Investigation of Nd:YVO₄/YVO₄ composite crystal and its laser performance pumped by a fiber coupled diode laser

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Received 31 October 2006; accepted 31 January 2007

Abstract

Thermal effect control is critical to scale the output power of diode end-pumping solid lasers to several watts up and beyond. Diffusion bonding crystal has been demonstrated to be an effective method to relieve the thermal lens for the end-pumping laser crystal. The temperature distribution and thermal lens in Nd:YVO₄/YVO₄ composite crystal was numerically analyzed and compared with that of Nd:YVO₄ crystal in this paper. The end-pumping Nd:YVO₄/YVO₄ composite crystal laser was set up and tested with z cavity. The maximum output power of 9.87 W at 1064 nm and 6.14 W at 532 nm were obtained at the pumping power of 16.5 W. The highest optical–optical conversion efficiencies were up to 60% at 1064 nm and 40% at 532 nm, respectively.

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PACS: 42.70.Hj; 42.65.Ky; 42.60.Pk; 42.55.Xi

Keywords: Thermal lens; Numerical simulation; Nd:YVO₄/YVO₄ composite crystal; Diode pumping

1. Introduction

High power diode pumping all-solid-state lasers have recently attracted much more interest for their unique merits, such as long lifetime, compact structure, high stability and optical–optical conversion efficiency, etc. [1–5]. To get an efficient fundamental mode operation with better beam quality (normally $M^2 < 1.5$), longitudinal pumping configuration of solid lasers has been developed. However, thermal effects control is very critical in highly scaling the output power of diode pumping solid state lasers to a few watts up and beyond, especially for end-pumping configuration. Large thermal gradient arises from the heat deposition within a very small volume near the pumping facet of the laser crystal in longitudinally pumping system, resulted in thermal lens and strong aberrations at the pumping facet. Low temperature reservation of the pumping facet and the crystal body could be adopted to relieve thermal effects and improve laser performance. This can be done by using diffusion bonding of doped laser crystal to a non-doped crystal [6–9], functioning as a heat sink for the pumping surface, which was first shown in end pumped Neodymium doped yttrium aluminum garnet (Nd:YAG) laser [10,11].

Neodymium doped yttrium orthovanadate (Nd:YVO₄) crystal has attractive laser performance which is much better than those of widely used Nd:YAG crystal such as broad absorption peak, large stimulated emission cross section, linearly polarized output, etc. However, the problem of thermally induced effects in Nd:YVO₄ crystal is much more significant as it has lower thermal conductivity than Nd:YAG crystal.
The aim of the present paper is to investigate theoretically and experimentally the impacts of the non-doped crystal on doped laser crystals in a Nd:YVO₄/YVO₄ composite crystal end-pumping by a diode laser. The temperature distribution and thermal lens in the composite crystal was numerically analyzed and compared with that of Nd:YVO₄ crystal. The end-pumping Nd:YVO₄/YVO₄ composite crystal laser was set up and tested with z cavity for evaluating the above calculation. The maximum output power of 9.87 W at 1064 nm and 6.14 W at 532 nm, respectively. The theoretical model and experimental results show that the end-pumping composite crystal laser ensure much higher power stability over the single Nd:YVO₄ crystal laser.

2. Theoretical simulation

In this section, the finite element method was first adopted to simulate the thermal effects in Nd:YVO₄/YVO₄ composite crystal and Nd:YVO₄ crystal longitudinally pumped by a fiber coupled diode laser while laser operation. Then the optical path difference for the paraxial beam propagating through the crystal was calculated and the focal length of the composite crystal was finally analyzed at different incident pumping power.

The Nd:YVO₄/YVO₄ composite crystal in Fig. 1 used in this experiment was provided by Coretech Crystal Co. The dimensions of the a-cut doped Nd:YVO₄ and non-doped YVO₄ crystal are 4×4×7 mm³ and 4×4×4 mm³, respectively. One end facet of the YVO₄ crystal was anti-reflectively (AR) coated at 808 nm and high reflectively (HR) coated at 1064 nm, the other end facet of Nd:YVO₄ in the bonded crystal was AR coated at 1064 nm. The crystal was wrapped with indium foil and fitted into a water-cooled copper housing which was maintained at a constant low temperature during laser operation. The cooling package was shown in Fig. 2, where b and c were the side lengths of the composite crystal.

