High-efficiency $Nd:YVO_4$ laser end-pumped with a diode laser bar

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ABSTRACT

Diode end-pumped solid-state lasers have the potential to yield high quality laser beams with high efficiency. However, its limited pump volume results in limited output power, usually under 1W. This paper presents a high-efficiency $Nd:YVO_4$ laser end-pumped by a 15W diode laser bar. An optical-optical efficiency as high as 42% and an output laser power of over 3W were obtained with a beam quality factor, M^2, of less than 1.2 and an output stability of ±0.5%. Theoretical calculations and experimental data showed that the pumping laser beam was well- matched to the intracavity laser mode.

Keywords: end pumping, $Nd:YVO_4$ laser, diode laser, beam quality, conversion efficiency, Q-switch

1. INTRODUCTION

Diode-pumped solid-state (DPSS) lasers are gaining acceptance in industrial applications due to the decreasing price and improving performance. It is reported that 4933 units were sold in 1998 and 6124 units are expected to be sold in 1999. This is an expected growth rate of 24%, twice that of flashlamp-pumped solid-state lasers in the same period[1]. It is expected that DPSS lasers will continue to penetrate the flashlamp-pumped solid-state laser market at a rapid rate, especially in low power systems (<20W).

The laser crystal can be pumped from the end or the side. End pumping can yield higher efficiency and higher beam quality with a more compact laser resonator, provided that the pump beam can be properly matched to the intracavity laser mode. However, the small beam size needed to pump the end surface of the crystal greatly limits the laser power that can be applied. Due to the fact that high power diode lasers are very asymmetric in their emitting aperture dimensions, with FWHM divergence angles of typically 30^o to 50^o in the fast-axis plane and 10^o to 25^o in the slow-axis plane[3], coupling of the diode beam to the laser crystal is a great challenge.

Recently there has been great interest in the $Nd:YVO_4$ crystal as a lasing media for low power DPSS lasers because of its large emission cross-section and high absorption coefficient over a broader pumping wavelength band. However, as its thermal conductivity is very low, thermally induced stresses as well as thermal lensing can be very serious in high power operation. The main specifications and applications of three typical Nd doped laser crystals are listed in Table 1[4].

2. LASER SET-UP

The schematic layout of the end-pumped $Nd:YVO_4$ laser with a fiber-coupled diode laser bar is shown in Fig. 1. The optical fiber cable is 1.5mm in diameter and has a maximum diode laser beam output of 15W. The beam from the fiber is collimated and focused onto a $Nd:YVO_4$ crystal. Both ends of the crystal are parallel. One end has a high-reflection coating for the 1064nm wavelength to function as a mirror for the resonator and an antireflection (AR) coating for the 808nm wavelength to allow the pump beam to enter the rod. The other end has an AR coating for the 1064nm. The resonator optics is plano-concave in configuration i.e. it consists of the planar rod surface and a concave mirror (output coupler) with a partial transmission coating to couple out the oscillating beam. Part of the laser beam is reflected into a laser beam analyzer by a beam splitter for laser beam quality measurement[5]. An alignment diode laser is used to align the laser resonator.

Table 1 Comparisons of YAG, YLF & Nd:YVO_4

	Nd:YAG	Nd:YLF	Nd:YVO_4
Lasing wavelength	1064nm, 1320nm	1047nm (π), 1053nm (σ)	1064nm, 1340nm
Full name	Neodymium yttrium aluminum garnet, Nd:$Y_3Al_5O_{12}$	Neodymium yttrium lithium fluoride, Nd:$YLiF_4$	Neodymium yttrium orthovanadate, Nd:YVO_4
Absorption bandwidth	10nm		21nm
Simulated emission cross section	$6.8\times10^{-19}cm^{-1}$		$20\text{-}30\times10^{-19}cm^{-1}$
Absorption coefficient	$3.4cm^{-1}$	$2.5cm^{-1}$	$13cm^{-1}$
Special features	High gain emission cross section, long fluorescence lifetime	Long fluorescence lifetime; Orientation effect; Gain bandwidth almost 3 times that of Nd:YAG; Lower thermal lensing & birefringence; Worse thermo-mechanical properties.	Short fluorescence lifetime; Orientation effect; Very high gain cross section; Very strong absorption and wide emission bandwidth; Low threshold; Poor thermal properties;
Applications	Q-switching, mode locking operation and intra-cavity frequency doubling	Q-switching and mode locking operation	Highly efficient laser operation, high repetition rate Q-switching and intra-cavity frequency doubling

