Optics Communications 282 (2009) 981–984

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High-efficiency $Nd:YVO_4$ laser emission under direct pumping at 880 nm

Xin Ding [a,b,*], Rui Wang [a,b], Heng Zhang [a,b], Xuan-Yi Yu [c], Wu-Qi Wen [a,b], Peng Wang [a,b], Jian-Quan Yao [a,b]

[a] College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, 92, Weijin Road, Nankai District, Tianjin 300072, PR China
[b] Key Lab. of Opto-electronics Information Science and Technology, Ministry of Education, Tianjin 300072, PR China
[c] College of Physics Science, Photonics Research Center, Nankai University, Tianjin 300071, PR China

ARTICLE INFO

Article history:
Received 14 April 2008
Received in revised form 18 November 2008
Accepted 19 November 2008

Keywords:
All-solid-state
High-efficiency
Direct pumping
$Nd:YVO_4$ crystal

ABSTRACT

We report a high-efficiency $Nd:YVO_4$ laser pumped by an all-solid-state Q-switched Ti:Sapphire laser at 880 nm in this paper. Output power at 1064 nm with different-doped $Nd:YVO_4$ crystals of 0.4-, 1.0- and 3.0-at.% under the 880 nm pumping was measured, respectively. Comparative results obtained by the traditional pumping at 808 nm into the highly absorbing $^4F_{5/2}$ level were presented, showing that the slope efficiency and the threshold with respect to the absorbed pump power of the 1.0-at.% $Nd:YVO_4$ laser under the 880 nm pumping was 17.5% higher and 11.5% lower than those of 808 nm pumping. In a 4-mm-thick, 1.0-at.% $Nd:YVO_4$ crystal, a high slope efficiency of 75% was achieved under the 880 nm pumping, with an optical-to-optical conversion efficiency of 52.4%.

1. Introduction

Excitation and lasing processes in solid-state lasers always result in heat generation within the laser material due to fundamental processes such as Stokes shift, quantum efficiency and parasitic effects including concentration quenching and upconversion. Heat generation would lead to thermal stress, stress birefringence and thermal-lens effect that could limit average output power and efficiency of laser emission, decrease the beam quality and the stability of the resonator. Many techniques were developed for dealing with the heat generation such as diffusion-bonded undoped end-cap composite rods [1], slab and disk [2,3] laser geometries, compensated resonator designs [4] and phase conjugation [5]. Recently, a direct pumping scheme, which was to pump Nd^{3+} ions directly into the $^4F_{3/2}$ upper lasing level, has attracted much attention for its advantages in increasing the slope efficiency and decreasing the heat generation.

The idea of direct pumping was first demonstrated in 1968 by Ross [6]. In last decade, more efficient Nd^{3+} lasers have been demonstrated. In 2000 [7], a Nd:YAG laser directly pumped by a Ti:Sapphire laser at 885 nm was achieved, the slope efficiency increased by 12% and heat generation suggested to be reduced by 40% compared with traditional pumping at 808 nm. A comparison of heat generation and laser performance of Nd:YAG oscillators pumped by Ti:Sapphire laser at 802 nm and 884.5 nm was reported in 2004 [8], the corresponding slope efficiencies were 52% and 57%. Moreover, the heat generated during lasing was found to be 27% lower with 884.5 nm pumping as compared to 802 nm pumping. In recent years, more efficient 885 nm diode-pumped Nd:YAG lasers with slope efficiencies of 61% and 63% were obtained [9,10]. Lupei et al. reported slope efficiencies with respect to the absorbed pump power of 67% for Nd:YAG under 885 nm diode-laser pumping [11] and of 70% for $Nd:YVO_4$ under Ti:Sapphire laser pumping at 879 nm [12]. Sato et al. reported a direct-pumped $Nd:YVO_4$ laser with 80% and 75% slope efficiencies with respect to the absorbed pump power under continuous-wave Ti:Sapphire laser and laser diode (with FWHM of $\sim$2.5 nm) pumping at $\sim$880 nm, respectively [13].

However, a problem for direct pumping is the low pump absorption efficiency, which limits the efficiency of the laser. Generally, adding a feedback system (lens–mirror combination) [14] and increasing the doping concentration of laser material were routine methods to enhance the efficiency. The latter was adopted in our experiment while the former was more complicated.

