第35卷第10期
2006年10月
光 子 学 报
ACTA PHOTONICA SINICA
Vol. 35 No. 10
October 2006

Design of a Compact Diamond-Cooled Yb^{3+} : YAG DPSSL

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Abstract A compact diamond window cooled Yb^{3+} : YAG disk laser has been demonstrated. In this cooling scheme, the rear face of disk is cooled directly by water while the front face of disk is applied in good thermal contact to a thin plate of chemical vapor deposition diamond window. The exceptionally good heat conduction properties of diamond can eliminate the temperature gradients perpendicular to laser beam thus previous difficulties with high average power pumping and efficient cooling are resolved. Simulation results show that with a pump intensity of 20 kW/cm^2 and repetition rate of 10 Hz, to keep the maximum temperature of the gain disk below a reasonable value, e. g., less than 320K, the heat exchange coefficient of water should be about 4000 W/m^2K.

Keywords Laser technology; Yb^{3+} : YAG; Diamond-cooled

CLCN TN248.41 **Document Code** A

0 Introduction

High-power-diode-pumped-solid-state-laser is very attractive for industrial, scientific and military applications. The Yb^{3+} : YAG crystal is chosen as an active medium in most papers due to its high Stokes efficiency, broad absorption bands, high doping levels possible without quenching and good thermo-mechanical properties of the laser host[1]. But Yb^{3+} : YAG need high pump power densities (~ 28 kW/cm^2) to overcome transparency threshold and results in a high heat power density, especially in high repetition rate operation[2]. If the heat is not removed efficiently, the temperature of the gain medium rises, thereby degrading the efficiency of the lasing action[2~3]. For quasi-three level laser medium the product of doping concentration and thickness is constant for fixed pumping condition. With taking into account the cooling effect, a thin medium is needed to obtain both high pump intensity and quick cooling. For example thin-disk configure, a hundreds μm medium is mounted in a copper sink, but that is the quasi-continuous wave laser or power laser. For the energy laser a thicker medium is needed to obtain high pump energy, e. g., the thicknesses are respectively 1.4 mm and 1.6 mm for the oscillator and amplifier of LUCIA, a 100 J/10 Hz/10 ns diode-pumping solid-state laser facility[4,5]. But the experiments show that rear face water cooling could not cooled the medium efficiently[4,5]. In this paper, the compound cooling technology will employed which combined Chemical Vapor Deposition (CVD) diamond window cooling the front face of disk with water directly cooling the rear face of disk to control temperature rises of disk efficiently.

1 Design of diamond window cooled Yb^{3+} : YAG disk laser

Cooling of a lasing disk along the axis of lasing is generally desirable, since the temperature gradient generated by the heat dissipation will be in the same direction as the axis of cooling. Consequently, the temperature will stay constant along the plane perpendicular to the cooling/lasing direction. In the diamond-cooled approach, the rear face of gain disk (the pumping side) is cooled directly by water, the front face of gain disk (lasing side) is applied in good thermal contact to a thin plate (0.3 mm) of CVD diamond window, CVD diamond windows are transparent at the laser wavelength and can be polished to optical quality so that they can be brought in close contact with the lasing disk. CVD thin diamond plates have exceptionally good thermal conduction properties. This property effectively causes the diamond plates to transfer the cooling effect of the peripherally applied water to the central areas of the plate, with minimal thermal resistance[6].

A cut-away view of a laser module is shown in Fig. 1. The laser crystal is a disk-shaped 12 mm × 10 mm × 1.6 mm (along x, y, and z directions, respectively), is face pumped (along the optical axis) by the output of laser diode arrays. To

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Received date: 2006-04-23

increase the extraction efficiency of the stored energy on upper laser level, a V-shaped unstable cavity is used. The two surfaces of the diamond window and the front face of gain disk are coated with antireflection coating at 1030 nm to minimize lasing loss. The rear face of the gain disk is coated with antireflection coating at 940 nm to minimize pumping loss and coated with anti-transmission coating at 1030 nm to minimize lasing loss. The pumping light is transmitted to the laser crystal via the water channels.