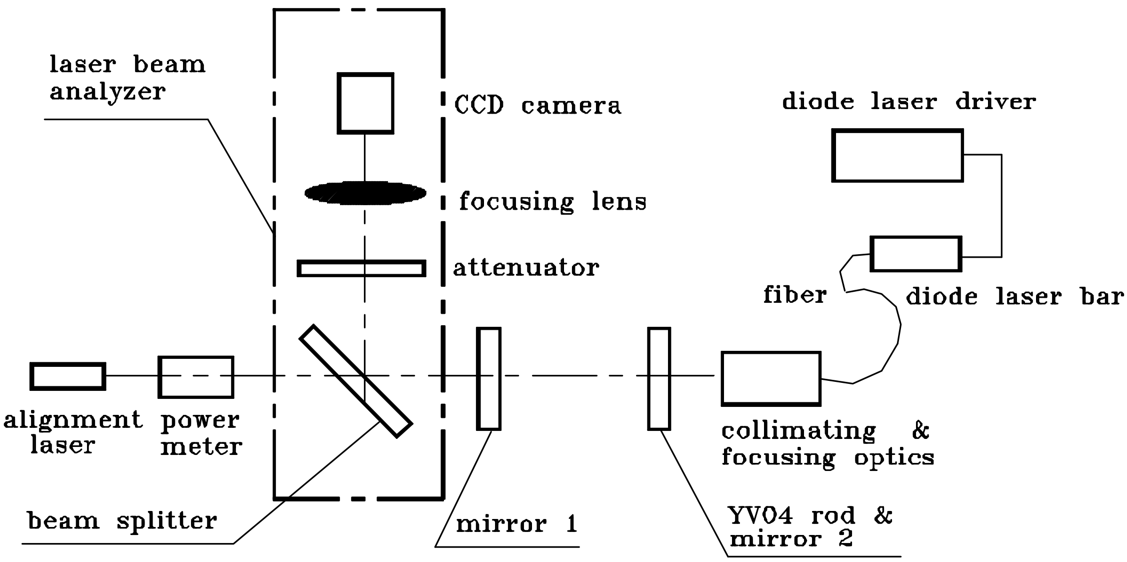


Fig. 1 Schematic layout of the fiber-coupled end-pumped Nd:YVO_4 laser

The collimating and focusing optics consists of two cemented doublets and a precision optimized aplanatic meniscus lens, as shown in Fig. 2. This configuration produces a smaller beam spot than when a single doublet is used, without lowering the performance. The first doublet is used to collimate the laser beam coming from the fiber, the exit surface of which should be placed in the focal plane of the first doublet. Using this system, the laser beam can be focused to a beam spot of 0.5mm in diameter.

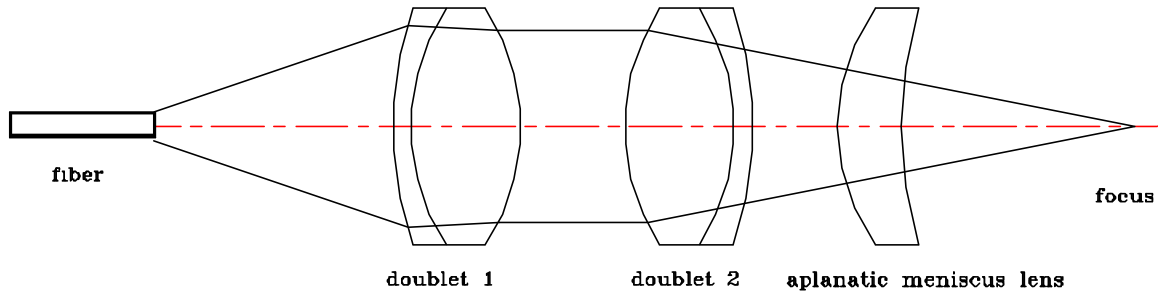


Fig. 2 Collimating and focusing optics

The Nd:YVO$_4$ crystal provided has a dimension of 5×3×3mm. The specified absorption coefficient is 9.6cm^{-1} for the wavelength of 808nm. The set up shown in Fig. 3 was used to measure the absorption coefficient of the crystal. The absorption coefficient is calculated by the formula

$$a = -\frac{\ln {I_T}/{I_0}}{l} \tag{1}$$

where α is the absorption coefficient, l is the length of the crystal, I_0 is the diode laser power from the fiber, and I_T is the transmitted diode laser power after the crystal.

