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# Efficient end-pumped Q-switched 1053 nm Nd:YLF laser with a plane-parallel resonator

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ABSTRACT

In this study, a compact and efficient Nd:YLF laser at 1053 nm has been reported without inserting optical intracavity element to suppress the stronger line of 1047 nm. According to theoretical analysis and calculation, the thermal focal length of 1047 nm is negative while that of 1053 nm is positive in plane-parallel resonator. Hence 1053 nm laser was stable in this cavity. In our experiment, 7.5 W laser output at σ-polarized 1053 nm has been obtained with optical–optical efficiency of 38.8%. As the pulse repetition rate is 20 kHz, the pulse width is 50 ns and the peak power is calculated to be 7.5 kW.



## 1. Introduction

Compared with other neodymium (Nd) laser crystals, such as Nd:YAG, Nd:YAP, Nd:$YVO_4$, and Nd:$GdVO_4$, Nd:YLF crystal has some unique advantages. First, it has a long lifetime of the upper laser level (480 μs), resulting in high energy storage [1]. Second, its natural birefringence is far more than thermally induced birefringence, thus inhibiting the thermal depolarization. Furthermore, the 1053 nm from Nd:YLF laser matches well with the wavelength of peak gain of the Nd-doped phosphatic glass, which makes it a wonderful source laser in a system of amplifiers [2]. In recent years, the Nd:YLF crystal has been widely applied in the Master Oscillator Power-Amplifier (MOPA), high-energy pulse, continuous wave picosecond and mode-locked laser etc. [3–5].

For Q-switched and amplifier applications, Nd:YLF is an attractive laser medium for near-infrared high power lasers because of its long storage lifetime [6]. Q-Switched Nd:YLF laser, as pump modulation of the optic parametric oscillator system, can achieve high parameter conversion efficiency [7]. Laser diode (LD) pumped Nd:YLF in Q-Switched operation can obtain short pulse width and high peak power, which has been widely used in optical data storage, laser range finder, nonlinear optical etc. [8].

The spectrum lines at about 1050 nm come from the $^4F_{3/2}$–$^4I_{11/2}$ transition in Nd:YLF crystal. The stimulated emission cross section of the 1047 nm transition ($1.8\times10^{-19}$ $cm^2$) is 1.5 times higher than that of 1053 nm ($1.2\times10^{-19}$ $cm^2$) [9]. The line of 1047 nm should be suppressed if the 1053 nm line is desired. B. Frei and J.E. Balmer had achieved 1053 nm by tilting the output mirror slightly from its optimum position [10]. J.M. Auerbach and R.L. Schmitt had achieved Nd:YLF laser operating at 1053 nm with a c-cut Nd:YLF rod [11]. Y.B. Zhang had selected the 1053 nm line by the method of coating film to add internal loss of 1047 nm spectral line [12]. Y.F. LÜ had inserted a prism inside the 1053 nm cavity to avoid the emission of 1047 nm [13]. Compared with the aforementioned several ways, we achieved the 1053 nm polarized laser with a very simple and compact cavity, which was designed on the basis of analyzing the thermal lens effect and stability for both 1047 nm and 1053 nm lines in plane-parallel resonator.

In our experiment an a-cut Nd:YLF crystal was chosen as laser medium. The positive or negative of the thermal focal lengths for both 1047 nm and 1053 nm was calculated to select the 1053 nm emission in a plane-parallel resonator. Efficient 1053 nm polarized laser was obtained in acousto-optical Q-switched operation. Under the absorbed pump power of 19.35 W, the output power was 7.5 W, with the optical–optical efficiency of 38.8% and the slop efficiency of 39.2%. When the average output power was 7.5 W with the pulse repetition rate of 20 kHz, the pulse width was 50 ns and the peak power was calculated to be 7.5 kW.

## 2. Theoretical analysis

In conventional practice, the laser crystal, which has thermal-lens effect, could be treated as an ideal thin lens with a certain focal length. The value of thermal focal length varies with pump power. Consequently, the variation of thermal focal length will lead to the changes of intracavity related parameters. In the meanwhile, it also affects the laser output characteristics, such as beam quality and

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**Table 1**
The basic parameters of Nd:YLF laser crystal.