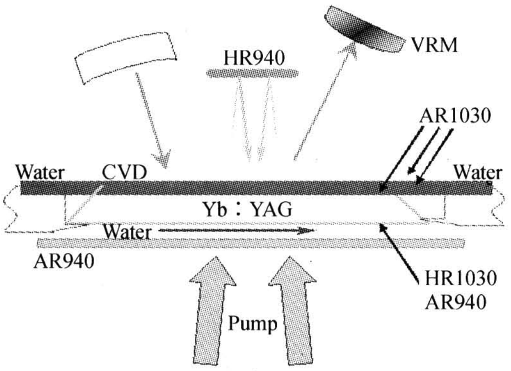


Fig. 1 Schematic layout cross-sectional view of a diamond cooling laser head

2 Heat transfer numerical simulation

2.1 Heat transfer equation and related parameters

According to the pumping absorption, it is know that the pumping light absorption or thermal power deposition along x, y, and z directions are not uniformly. Generally, $P_{\mathrm{th}}(y)$ has a very high order of Super-Gaussien because of the use of lensduct. $P_{\mathrm{th}}(x)$ is dependent on the alignment of each stack of LD and cylindrical lens which is used to collimate the LD output along rapid axis. $P_{\mathrm{th}}(z)$ is related to the doping concentration. However, some reasonable assumptions can be made to simplify the problem. In the pumping area (about 6.8 mm × 7.6 mm), thermal power is uniformly distributed along the medium surface. Then the heat generation rate is calculated as follows

$$P_{\mathrm{th}}(x,y,z)=I_{\mathrm{abs}}(x,y,z)\times\eta_{\mathrm{th}}/l \tag{1}$$

Where, I_{abs} ($\mathrm{W/m^2}$) is the absorption of pump intensity, η_{th} is the thermal efficiency, and l m is the thickness of medium. Taking into account the quantum efficiency, the Stokes loss of $\mathrm{Yb^{3+}}$: YAG of 8.6% ($1-\lambda_{\mathrm{p}}/\lambda_{\mathrm{L}}$), and the experimental results[5], the thermal efficiency η_{th} is fixed at 11% in our calculations. Fig. 2 gives the thermal power distributions along z directions of the gain medium.

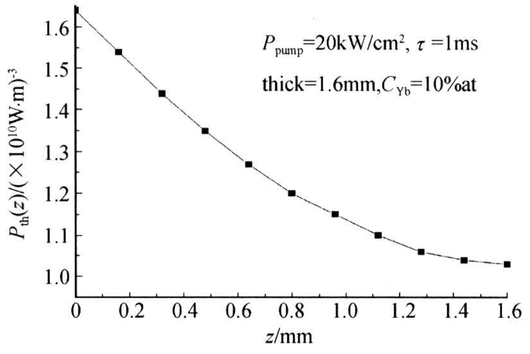


Fig. 2 Thermal power distributions along z directions

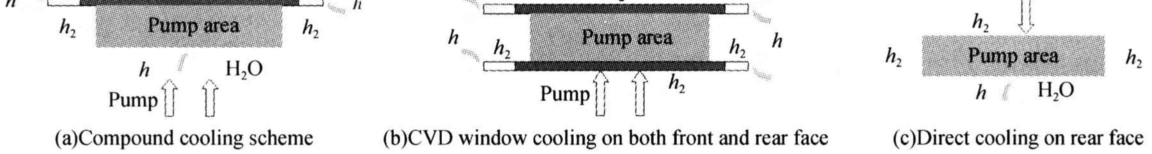
The heat transfer equation is thus as follows

$$\rho\cdot C_{\mathrm{p}}\cdot\frac{\partial T(x,y,z;t)}{\partial t}=\kappa(T,C_{\mathrm{Yb}})\cdot\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+P_{\mathrm{th}}(x,y,z) \tag{2}$$

where, ρ is the mass density, C_{p} is the heat capacity, $P_{\mathrm{th}}(x,y,z)$ is the heat generation rate within the gain medium introduced by pumping absorption. $\kappa(T, C_{\mathrm{Yb}})$ is the heat conductivity.

2.2 Numerical results and discussion

In order to emphasize the advantage of cooled by diamond window over cooled directly by water we have simulated their behavior based on three cooling scheme which have same pumping conditions as show in Fig. 3.