It is found that the absorption coefficient varies slightly with pump power (within ±9.5%) and has an average value of 6.84cm^{-1}.

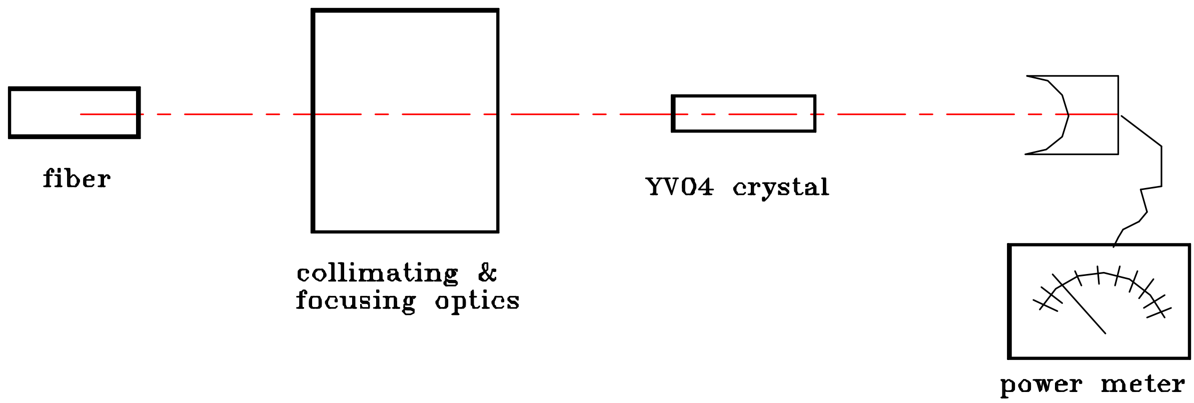


Fig. 3 Schematic set up for measuring absorption coefficient

3. EXPERIMENTS AND ANALYSES

3.1 Output power from the fiber-coupled diode laser

Fig. 4 shows the laser power output from the fiber-coupled diode laser bar as a function of pump current. The threshold pump current is 6.5A. It can be seen that the output laser power increases linearly with the pump current. The maximum power output is 15W when the pump current is 27A. The experiments also show that there is no obvious influence of the temperature of cooling water on the output power. However, the spectrum of the laser beam will shift with the temperature of cooling water at a rate of 0.3nm/^{o}C.

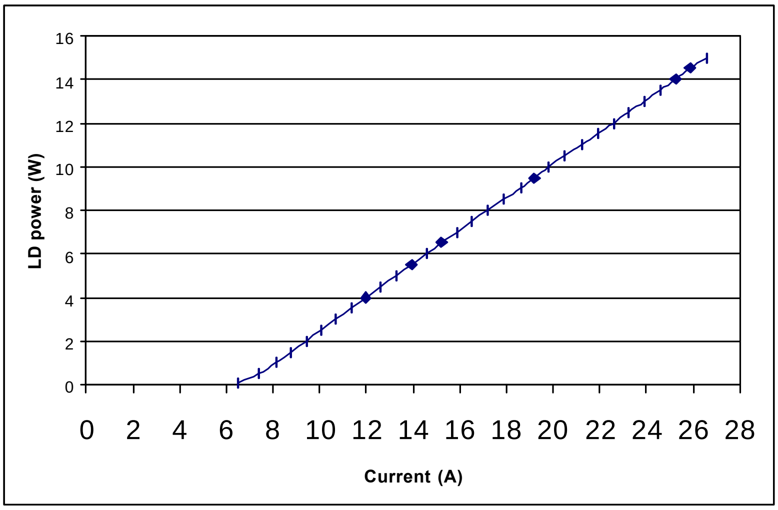
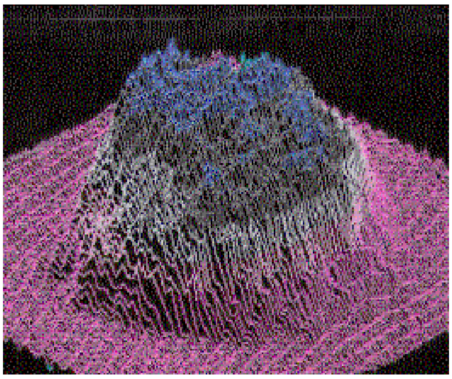
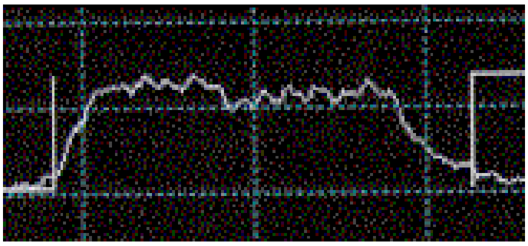