| | |
|---|---|
| Thermal conductivity (*K*) | 0.063 W/cm × K |
| Thermal expansion coefficients (α) | $13.3\times10^{-6}\,K^{-1}(\pi)$; $8.3\times10^{-6}\,K^{-1}(\sigma)$ |
| Refractive indices (n) | $n_e=1.470$ (π); $n_o=1.448$ (σ) |
| Thermo-optical coeffecient (dn/dT) | $-4.3\times10^{-6}\,K^{-1}(\pi)$; $-2.0\times10^{-6}\,K^{-1}(\sigma)$ |
| Simulation emission cross section (σ) | $1.8\times10^{-19}\,cm^2$ (π); $1.2\times10^{-19}\,cm^2$ (σ) |

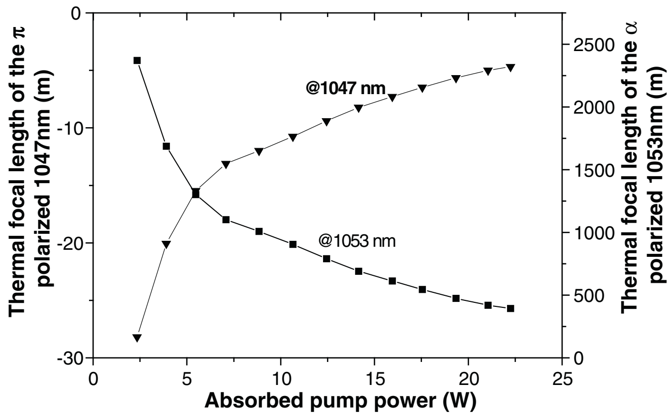


**Fig. 1.** The thermal focal length varied with absorbed pump power.

stability. So the research on the thermal focal length of laser crystal under different pump power plays a significant role in laser design and optimization.

The total thermal distortion of a laser crystal contains three independent effects. First part is the refractive index of laser crystal changing with the temperature (dn/dt). Second is the nonuniform expansion leading to stress in the crystal, called stress-induced birefringence. Third is the crystal expanding with temperature resulting longitudinal bulging. The second effect, the stress-induced birefringence, is of minor importance in YLF crystal, because of its strong natural birefringence [14]. So the influence on the thermal focal length for Nd:YLF crystal is described by:

$$f=\frac{KA}{P_a}\left(\frac{1}{2}\frac{dn}{dT}+\frac{\alpha r_0(n-1)}{L}\right)^{-1} \quad (1)$$

In this formula, *A* is the geometric cross section of the laser crystal; *Pa* represents the pump power that is transformed to heat in the laser crystal; L and $r_0$ are length and radius, respectively. These parameters are