(a)Compound cooling scheme (b)CVD window cooling on both front and rear face (c)Direct cooling on rear face

Fig. 3 A schematic diagram of the different cooling schemes

The fixed parameters of lasing disk used in all calculations are: the mass density(ρ) of $4.56\times10^3\ \mathrm{kg/m^3}$, the heat capacity ($C_{\mathrm{p}}$) of 0.59×10^3 J/kgK, the heat conductivity of 8 W/m/K, the temperature of 300 K for water and air. Parameters of CVD Diamond used in calculations are: the dimension of 16 mm×14 mm×0.3 mm, the mass density (ρ) of $3.515\times10^3\ \mathrm{kg/m^3}$, the heat capacity($C_{\mathrm{p}}$) of 0.502×10^3 J/kgK, the heat conductivity of 1800 W/m/K. Because we do not know exactly the heat exchange coefficients of water (h), as show in Fig. 3, we calculate here the final steady state temperature distribution of the gain disk at different values of h, which is usually between 1000-6000 W/m^{2}K. During the calculations, the heat exchange coefficient of 5 W/m^{2}K on the side area of medium disk and the surface of CVD diamond are used because of a free convection of air (h_2).

From the results presented in Fig . 4 , it can show see that the rising of temperature in the gain disk could not be controlled efficiently by water directly cooled on the rear face. In contrast, when a diamond window plate is used, it can cool gain disk on both rear face and front face efficiently because diamond are transparent at the pump and laser wavelength and can be polished to optical quality, so that they can be brought in close contact with the gain disk. Although the cooling effect of using double diamond windows cooled both on rear and front face of disk is the best (as show in Fig. 4), the compound cooling technology which is combined diamond windows cooling front face of disk with directly water cooling rear face of disk is a more feasible cooling scheme taken into account costliness of single crystal synthetic diamond. In this cooling scheme, as show in Fig. 1, the heat transfer from Yb^{3+} : YAG to the diamond, in the direction of the optical axis, and then rapidly conducted radically outward through the diamond to the cooling fluid circulating at the circumference of the diamond/ Yb^{3+} : YAG assembly. Fig. 5 is the distribution of the stable state temperature in pumping area of disk, the value of heat exchange coefficient of water is 1000 W/m^{2}K.

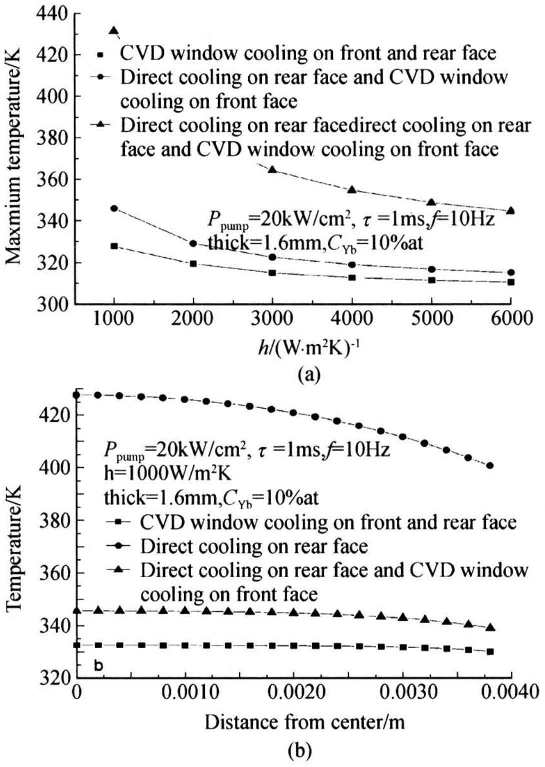


Fig. 4 (a) Maximum temperature in the disk versus the heat exchange coefficients of water at a pumping intensities of 20 kW/cm^2 and 10 Hz; (b) Temperature distribution of the disk along the x direction centerline

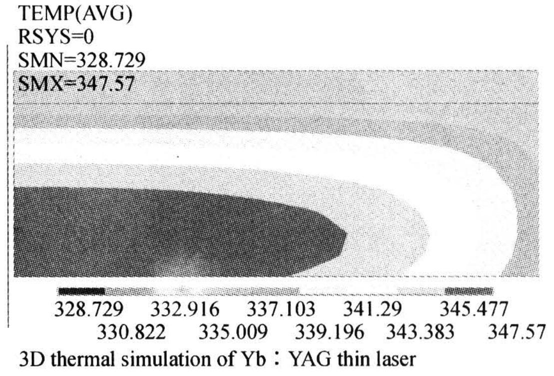
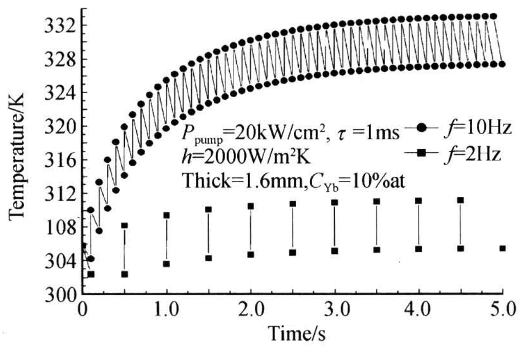


