Vol 14 No 7, July 2005
1009-1963/2005/14(07)/1387-05

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

1.34μm Nd:YVO_4 high efficiency laser end-pumped by diode-laser of flat-concave cavity type*

Shang Lian-Ju(尚连聚)[a)b)†] and Ning Ji-Ping(宁继平)[a)]

[a)] *College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China*

[b)] *Department of Physics, Qufu Teachers' University, Qufu 273165, China*

(Received 3 December 2004; revised manuscript received 5 January 2005)

The parameters of 1.34μm Nd:YVO_4 laser end-pumped with flat-concave cavity are theoretically analysed. The analysis in this paper may be helpful to the designing of kindred lasers. The operation of 1.34μm Nd:YVO_4 laser end-pumped by a diode-laser with flat-concave cavity is achieved. The output power of 3.51W at 1.34μm and optical to optical conversion efficiency of 39.0% are obtained at the pump power of 9.0W.

Keywords: diode-laser, Nd:YVO_4 crystal, flat-concave cavity, round-trip matrices
PACC: 4255R, 4260B, 4260D

1. Introduction

Solid-state lasers pumped by diode-laser (DPSL) have many merits, which combine high efficiency, compact size, long life and high quality of light beam, etc. DPSL are very attractive sources in many applications such as the military, industry, medicine and research.[1] Many laser crystals are suitable for being pumped by diode-laser. Nd:YVO_4 crystal is especially favourable thanks to its good properties.[2,3] It has been the ideal gain medium of DPSL. The Nd^{3+} $^4F_{3/2}$–$^4I_{11/2}$ level transition produces 1.34μm laser. The stimulated emission cross section at 1.34μm is $(6\pm1.8)\times10^{-19}$cm^2, which is comparable with Nd:YAG crystal's (4.6×10^{-19}cm^2) at 1.06μm. Therefore it is easy to obtain 1.34μm laser output for a Nd:YVO_4 crystal. A 1.34μm laser is safe to the eye, and it is consistent with the low dispersive wavelength of silica fibre. The 1.34μm laser has wide applications in the field of laser medicine, fibre communication, laser sensing, and the pump source of mid-infrared parameter oscillator.[1,4] In recent years, the Nd:YVO_4 lasers of 1.34μm have been developed, but their efficiencies were relatively low.[5–9] We have designed the 1.34μm Nd:YVO_4 laser end-pumped by a diode-laser with flat-concave cavity on the basis of analysing some important parameters, and the efficiency is higher than what we have known. The research work of this paper is the continuation of our former series of work.[10–12]

2. Experimental setup

The experimental setup is shown in Fig.1. The diode-laser (LD) with output coupled fibre is SDL-3460-P6 module of SDL Corporation of USA, and its parameters are as follows: core diameter 600μm, NA 0.37, maximum power 16W and peak wavelength 808.9nm. The focal length of optics coupler is 35mm. Passing through the coupler, the pump beam waist radius is 120μm. The curvature radius of flat-concave mirror M_2 is 100mm. The Nd:YVO_4 crystal, which was grown in Institute of Physics, Chinese Academy of Sciences, has cuboidal shape of size 3mm×3mm×5mm. The length of light path through crystal is 5mm. Nd:YVO_4 crystal is cut along 'a' axis. Nd^{3+}-concentration is about 0.7at%. During experiment, we fix Nd:YVO_4 crystal to a copper clamp which is cooled by pure water. The temperature of cooling water is controlled by a Constant Temperature Water Circulator (HX-10555 model). The temperature controlling precision is $\pm0.2^\circ$C. In order to maintain close contact with the copper clamp, the sides of Nd:YVO_4 crystal are packed in indium slice. The thermal conductivity of indium slice is very good, therefore heat of the laser crystal can be transferred

*Project supported by the Foundation of Educational Committee's Second Level Item of Shandong Province, China.
†E-mail: shanglianju@yahoo.com.cn