Fig. 4 Laser power output from fiber-coupled diode laser bar as a function of pump current

The beam energy distribution from the fiber-coupled diode laser has a top-hat profile, as shown in Fig. 5, with a beam divergence of more than 26mrad. It is focused by the collimating and focusing optics to a spot of 0.5mm diameter on the Nd:YVO_4 surface.



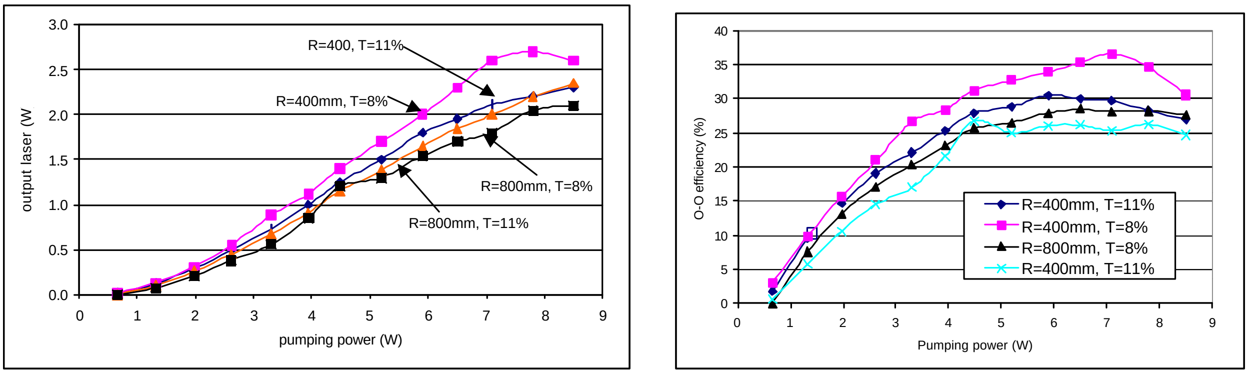


(a) 3D distribution (b) cross section distribution

Fig. 5 Energy distribution of the beam from the fiber

3.2 Nd:YVO_4 laser power

Figs. 6(a) and 6(b) show the output laser power and optical-optical (O-O) conversion efficiency as functions of pump power for the case where the resonator length is 74.5mm. They show that the optimum transmission and radius of curvature of the output coupler are T = 8% and R = 400mm respectively. The minimum pumping power necessary to produce an output is 600mW. The Nd:YVO_4 laser power increases linearly with the pump power until 7.1W. The corresponding slope efficiency is 45.8% and the optical-optical conversion efficiency reaches its maximum of 36.6% at the pump power of 7.1W. Beyond that, the Nd:YVO_4 laser power and its corresponding O-O conversion efficiency decrease with increasing pump power. The reason is believed to be due to serious thermal lensing effects[6].



(a) $Nd:YVO_4$ laser beam powers vs pumping powers (b) O-O conversion efficiencies vs pumping power

Fig. 6 $Nd:YVO_4$ laser beam powers and O-O conversion efficiencies vs pumping powers

The pump threshold of an end-pumped laser can be expressed as[7]

$$P_{th} = \frac{hn}{s_n t h_p} \bullet \frac{p}{2} \bullet \frac{d}{2} \bullet \left(w_p^2 + w_0^2\right) \tag{2}$$

where hν is the pump photon energy, σ_n is the net gain cross section, τ is the life time of the upper energy level of the $Nd:YVO_4$ crystal, δ is the loss of the resonator, η_p is the pump quantum efficiency, ω_p and ω_0 are the radii of the pump beam spot size and intracavity TEM_{00} mode size respectively. If the absorption of excited states is negligible[8], σ_n can be replaced by the simulated emission cross section σ_e.