In this paper, a high-efficiency $Nd:YVO_4$ laser directly pumped by an all-solid-state Q-switched tunable Ti:Sapphire laser at 880 nm was experimentally demonstrated. Output power and heat generation for different-doped $Nd:YVO_4$ crystals under 808 and 880 nm pumping were measured and compared. Under direct pumping, a high slope efficiency of 75% and a maximum output power of 1.1 W were achieved in a 4-mm-thick, 1.0-at.% $Nd:YVO_4$ crystal while the incident pump power was 2.1 W, leading to an optical-to-optical conversion efficiency of 52.4%. For the 1.0-at.% $Nd:YVO_4$ crystal, the slope efficiency and the threshold with respect to the absorbed pump power increased by 17.5% and de-

* Corresponding author. Address: College of Precision Instrument and Opto-Electronics Engineering, Tianjin University, 92, Weijin Road, Nankai District, Tianjin 300072, PR China.
E-mail address: dingxin@tju.edu.cn (X. Ding).

0030-4018/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2008.11.054

creased by 11.5%, respectively, while heat generation decreased by 27% under 880 nm than those of 808 nm pumping.

2. Theory

The energy level diagram [12] of Nd:YVO_4 is shown in Fig. 1. Process A indicates the traditional 808 nm pumping. The laser active ions are pumped from the Z_1 sublevel of the $^4I_{9/2}$ ground-state level to the $^4F_{5/2}$ level, and then relax to the $^4F_{3/2}$ upper lasing level with heat generation. Process B indicates the 879 nm direct pumping which is to pump laser active ions from the Z_1 sublevel of the $^4I_{9/2}$ ground-state level directly to the R_2 sublevel of the $^4F_{3/2}$ level without relaxation process while the process C indicates the laser emission of 1064 nm.

A rate equation describing the inversion density of Nd^{3+} ions at the $^4F_{3/2}$ level under a steady state can be written as [15]

$$dN(r,z)/dt = \sigma_p I_p(r,z)[N_o - N(r,z)]/h\nu_p - \sigma_e I_e(r,z) \times N(r,z)/h\nu_e - N(r,z)/\tau_f(N_0) = 0 \quad (1)$$

where subscripts p and e represent the pumping and laser beams, respectively; r is the transverse radial coordinate; z is the coordinate along the axis of the laser propagation; $N(r,z)$ is the inversion density; N_0 is the Nd^{3+} concentration in units of ion/cm^3; σ_j ($j = p,e$) are the cross sections of the absorption at the pumping wavelength and the emission at the laser wavelength, respectively; $I_j\,(r,z)$ is the beam intensity; h is the Planck constant; ν_j denotes the beam frequency and $\tau_f\,(N_0)$ is the fluorescence lifetime of the $^4F_{3/2}$ level as a function of Nd^{3+} concentration N_0 and describes the effect of concentration-dependent fluorescence quenching. Accordingly the output power and the slope efficiency for incident pump power can be expressed as follows:

$$P_{out} = \frac{P_p \lambda_p T[1 - \exp(-2\sigma_p N_0 L)]}{\lambda_e (2 - T)(\delta L - \ln\sqrt{1 - T})} \quad (2)$$

$$\eta_{in} = \frac{\lambda_p T[1 - \exp(-2\sigma_p N_0 L)]}{\lambda_e (2 - T)(\delta L - \ln\sqrt{1 - T})} \quad (3)$$

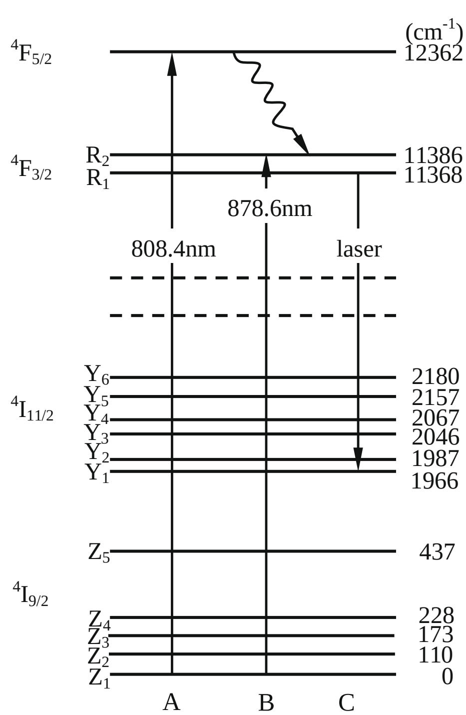

Fig. 1. The energy level diagram of Nd:YVO_4.