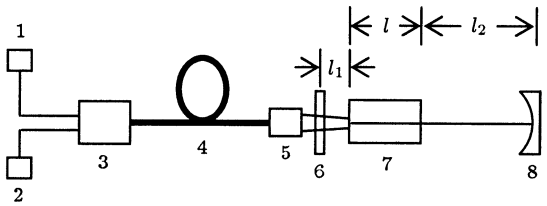


Fig.1. Setup of 1.34μm Nd:YVO_4 solid-state laser pumped by a diode-laser. (1) Electrical source of LD, (2) Temperature controller of LD, (3) LD, (4) Coupling fibre of LD, (5) Optical coupling system, (6) Flat mirror M_1, (7) Nd:YVO_4 crystal, (8) Flat-concave mirror M_2.

to the copper clamp, and then carried away by cooling water. In order to regulate the crystal's position accurately, we fix the cooling facility to a five-dimension regulator, which makes it easy to guarantee the pump light 'π' polarization to Nd:YVO_4 crystal, so the pumping can be very effective. In order to restrain the 1.06μm signal from oscillating, the input mirror M_1 has a thin film with high transitivity both at 1.06μm & 808.9nm and high reflectivity (>99.7%) at 1.34μm. The two ends of Nd:YVO_4 crystal have a thin film with high transitivity at 1.34μm to reduce the loss of reflection. The flat-concave mirror M_2 has a thin film with transfer ratio 5.3% at 1.34μm and high transitivity at 1.06μm, and it is the output coupled mirror.

3. Analysis of design scheme

3.1. Parameter selection of laser cavity

When laser operates on the edge of stable range of cavity, TEM_{00} mode is easy to obtain;[13] moreover, mode loss is less and mode volume is larger than that of a stable cavity, and the pumping threshold is not high. If the no-source cavity length is less than the radius of curvature of M_2 (which is 100mm), the resonant cavity is a stable cavity,[14] and the edge of its stable range is $L = R$. But when we put the Nd:YVO_4 crystal into the cavity, the stable range will lessen markedly. Therefore we need to determine the stable range of resonant cavity anew.

Now, let us see the stable-state condition of the resonant cavity. According to correlative theory of resonant cavity,[15] the side-axis light round-trip matrices are

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & l_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & l/n \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & l_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -2/R & 1 \end{bmatrix} \begin{bmatrix} 1 & l_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & l/n \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & l_1 \\ 0 & 1 \end{bmatrix},$$

where n is refractive index of laser crystal to signal light, and l is the length of light path in the laser crystal, and R is the curvature radius of M_2. According to the stable-state condition $\dfrac{|A+D|}{2} < 1$ of resonant cavity, we programmed the computer using C language to plot stable range graph of flat-concave cavity, where l_1 and l_2 are coordinate variables, and l=5mm, n=2.15, R=100mm. Figure 2 is the relevant stable range graph of flat-concave cavity.

Selecting optimal l_1 and l_2 is very important. In Fig.1, l_1 should be possibly minimal, because the resonant light waist is close to mirror M_1. But if l_1 is too small, there will be some inconveniences of adjusting mirror M_1 and laser crystal. So the value of l_1 is selected generally within the range between 3mm and 8mm. Appropriate selecting of l_1 and l_2 will satisfy our requirements. From the above analysis, we select l_1=5mm and l_2=61mm in our experiment.

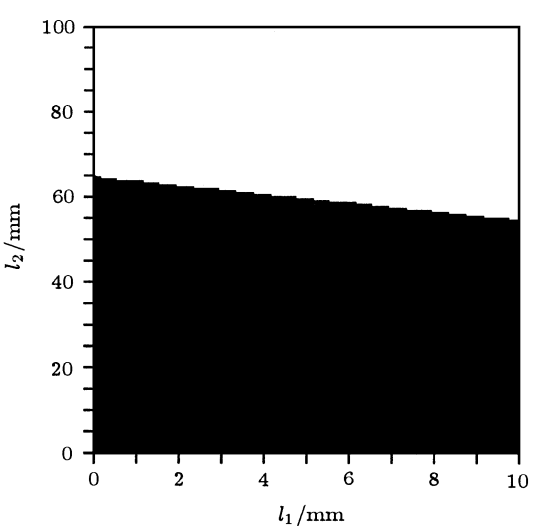


Fig.2. Stable range graph of flat-concave cavity.