The loss of the resonator is given by[7]

$$d = h_p \bullet \frac{l_p}{l_L} \bullet \frac{T}{h_s} \tag{3}$$

where λ_p and λ_L are the wavelengths of pump light and $Nd:YVO_4$ laser beam respectively, T is the transmission of the output coupler, and η_s is the slope efficiency.

Substituting Eq. (3) into Eq. (2), we get

$$P_{th} = \frac{phcT}{4 s_e t h_s l_L} \bullet \left(w_p^2 + w_0^2\right) \tag{4}$$

where c is the light velocity.

In our set up, T = 8%,
$\eta_s = 45.8\%$,
$\sigma_e = 25\times10^{-19}cm^2$,
$\tau = 90\mu s$,
$\lambda_L = 1064nm$,
$\omega_0 \approx \omega_p \approx 0.5mm$.

Substituting the parameters above into Eq. (4), the calculated threshold is 569.5mW, which is very close to the experimental threshold of 600mW. This shows that the pump beam is well matched to the intracavity laser mode.

3.3 Optimization of resonator parameters

The resonator parameters are critical in improving the laser beam quality. Fig. 7 shows the $Nd:YVO_4$ laser power as a function of pumping power at different resonator lengths, where R and T of the coupler are 400mm and 8%, respectively. The relevant laser beam quality parameters are shown in Table 2.

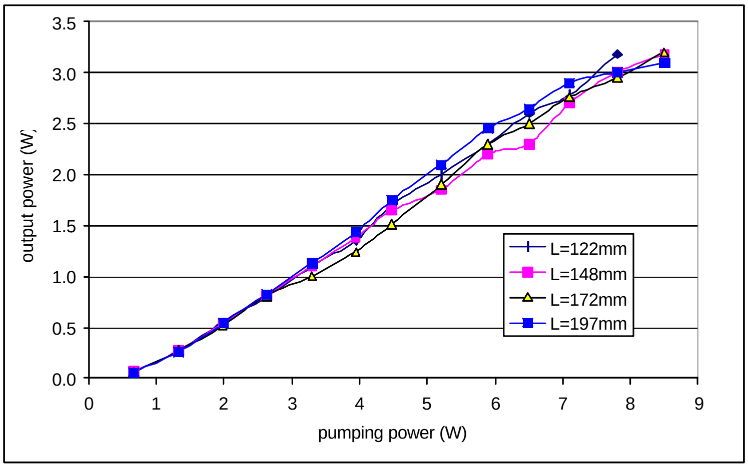


Fig. 7 $Nd:YVO_4$ laser powers vs pumping powers

Table 2 Laser beam quality parameters

Resonator length (mm)	122	148	172	197
M^2	2.32	2.06	1.99	2.09
Measured focus dia. (mm) (f=89mm)	0.217	0.197	0.236	0.205
Measured beam divergence (mrad)	2.44	2.21	2.65	2.30
Calculated TEM_{00} dia. (mm)	0.50	0.51	0.52	0.52
Calculated TEM_{00} beam divergence (mrad)	2.71	2.65	2.60	2.60

In order to further improve the laser beam quality, an output coupler with a radius of curvature of 800mm and a transmission of 8% is used. The measured M^2 and beam divergence are 1.19 and 1.74mrad, respectively. The calculated TEM_{00} beam diameter and divergence are 0.68mm and 1.98mrad, respectively. The dependence of the $Nd:YVO_4$ laser power output and O-O conversion efficiency on pumping power is shown in Fig. 8. The maximum O-O conversion efficiency is 42.19% at a pump power of 5.2W.