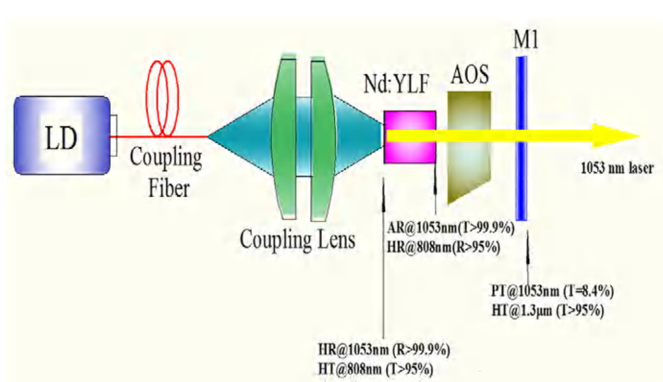


**Fig. 2.** The schematic diagram of the experimental setup.

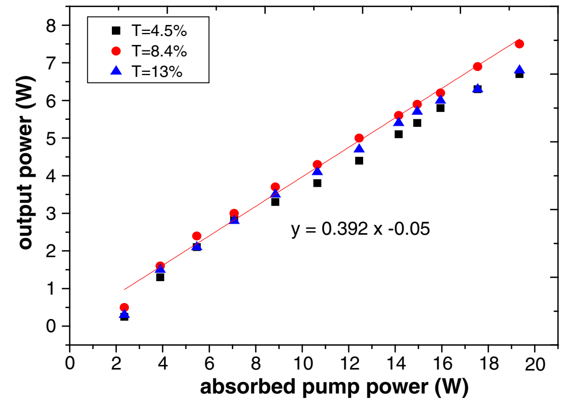


**Fig. 3.** Output power versus absorbed pump power.

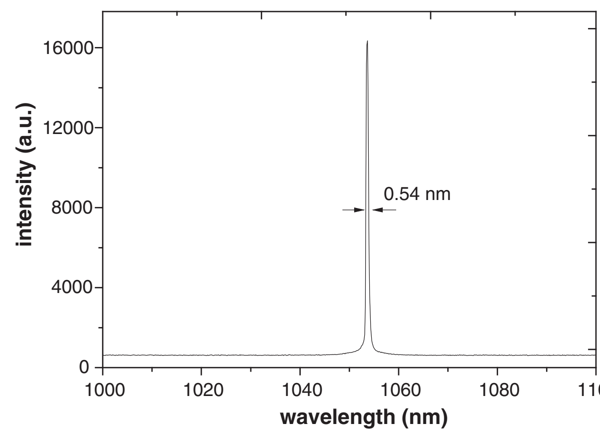


**Fig. 4.** The spectrum of 1053 nm.

listed in Table 1. A Nd:YLF crystal with a dimension of $4\times4\times10\ mm^3$ was selected in our experiment.

According to the calculation in our experiment, the thermal focal lengths varied with absorbed pump power are shown in Fig. 1. It can be found that the thermal focal length of 1047 nm is negative while that of 1053 nm is positive. As a result, the 1047 nm laser is unstable in plane-parallel resonator, but the 1053 nm laser remains stable with an a-cut Nd:YLF.

## 3. Experimental setup

The schematic diagram of the end-pumped Q-switched Nd:YLF laser system is shown in Fig. 2. According to the theoretical analysis above, a

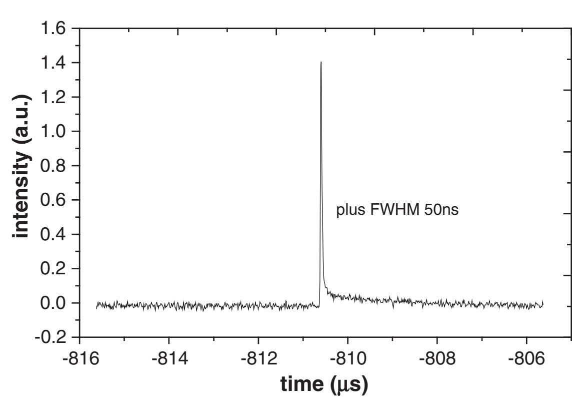


**Fig. 5.** The temporal profile of a single pulse.

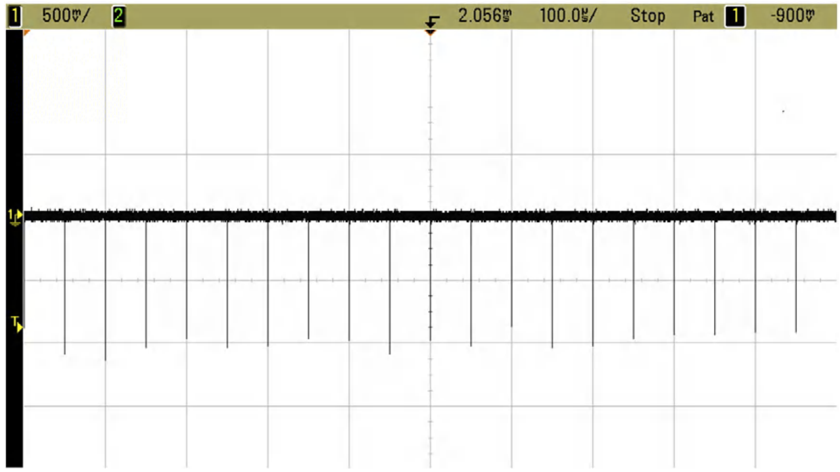


**Fig. 6.** The stabilization of the pulse train.

simple and compact plane-parallel cavity was exactly designed to obtain laser output at 1053 nm directly. The pump resource was provided by a fiber-couple laser diode at 808 nm, with 200 μm in core diameter, 0.22 in numerical aperture, and 27 W maximum output power. An optical system made of two achromatic lenses was employed in order to image the fiber end into the laser crystal. The laser crystal (from CASTECH.INC) was an a-cut 1.0 at.% doped Nd:YLF, with a dimension of $4\times4\times10\ mm^3$. The pumping side (S1) of the crystal was acting as input mirror of the resonant cavity, coating with antireflection (AR) at 808 nm and highly reflection (HR) at 1053 nm. The other side (S2) was coated with AR for 1053 nm, and HR for 808 nm as to increase the pump absorption efficiency. The crystal was wrapped with indium foil and mounted in a copper holder, which was kept at a constant temperature for 18 °C by a thermo-electric cooler. The acoustic-optic Q-switch (AOS, from Gooch & Housego Co.), with high transmission at 1.0 μm, was used for intra-cavity Q-switching operation. The output mirror was a plane mirror (M1), with a partial transmission (PT) at 1053 nm. The geometric cavity length was about 60 mm.