3.2. Cavity mode size calculating of signal light

Because of the shortness of laser crystal length, the signal light beam radius $\omega_s(z)$ inside crystal is approximately equal to the size of signal light waist ω_{0s}. The formula of signal light waist of the flat-concave cavity is[3]

$$\omega_{0s} = [\lambda^2 L(R-L)/\pi^2]^{1/4},$$

where λ is the wavelength of signal light. $L = l_1 + l_2 + l$ is the cavity length. Using these data, we calculate that the value of ω_{0s} is 139μm. The size of signal light waist ω_{0s} can be the criterion of selecting cavity mode size of pump light when the questions about cavity mode matching are considered.

3.3. Cavity mode size selecting of pump light

The pump light beam radius $\omega_p(z)$ inside the crystal is also approximately equal to the size of pump light waist ω_{0p}. The value of ω_{0p} is selected in terms of the functional dependence of η_c on ω_{0p}. We define the overlap efficiency $\eta_c = \dfrac{J_1^2}{J_2}$, which influences the spatial overlap degree between pump light and signal light. Respectively, the simplified formulae[16] of J_1 and J_2 are

$$J_1 = \frac{2}{\pi L(\omega_{0p}^2 + \omega_{0s}^2)},$$

$$J_2 = \frac{4}{\pi^2 \omega_{0s}^2 L^2 (2\omega_{0p}^2 + \omega_{0s}^2)}.$$

According to the above two formulae and overlap efficiency, Fig.3 shows the influence of pump light waist ω_{0p} on the overlap efficiency η_c. The value of ω_{0p} should be appropriate while ω_{0s}=139μm. If ω_{0p} is too small, it would be not only easy to damage the laser crystal, but also possible to lower the coupled efficiency because of the larger divergence angle. If ω_{0p} is too large, the overlap efficiency would be also low, since the pumping energy can not be coupled effectively into the signal light mode volume. According to the relation shown in Fig.3, we select the value of ω_{0p}=120μm in our experiment. In this case, the overlap efficiency can reach 85% of the maximum. Furthermore, the pump waist ω_{0p} being comparatively large, the thermal effect is not obvious during operation. Such size selection of ω_{0p} not only guarantees the stabilization of laser operation, but also prolongs the life of laser crystal.

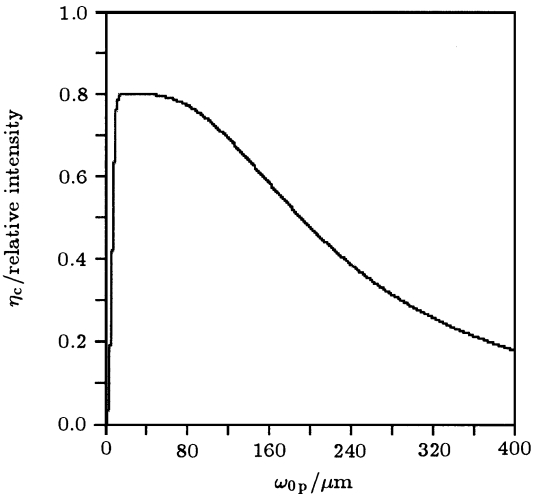


Fig.3. Overlap efficiency η_c as a function of pump waist ω_{0p}.