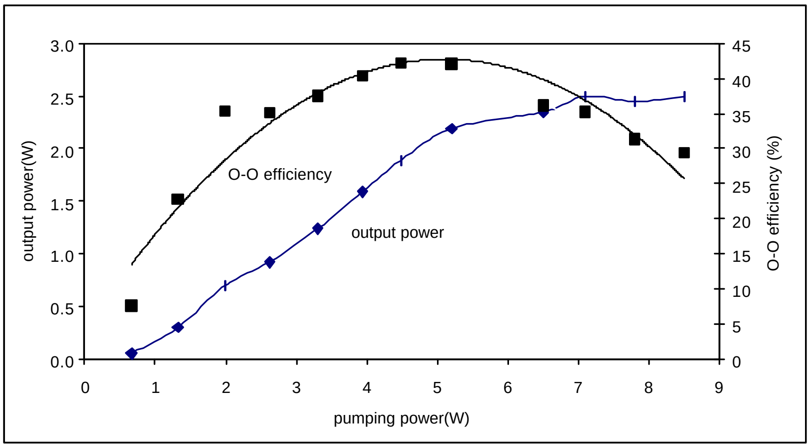


Fig. 8 Output powers and O-O conversion efficiencies vs. pumping powers

3.4 Influence of pumping beam size on output laser power

It is found that the output power and O-O conversion efficiency change with the spot size of the pump beam on the laser medium, as shown in Fig. 9. The resonator parameters used are: L = 74.5mm, T = 8% and R = 800mm. The calculated TEM_{00} beam diameter is 0.56mm.

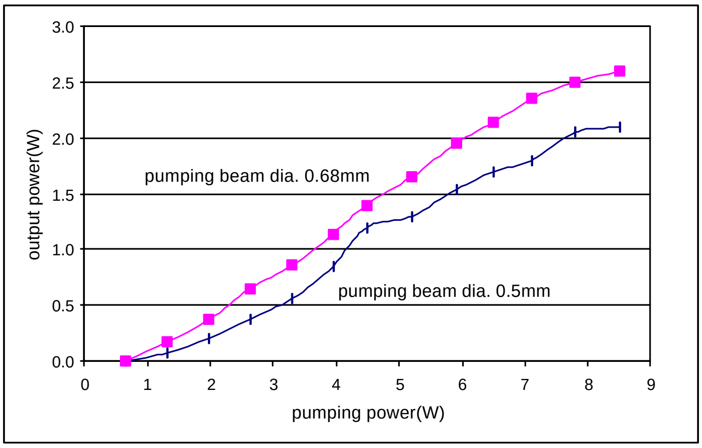
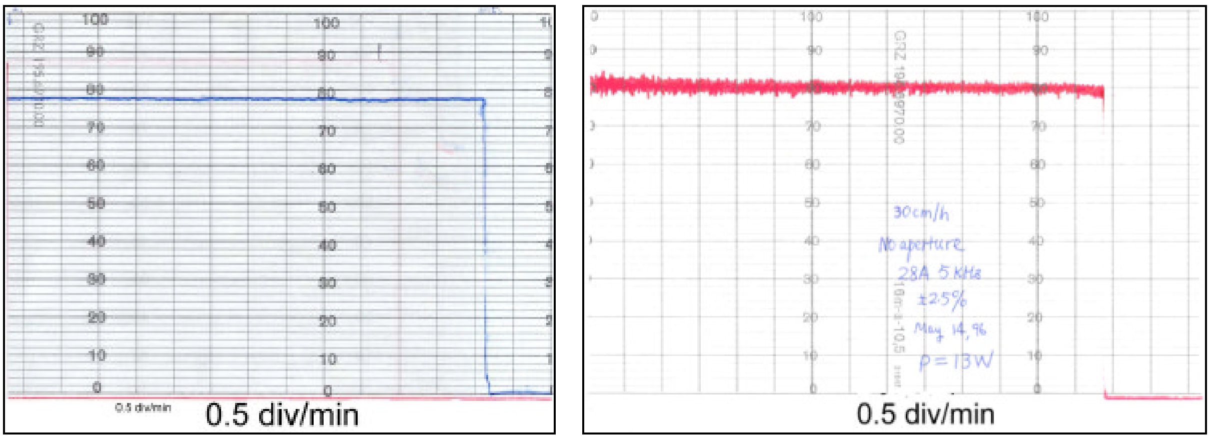


Fig. 9 Output laser power vs pumping power for different pumping beam diameters

It is also observed from Fig. 9 that the pump beam diameter should be slightly bigger than the TEM_{00} beam diameter of the resonator. Further experiments show that the laser beam is a multi-mode distribution if the pump beam diameter is too much bigger than the TEM_{00} beam size.