The steady state temperature profile in the crystal is expressed by the three dimensional Possion equation as below:

\[ K_x \frac{\partial^2 T(x,y,z)}{\partial x^2} + K_y \frac{\partial^2 T(x,y,z)}{\partial y^2} + K_z \frac{\partial^2 T(x,y,z)}{\partial z^2} + q(x,y,z) = 0 \]  

(1)

where \( q(x,y,z) \) – the thermal density arising from the pumping power and \( K_x, K_y, K_z \) – the heat conductivity of the crystal along x, y, z orientations.

The thermal density \( q(x,y,z) \) was assumed to be same as the shape of the pumping light absorption under a non-divergent pump beam, which could be expressed as Gaussian function along the resonator axis in the crystal [10]

\[ q(x,y,z) = \frac{2Q\pi}{\pi\omega_p^2} (1 - e^{-2z})e^{-2[(y-z)^2 + (y-z)^2]/\omega_p^2} e^{-2z} \]  

(2)

where \( Q \) – the total thermal load, \( z \) – the absorption coefficient, \( \omega_p \) – the Gaussian beam waist of pumped light, and \( l \) – the laser crystal length.

In our theoretical analysis, Eq. (1) can be solved numerically by Dirichlet method [12]. Part of the absorbed pumping energy was assumed to transfer into heat dissipated locally in the laser crystal due to the quantum defect mechanism. The copper heat sink around the periphery of the composite crystal was cooled by water at a constant temperature. Considering that the thermal conductivity of the heat sink is much greater than that of the crystal, the temperature at the surrounding surfaces of composite crystal was supposed to be the same as water temperature at 293 K. In addition, as the surface convection coefficient is much higher than that of the end facet exposed to air, the thermal boundary condition at both of the end facets are supposed to be adiabatic. Thus the boundary conditions are:

![Fig. 1. Nd:YVO₄/YVO₄ composite crystal.](image1)

![Fig. 2. Water cooling setup for crystal.](image2)
The thermal distribution in the Nd:YVO₄/YVO₄ composite crystal was numerically calculated at the pumping power of 18 W and the pump beam radius of 0.32 mm. For all calculations the mesh was chosen with 40 × 40 elements in the x–y section and 110 along the z axial direction. Under the same condition, we also calculated a conventional Nd:YVO₄ crystal with dimension of 4 × 4 × 7 mm³ as a comparison with the composite laser crystal. The parameters of Nd:YVO₄ crystal were $K_x = 5.23$ K/m, $K_y = 5.10$ K/m, $K_z = 5.10$ K/m, $\alpha = 14.8$ cm⁻¹. Figs. 3 and 4 show the calculated results.

The highest temperature in the Nd:YVO₄/YVO₄ composite crystal and Nd:YVO₄ were 425 and 640 K, leading to the temperature rising of 136 °C and 351 °C, respectively. The inhomogeneous temperature distribution in crystal leads to stress, strains and displacement of the crystal, which resulted in the changes of refractive index inside the crystal. For light propagating along the resonator axis, the beam distorted and variation of wavefront appeared. Leads to stress, strains and displacement of the crystal, respectively.

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Fig. 5. Thermal distortion distribution of Nd:YVO₄ and Nd:YVO₄/YVO₄ composite crystal at the pumped facets with pump power of 18 W.

Fig. 6. The OPD in Nd:YVO₄/YVO₄ crystal at different pump power versus x with y = 0.

Fig. 7. The focal length of thermal lens in Nd:YVO₄/YVO₄ composite crystal at different pump power.

Fig. 8. Schematic of the Nd:YVO₄/YVO₄/KTP green laser.

Fig. 9. Radii of the fundamental mode TEM₀₀ spot at 1064 nm versus the incident pump power.