3.4. Determination of focus position of pump light

The focus position (distance between focus and crystal front surface) of pump light inside crystal influences pumping threshold directly, thus we determine the focus position of pump light according to the relevant relationship. Radiation of Nd:YVO_4 crystal has a typical course of four-level transition. According to the velocity function theory of a four-level system, the pumping threshold[16] is

$$P_{th} = \frac{h\nu_p}{\eta_t \times \eta_\alpha} \times \frac{1}{\sigma \tau_f} \times \frac{\delta n}{2L} \times \frac{1}{J_1},$$

where $h\nu_p$ is the pumping photon energy, η_t is the efficiency of optical coupler, η_α is the absorption efficiency of gain medium, σ is the stimulated emission cross section, τ_f is the fluorescent life of active medium, δ is the cavity's loss of back and forth, n is the refractive index of laser crystal to signal light, L is the cavity length, and J_1 is an overlap integral[4] between pump light mode and resonant light mode. Respectively, the theoretical formulae of η_α and J_1 are

$$\eta_\alpha = 1 - \exp(-\alpha_p l),$$

and

$$J_1 = \frac{2\alpha_p}{\pi L[1-\exp(-\alpha_p l)]} \int_0^l \frac{\exp(-\alpha_p z)}{\omega_p^2(z) + \omega_{0s}^2} \mathrm{d}z,$$

where α_p is the absorption coefficient of gain medium to pump light. Generally, the pump light beam radius $\omega_p(z)$ is $\omega_p(z) = \omega_{0p} + \theta\,|z - z_{0p}|$, where z_{0p} and θ are the focus position of pump light and the divergent angle of pump light, respectively.

The formula of pumping threshold indicates that the focus position of pump light has an optimal value

$z_{0p,s}$, which makes the pumping threshold minimal. According to the formula of pumping threshold, by means of numerical integration, we draw the function curve showing the influence of the focus position z_{0p} of pump light on the pumping threshold. The plot of P_{th} versus z_{0p} is shown in Fig.4.

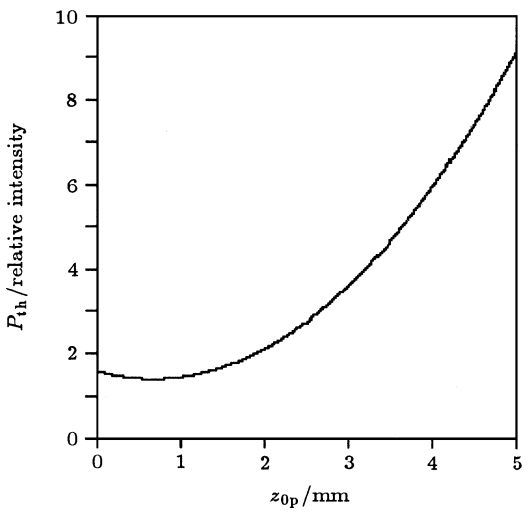


Fig.4. Pumping threshold P_{th} as a function of waist position z_{0p} of pump light.

From Fig.4, when other conditions are fixed, for the case of end-pumping, there is an optimal z_{0p} which makes the pumping threshold minimal. Using the parameters given above, by means of numerical calculation, we obtained the optimal focus position $z_{0p,s}$ of 0.7mm of the pump light.

4. Measuring scheme of output power

The 1.34μm output light beam includes the ingredient of pump light. It is general to adopt light filter or triple prism to filter out pumping ingredient. But the light filter cannot filter the pump light completely, and the loss of triple prism is high. Therefore the two methods are not suitable for measuring 1.34μm output power. In this experiment, we adopt an ingenious method which measures 1.34μm output power accurately. The measuring scheme is as follows. Firstly, we measure the output power directly as P_1. Power P_1 includes pump light power X_1 and 1.34μm light power X_2, where $P_1 = X_1 + X_2$. Secondly, we place a spare flat mirror of cavity between output mirror and power meter, which has a thin film with accurate transfer ratio T_1 at 808.9nm and T_2 at 1.34μm. And then we measure the output power as P_2, so there is $P_2 = X_1T_1 + X_2T_2$. Thirdly, basing on the equations of P_1 and P_2, we calculate 1.34μm light power $X_2 = \dfrac{P_1T_1 - P_2}{T_1 - T_2}$. During experiment, we measure the output power under any circumstances using the above scheme. The power meter we used is EPM-2000 model, USA, and power-level detectors are PM30V1 model with sensitivity 10mW / maximal applicable power 30W / spectrum range 0.19μm–6.0μm and PM3Q model with sensitivity 0.01mW / maximal applicable power 3W / spectrum range 0.19μm–11.0μm, respectively.