3.5 Laser power stability

The output laser power stability is shown in Fig. 10(a). It is observed that the power stability is within ±0.5%. In comparison, Fig. 10(b) shows the laser power stability of a flashlamp-pumped Nd:YAG laser at Gintic. Its power stability is about ±2.5%.



(a) Diode-pumped Nd:YVO_4 laser (b) A flashlamp-pumped YAG laser

Fig. 10 Comparison of laser power stability between a diode-pumped Nd:YVO_4 laser and a flashlamp-pumped YAG laser

3.6 Q-switched laser pulse width

An A-O Q-switch element is used in the diode-pumped $Nd:YVO_4$ laser[9]. The laser pulse width at a pulse repetition rate of 10kHz is 25ns as shown in Fig. 11. The output laser power is 0.98W.

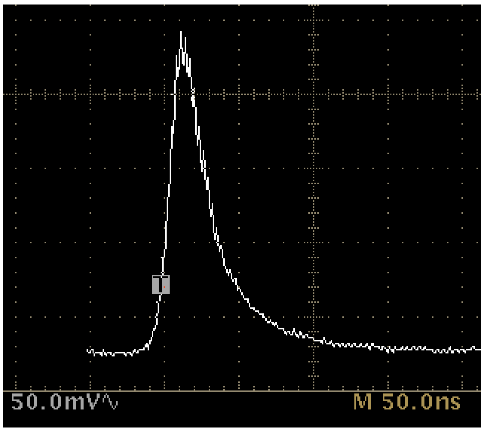


Fig. 11 Q-switched pulse shape

4. CONCLUSION

An efficient $Nd:YVO_4$ laser end-pumped with a fiber-coupled diode laser has been developed. An average output power of 3W has been obtained from the laser with an optical efficiency of 42%, the beam quality factor M^2 of 1.19, and an output laser power stability of ±0.5%.

5. ACKNOWLEDGMENTS

The authors wish to acknowledge the support of National Science and Technology Board of Singapore and Hypertronics Pte Ltd and would also like to thank their colleagues in the Advanced Machining Group of Gintic Institute of Manufacturing Technology for their helpful discussion and technical assistance.

6. REFERENCE

1. S. G. Anderson, "Review and forecast of laser markets: 1999 – Part I", *Laser Focus World*, Vol. 35, No. 1, pp. 80-100, 1999.
2. G. Feugnet, C. Bussac, C. Larat, M. Schwarz, and J. P. Pocholle, "High-efficiency TEM_{00} $Nd:YVO_4$ laser longitudinally pumped by a high-power array", *Optics Letters*, Vol. 20, No. 2, pp. 157-159, 1995.
3. Y. F. Chen, C. F. Kao, C. L. Wang, and S. C. Wang, "Optimization in scaling fiber-coupled laser-diode end-pumped lasers to higher power: influence of thermal effect", *IEEE J. of Quantum Electronics*, Vol. 33, No. 8, pp. 1424-1429, 1997.
4. C. Pfistner, R. Weber, H. P. Weber, S. Merazzi, and R. Gruber, "Thermal beam distortion in end-pumped Nd:YAG, Ng:GSGG, and Nd:YLF rods", *IEEE J. of Quantum Electronics*, Vol. 30, No. 7, pp. 1605-1615, 1994.
5. Y. H. Chen, "Studies on laser design and laser micro-machining", PhD thesis of Nanyang Technological University, p. 70, 1998.
6. A. S. Asundi, Pen Xioayuan, Chen Yihong, Xiong Zhengjun, G. C. Lim, and Zheng Hong Yu, "Study of the thermal effects of diode end-pumped $Nd:YVO_4$ solid-state laser", Proc. of SPIE, Vol. 3898, 1999
7. T. Y. Fan and M. R. Kokta, "End-pumped $Nd:LaF_3$ and $Nd:LaMgAl_{11}O_{19}$ lasers", *IEEE J. of Quantum Electronics*, Vol. 25, No. 8, p.1845, 1989.
8. W. Koechner, *Solid-state laser engineering*, 3rd edition, Spronge-Verlag, pp. 381-413, 1992.
9. Y. H. Chen, S. C. Tam, W. L. Chen and H. Y. Zheng, "Application of the Taguchi method in the optimization of laser micro-engraving of photomasks", *International Journal of Materials and Product Technology*, Vol. 11, No. 3/4, pp. 333-344, 1996.