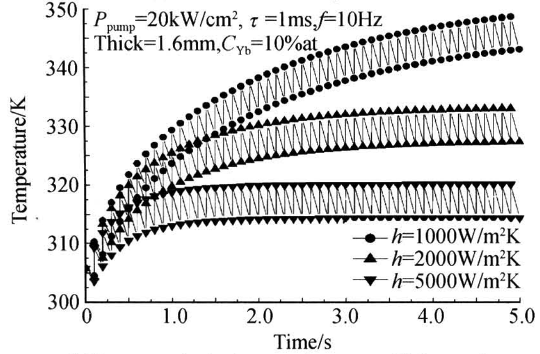
Fig. 5 Distribution of the temperature field in pumping area

Fig. 5 illustrate that the exceptionally good heat conduction properties of diamond can eliminate the temperature gradients perpendicular to beam thus effectively reduces the thermal lensing in the gain disk. It can see from Fig. 4 (a), with a pump intensity of 20 kW/cm^2 and repetition rate of 10 Hz, and doping concentration of 10at% at a 1. 6 mm-thick Yb^{3+} : YAG, to keep the maximum temperature of the lasing slab below a reasonable value, e. g. , less than 320 K, the heat exchange coefficient of water should be about 4000 W/m^{2}K.

Fig. 6 show the transient temperature oscillates (about 5℃) under repetitively pump. Temperature build-up is obtained at the end of each pump pulse, during the pulse interval time the temperature decreases, of course. The higher of the pump-pulse repetition rate, or the lower of heat exchange coefficient of water, the longer time is needed for the temperature reached periodical distribution with time.



(a)Parameter is the repetition rate



(b)Parameter is the heat exchange coefficients of water

Fig. 6 Temperature behaviour in the center of the gain disk under repetitively pumped versus time

3 Conclusions

Using finite element methods compares three different cooling schemes. Simulation results shows that the compound cooling technology which is combined diamond windows cooling front face of disk with water directly cooling rear face of disk can cooled gain disk efficiently. In the cooling approach for a pump intensity of 20 kW/cm^2 and repetition rate of 10 Hz, and doping concentration of 10 at% at a 1.6 mm-thick Yb^{3+} : YAG, to keep the maximum temperature of the gain disk below a reasonable value, e. g. , less than 320 K, the heat exchange coefficient of water should be about 4000 W/m^{2}K.

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金刚石窗口冷却 Yb^{3+} : YAG DPSSL 设计

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收稿日期：2006-04-23

摘　要　针对高功率二极管重复率抽运的 V 型非稳腔 Yb^{3+} : YAG 激光头，提出了利用金刚石窗口冷却和直接水冷相结合的复合冷却设计．在 YAG 片的抽运面进行直接水冷，同时在激光提取面利用金刚石窗口冷却介质．金刚石优异的导热性能不仅能够有效地冷却激光介质，还能消除横向的温度梯度，解决了高功率激光器冷却和高功率抽运的矛盾．模拟结果表明对掺杂 10 at% 厚度为 1.6 mm 的 Yb^{3+} : YAG 片在抽运功率密度为 20 kW/cm^2，重复频率为 10 Hz 的条件下，要将最高温度控制在可接受的范围内(比如 320 K)，周围冷却水的对流换热系数约为 4000 W/m^{2}K.

关键词　激光技术，Yb^{3+} : YAG，金刚石冷却

Cao Dingxiang was born in 1973. He received the B. S. degree in 1996 and the M. S. degree in 2002 from National University of Defence Technology. Now he is studying for his Ph. D. degree in National University of Defence Technology. He works at Laser Fusion Research Center of CAEP. His major research focuses on high power solid state lasers.