## 4. Results

The output power at 1053 nm, been a function of absorbed pump power under different output couplers, was measured with a laser powermeter (LPM-100). The experiment data w fitted by a linear curve as shown in Fig. 3. At the maximum absorbed pump power of 19.35 W, the output power was 7.5 W, with the optical–optical efficiency at 38.8% and the slop efficiency at 39.2%. It can be seen that the laser threshold was about 2 W for these three output couplers. But the maximum output power was obtained when the output coupler is T = 8.4%. Due to the thermal expansion of the laser crystal, the input face (S1) changes into a convexity. As the pump power increase, the deformation must be much stronger. Namely, the input mirror of the resonant cavity, the highly reflection film coated on S1, makes the resonant cavity a concave-flat cavity. Then the spectrum line of 1047 nm with negative thermal lens turns into its stable region in such a cavity. It will come out with the company of 1053 nm under the absorbed pump power higher than 20 W.

The spectrum of 1053 nm laser was measured by a grating monochromator (Model 1000 M, SPEX CertiPrep Group) with the spectral resolution of 0.1 nm. The measured spectrum was displayed in Fig. 4. It can be seen from it that the center wavelength locates at 1053.4 nm, which has a top-spike intensity distribution and the spectral width (Full Width at Half Maximum) was 0.54 nm.

During Q-switched operation, the temporal profile of a single pulse and the stabilization of the pulse train are shown in Figs. 5 and 6. Under the maximum average power of 7.5 W at 20 kHz, the pulse width was 50 ns and the peak power was calculated to be 7.5 kW.

## 5. Conclusions

In conclusion, we have demonstrated an efficient diode-end-pumped Q-switched Nd:YLF laser at 1053 nm using a configuration of plane-parallel resonator. The maximum output power of 7.5 W was achieved at the absorbed pump power of 19.35 W and the PRF of 20 kHz. The experiment data show that the optical–optical efficiency is 38.8% and the slope efficiency is 39.2%. Peak power of 7.5 kW was obtained with a pulse width of 50 ns. The AQ diode end-pumped 1053 nm Nd:YLF laser is compact and effective due to no elements for selecting wavelength inside the cavity.

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## References

[1] Zhe Ma, Jiancun Gao, Daijun Li, Junlin Li, Nianle Wu, Keming Du, Optics Communication 281 (2008) 3522.
[2] P.J. Hardman, W.A. Clarkson, G.J. Friel, M. Pollnau, D.C. Hanna, IEEE Journal of Quantum Electronics 35 (1999) 647.
[3] Y.F. Lü, X.D. Yin, J. Xia, L. Bao, X.H. Zhang, Laser Physics Letters 6 (2009) 860.
[4] R. Sarrouf, T. Badr, J.J. Zondy, Journal of Optics A: Pure and Applied Optics 10 (2008) 104011.
[5] Y. Louyer, F. Balembois, M.D. Plimmer, T. Badr, P. Georges, P. Juncar, M.E. Himbert, Optics Communication 217 (2003) 357.
[6] Z. Hengli, D. Li, P. Shi, R. Diart, A. Shell, C.R. Haas, K. Du, Optics Communication 250 (2005) 157.
[7] W. Żendzian, J.K. Jabczyński, J. Kwiatkowski, Opto-Electronics Review 17 (2009) 45.
[8] Y. Sun, H. Zhang, Q. Liu, L. Huang, Y. Wang, M. Gong, Laser Physics Letters 7 (2010) 722.
[9] T.M. Pollak, W.F. Wing, R.J. Grasso, E.P. Chicklis, H.P. Jenssen, IEEE Journal of Quantum Electronics 18 (1982) 159.
[10] B. Frei, J.E. Balmer, Applied Optics 33 (1994) 6942.
[11] J.M. Auerbach, R.L. Schmitt, Optics Letters 16 (1991) 1171.
[12] Y.B. Zhang, Y.X. Zheng, Y.H. Jia, D.P. Qu, Q. Zheng, L. Zhao, Laser Physics 20 (2010) 1580.
[13] Y.F. Lü, J. Lu, L.J. Xu, G.C. Sun, Z.M. Zhao, X. Gao, J.Q. Lin, Laser Physics Letters 7 (2010) 719.
[14] M. Pollnau, P.J. Hardman, M.A. Kern, W.A. Clarkson, D.C. Hanna, Physical Review B 58 (1998) 16076.