where P_p is the incident pump power; T is the transmission of the output coupler at the laser wavelength; δ is the internal loss of per unit gain medium length; L is the length of gain medium while λ is the wavelength. From Eq. (3), the corresponding slope efficiency for the absorbed pump power is

$$\eta_{abs} = \frac{\eta_{in}}{1 - \exp(-2\sigma_p N_0 L)} = \frac{\lambda_p T}{\lambda_e (2 - T)(\delta L - \ln\sqrt{1 - T})} \quad (4)$$

Assuming that all the parameters in Eq. (4) except λ_p are invariable under different pumping wavelengths, we can deduce that the slope efficiency is proportional to λ_p. While for different doping concentrations, the slope efficiency is affect by the passive losses.

Moreover, the fractional thermal loading η_h (the fraction of the pump power that is dissipated as heat) can be expressed as follow [16]:

$$\eta_h = 1 - \eta_p[(1 - \eta_l)\eta_{qe}\eta_{qd}^f + \eta_l \eta_{qd}^l] \quad (5)$$

where η_p is the pump level efficiency (the fraction of the ions excited in the pump level that de-excite non-radiatively to the emitting level) and that is ~1 for the most important laser materials, and η_l represents the laser extraction efficiency; η_{qe} is the emission quantum efficiency and η_{qd} expresses the quantum defect ratio, the superscripts f and l of η_{qd} refer to fluorescence and lasing emission, respectively. For efficient lasing emission (i.e. $\eta_l \sim 1$), η_h is determined by $\eta_{qd}^l = \lambda_p/\lambda_l$. For the 1064 nm emission and pumping wavelength of 808 or 880 nm, η_h is 0.241 and 0.174, respectively. It was concluded that the heat generation could less ~28% under 880 nm pumping than that of 808 nm pumping.

3. Experimental setup

The experimental setup of the Nd:YVO_4 laser is shown schematically in Fig. 2. An all-solid-state Q-switched Ti:Sapphire laser with repetition rate of 6.8 kHz and a tunable range from 700 to 950 nm was used as the pump source. The maximum output power (measured with a laser powermeter: Molectron EPM1000) is 2.7 W at 808 nm and 2.5 W at 880 nm, respectively, with typical FWHM spectrum width of ~3 nm and pulse duration of 38.4 ns. F was a focus lens with the focal length of 150 mm, which was used to enhance the density of pump power and obtain good volume matching between the pump and oscillating beam. The pump beam of 808 or 880 nm was focused into the Nd:YVO_4 crystal with a waist spot radius of around 200 μm.

In the experiment, a plano-concave cavity was carefully designed. The plane-reflector mirror M_1 was high reflectivity ($R > 99\%$) coated at the lasing wavelength of 1064 nm and high transmission ($T > 99\%$) coated at the pump wavelengths of 808 and 880 nm. A plano-concave mirror M_2 with a curvature-radius of 220 mm was employed to obtain smaller waist spot of oscillating beam, with a transmission of 10% at 1064 nm. Three pieces Nd:YVO_4 crystals with the same dimensions of 3 mm × 3 mm × 4 mm and different doping concentrations of 0.4-, 1.0- and 3.0-at.%, respectively, were a-cut to obtain the high-gain π transition. Under the 880 nm pumping, the absorption efficiency is 78%, 86% and 93% for the 0.4-, 1.0- and 3.0-at.% Nd:YVO_4 crystals, respectively, while the pump power at 808 nm is almost totally absorbed for all the crystals. The Nd:YVO_4 crystal, both surfaces were antireflection (AR) coated at 1064 nm and high transmission ($T > 99\%$) coated at 808 and 879 nm, was wrapped in indium foil and clamped in a copper holder while the water temperature was kept at 15 °C. The maximum pump power for 808 and 880 nm pumping is 2.2 and 2.3 W after the focus lens, respectively.

To obtain high efficiency and better beam quality of 1064 nm emission, the mode-volume of the Nd:YVO_4 laser must be well matched with that of the pump laser in the Nd:YVO_4 crystal. More-