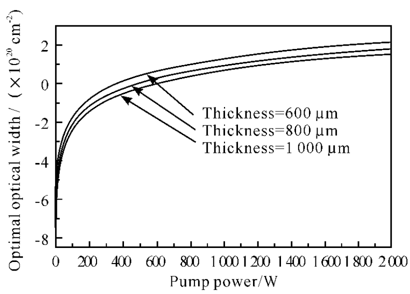

Fig. 2 Variation of the optimal optical crystal width with pump power

Yb : YAG and slab thick-ness of 600 μm the optimalslab length is 9.4 mm at the pump power of 1 kW. In order to make a comparison with the results cited by Ref. [17], the maximal single pass gain can also be given by differentiating Eq. (6) with respect to and make the differential equation zero. Therefore, under the condition of the maximal single pass gain, the optimal slab width (W) of the slab satisfies the following equation

$$(N_{tot}\sigma_a W+1)\exp^{(-N_{tot}\sigma_a W)}=1 \tag{7}$$

We find that this expression has greatly difference with the results cited by Ref. [17], where the product of the absorption coefficient and the slab width is approximately equal to unity. The optimal slab width (W) of the slab is independent of the pump power density.

By using similar process mentioned above for diode-end-pumped composited Yb : YAG slab geometry, we get the maximal single pass gain and the optimal optical length ($N_{tot}L$) of the slab as

$$(g_0)_{max}=(f_1+f_2)\tau\eta_q \frac{P_p/S_e}{h\upsilon_p}-\frac{f_1}{\sigma_a}\left\{1+\ln\left[\left(\frac{f_1+f_2}{2}\right)\tau\eta_q\sigma_a\frac{P_p/S}{h\upsilon_p}\right]\right\}\sigma \tag{8}$$

$$(N_{tot}L)_{opt}=\frac{1}{\sigma_a}\ln\left\{\left(\frac{f_1+f_2}{f_1}\right)\tau\eta_q\sigma_a\frac{P_p/S}{h\nu_p}\right\} \tag{9}$$

In calculation, the pump power changes from 0 to 2 000 W, the doping cross-section S of the composited slab is chosen as 600 μm × 600 μm, 800 μm×800 μm, and 1000 μm×1000 μm.

Variation of the maximal single pass gain with pump power for the different cross-section of the composite Yb : YAG slabs is calculated and shown in Fig. 3.

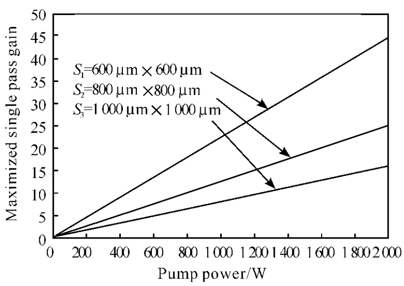

Fig. 3 The maximized laser gain versus pump power

Fig. 3 shows that the maximal gain depends on the pump power and the cross section of the composite slab. For pump power of 2 kW the gain is 44 for the cross section of 0. 36 mm^2; and about 16 for that of 1. 0 mm^2. The refore, this structure is favourite for quasi-three level laser requiring high intense pump.

The optimal optical crystal length ($N_{tot}L$) of the slab is given by Fig. 4.

Fig. 4 shows that the optimal slab length is got for different doping concentration for a given pump power and pumping cross section of laser slab. For example, for 5 at. % doped Yb : YAG and cross section of S_1 the optimal slab length is 10 mm at the pump power of 1 kW.

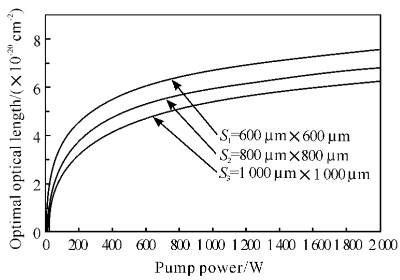

Fig. 4 Variation of the optimal optical crystal length with pump power

4 Conclusion

In conclusion, we have derived the variation of laser gain, and optimal optical length and width of quasi-three-level slab solid-state lasers with pump power density in diode-edge-pumped geometries. The laser gain, and the optical length and width of the slabs are optimized and simulated when pump power changes from 0 to 2 kW. These results can also be applied to the design of other quasi-three-level solid-state lasers.

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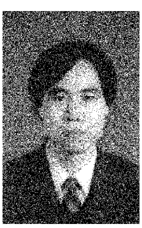

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