5. Experimental results and analysis

(1) Figure 5 shows the output power as a function of pump power.

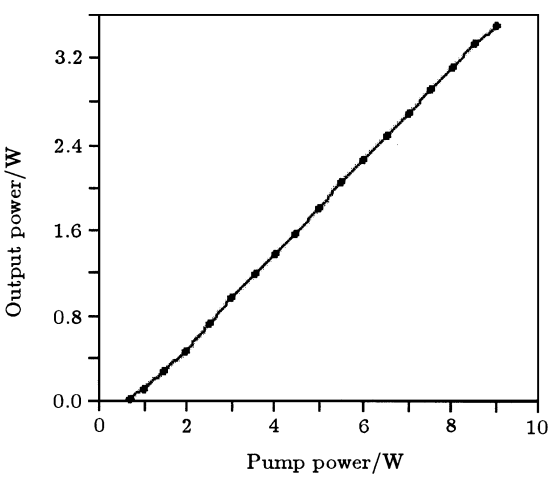


Fig.5. Output power as a function of input power.

(2) The pumping threshold is about 700mW, which is consistent with the theoretical calculation.[16] The output power of 3.51W at 1.34μm and optical to optical conversion efficiency of 39.0% are obtained at the pump power of 9.0W. The slope efficiency is about 42.3%. Simultaneously, we have confirmed that 1.34μm laser mode is a single TEM_{00}.

(3) We have measured the laser's operation stability for about 30 minutes, finding that the instability of output power is less than 1%.

(4) The output power of 3.51W is not the saturated maximum, so the output power may increase in case of increasing the pump power, but the stability and optical to optical conversion efficiency might decrease. We think that the output power of 3.51W is a nice level, which can satisfy a good many requirements.

(5) After finding a nicer scheme of solving thermal effect, we will increase pump power to increase output power; thereby the output power could be higher.

(6) We think the analysis in this letter may be of importance to designing the kindred lasers.

References

[1] Zhang H L *et al* 1998 *Acta Phys. Sin.* **47** 1579 (in Chinese)
[2] Wang C Q *et al* 1998 *Chin. J. Lasers* **25** 1129 (in Chinese)
[3] Wang C Q *et al* 1996 *Acta Opt. Sin.* **16** 1393 (in Chinese)
[4] Feng Y *et al* 2001 *Acta Phys. Sin.* **50** 335 (in Chinese)
[5] Wang J Y *et al* 1999 *Chin. J. Lasers* **26** 481 (in Chinese)
[6] Chen Y F *et al* 1999 *Opt. Commun.* **163** 198
[7] Agnesi A *et al* 2001 *Opt. Commun.* **194** 429
[8] Zhang H J *et al* 2002 *Opt. Lasers Eng.* **38** 527
[9] Zhang H J *et al* 2003 *Opt. Mater.* **23** 449
[10] Shang L J *et al* 2002 *Acta Phys. Sin.* **51** 2015 (in Chinese)
[11] Shang L J *et al* 2003 *Acta Phys. Sin.* **52** 1408 (in Chinese)
[12] Shang L J *et al* 2003 *Acta Phys. Sin.* **52** 2476 (in Chinese)
[13] Lan X J 2000 *Laser Technology* (Beijing: Science Press) p175 (in Chinese)
[14] Wang Q P, Zhang X Y, Zhao S Z 1993 *Laser Physics* (Jinan: Shandong University Press) p126 (in Chinese)
[15] Zhou B K, Gao Y Z, Chen J H 1995 *Principle of Laser* (Beijing: National Defense Industry Press) p29 (in Chinese)
[16] He J L 1998 *Doctoral Dissertation* (Institute of Physics, Chinese Academy of Sciences)