Fig. 10. Average output power at 1064 nm and 532 nm as a function of incident pump power.
length of the thermally induced lens numerically obtained at different pumping power.

3. Experiment

In order to verify our theoretical investigation, a 4-mirror folded cavity was adopted in this experiment to investigate laser performance for Nd:YVO4/YVO4 composite crystal. Fig. 8 shows the laser setup. The a-cut Nd:YVO4/YVO4 composite crystal has a Nd³⁺ concentration of 0.5 at.%. Flat mirror M1 coated on YVO4 crystal acted as one resonator mirror. The second-harmonic generator KTP crystal was 4 × 4 × 11 mm³, and AR coated both at 1064 nm and 532 nm. M₂ and M₃ were HR coated at 1064 nm with radii of curvature of 20 cm and 10 cm, respectively. The output coupler M₄ was a flat mirror HR coated at 1064 nm and AR coated at 532 nm. Both of Nd:YVO₄/YVO₄ and KTP crystal were water cooled. The Nd:YVO₄/YVO₄ composite crystal was end-pumped by a fiber coupled diode laser at 808 nm. The pump beam was compressed to a spot at the radius of 0.32 mm on interface of the laser crystal.

The cavity parameters were rationally optimized based on the above analysis. The length of three arms, L₁, L₂ and L₃, were 280 mm, 200 mm, and 110 mm, respectively. The total cavity length should be about 600 mm.

Considering the thermal effects in laser crystal, the TEM₀₀ mode radii inside the Nd:YVO₄/YVO₄ composite crystal and KTP can be calculated by [14]

\[
\omega = \frac{\sqrt{2B}}{\pi} \left[1 - \frac{(A + D)}{2}\right]^{-1/4}
\]

(9)

where \(\lambda\) was the oscillating wavelength.

Fig. 9 shows the relationship between the available incident pumping power and the TEM₀₀ mode radii. As the pump power rising, the TEM₀₀ mode radii had remained at 300 μm, approximately equal to the pump beam waist of 320 μm.

In order to test the fundamental laser performance, a flat mirror M₃ with transmission of T = 10% at 1064 nm was employed to substitute for M₄ and KTP crystal, as showed in Fig. 8. Fig. 10a shows the relationship between the output power at 1064 nm and the incident pumping power. The maximum output power of 9.87 W at 1064 nm was obtained at the pumping power of 16.5 W, corresponding to the highest optical–optical conversion efficiencies up to 60%.

Fig. 10b shows 532 nm laser performance for z cavity setup. The oscillation threshold was about 1.2 W, the maximum power of 6.14 W green laser was obtained at the incident pumping power of 16.5 W. The highest optical–optical conversion efficiencies was up to 40% at the pump power of 13 W.

The green laser operated at TEM₀₀ mode while raising the LD pumping power. The output power fluctuation \(\Delta P\) of the lasers was tested with LP-3C power meter at 1064 nm and 532 nm while the incident power operated at 13 W. The laser powers in Table 1 were measured at a time interval of 10 min for one hour.

\[
\Delta P = \left[\frac{\sum_{i=1}^{n} (P_i - \overline{P})^2}{n}\right]^{1/2}
\]

The instability \(\Delta P/\overline{P}\) of the lasers at 1064 nm and 532 nm were 0.18% and 1.88%, respectively.

4. Conclusion

In summary, thermal effect in LD end-pumping laser had been fully investigated numerically and experimentally in this paper. The heat deposition in Nd:YVO₄ crystal and Nd:YVO₄/YVO₄ composite crystals were analyzed and compared, the laser performance was tested to verify our results. A diode end-pumping Nd:YVO₄/YVO₄ composite crystal fundamental laser and green laser were designed to investigate the thermal model. The maximum output power of 9.87 W at 1064 nm and 6.14 W at 532 nm were obtained at the pumping power of 16.5 W. The highest optical–optical conversion efficiency were 60% at 1064 nm and 40% at 532 nm, respectively.

Acknowledgements

This work is supported by the Science and Technology Research Fund of Shandong Province (031080125). The authors would like to appreciate for the support from Science and Technology Board of Shandong Province.

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