High Power Q-switched TEM$_{00}$ Nd:YVO$_4$ Laser with Self-Adaptive Compensation of Thermal Lensing Effect

H. Chen, Q. Liu, X. Yan, and M. Gong*

State Key Laboratory of Tribology, Center for Photonics and Electronics, Department of Precision Instruments, Tsinghua University, Beijing, 100084 China
*e-mail: gongml@mail.tsinghua.edu.cn

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Abstract—A high power dual-end-pumped Nd:YVO$_4$ laser with adaptive compensation of thermal lensing effect by adjusting HR mirror along the optical axis was proposed. In Q-switching operation at 70 kHz, the laser worked at different pump power (from 90 W to 70 W) with stable beam quality ($M^2$ ~ 1.15) and high output power (from 39 to 28.4 W), corresponding to the absorbed-output conversion efficiency of 55%. In the meantime, the pulse duration was increased from 24 to 31.7 ns. At various repetition rate from 60 to 100 kHz, the beam quality factors were all measured less than 1.2.

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1. INTRODUCTION

The high-beam-quality, high-average-power diode pumped solid-state laser (DPSSL) is attractive for a variety of applications in industrial and scientific fields, such as material micro-precision processing of marking, drilling, welding, cutting, spectroscopy, optical data storage, rapid prototyping, optical data storage, medical treatment, and so on [1, 2].

High beam quality is essential for micro-precision processing. In order to ensure the accuracy of processing, the best way is to obtain a TEM$_{00}$ laser output. However, the beam quality is affected by thermal lensing effect. To obtain TEM$_{00}$ laser output, some methods, including adding compensation lens, changing the end-face of gain medium and using dynamic stable resonator, have been utilized to restrict the effect of thermal lensing [3, 4].

Adding a negative lens which has the same absolute value of focal length with the thermal lensing, quite similar to the way of changing the end-face of gain medium, only makes a good compensation effect for a constant thermal focal length. When thermal focal length is changed, for example, in order to drilling holes of different depths by adjusting the pump power, it is difficult to achieve TEM$_{00}$ laser output under different pump power, due to the effect of overcompensation or undercompensation. Meanwhile, these methods also enhance the laser system’s complexity. In the traditional sense of dynamic stable resonator [5, 6], laser is fixed on working at the stable region to ensure the stability of laser mode radius in the gain medium, and thus a stable TEM$_{00}$ laser output is obtained.

As for the high-average-power diode end-pumped lasers, an alternative approach is proposed by exploiting the aberrated nature of thermal lensing to discriminate against unwanted transverse modes. This method to achieve this often refers to utilizing a stable resonator design, but laser operates close to the stability edge [7]. However, this is not a dynamic stable resonator. As the pump power being altered, laser will no longer work close to the stability edge. To solve this problem, some novel schemes of self-adaptive compensating for thermal lensing effect have been put forward, based on thermal effects themselves [8].

In 2008, Li et al. [9] reported an effective pulsed TEM$_{00}$ laser operation using a grown-together Nd:YVO$_4$/YVO$_4$ composite rod. A maximum average output power of about 10.5 W, a pulse width of 19.8 ns and a peak power of about 5.3 kW were achieved at 100 kHz. Gong et al. [10] presented a LD bar end-pumped Nd:YVO$_4$ slab laser, which used a simple coupling system and a compact quasi-concentric resonator. A TEM$_{00}$ output was obtained with the size of pump beam at the width direction of crystal varied from 2.57 to 9.44 mm and the slope efficiency was kept at about 48%. Chen et al. [11] presented a passively mode-locked TEM$_{00}$ Nd:YVO$_4$ oscillator generating 12 ps pulses with an output power of 1.7 W. The laser used an intra-cavity “White-cell” type multipass configuration, enabling a very compact set-up with a repetition rate as low as 16 MHz. In 2009, Yan et al. [12] reported a 32.1 W laser-diode-stack pumped acousto-optic Q-switched Nd:YVO$_4$ slab laser with hybrid resonator at 1064 nm. With the pumping power of 112 W, the beam quality $M^2$ factors in CW operation were measured to be 1.3 in stable direction and 1.6 in unstable direction.

In this paper, a thermal stable resonator with self-adaptive compensation of thermal lensing by adjusting the HR mirror along optical axis was proposed. In
CW/Q-switching operation, at full pump power of 90 W, a 42.1 W/39 W @70 kHz TEM$_{00}$ laser output was achieved corresponding to the absorbed pump power—output power conversion efficiency of 60.1%/55.7% respectively. As the pump power was decreased, the beam quality deteriorated and hence a non-TEM$_{00}$ laser beam. However, by adjusting the position of HR mirror along the optical axis, thermal lensing effect was compensated, and thus an output power adjustable, Q-switched, TEM$_{00}$ laser output with stable beam quality ($M^2 \sim 1.15$) and high absorbed-output conversion efficiency (~55%) was obtained.

2. EXPERIMENTAL SETUP

The experimental arrangement of the dual-end-pumped Q-switched Nd:YVO$_4$ laser with fiber coupled diodes is shown in Fig. 1. The thermally bonding Nd:YVO$_4$ crystal composed of two un-doped YVO$_4$ end caps ($3 \times 3 \times 2$ mm$^3$) and a $a$-cut, 0.3 at % doped Nd:YVO$_4$ laser crystal ($3 \times 3 \times 16$ mm$^3$), was used to reduce thermal lensing effect of high intensity pumping [13, 14]. This scheme of using end caps and low doping concentration can reduce the thermal loading density. This in turn, leads to a mitigation in the thermal lens aberrations, the likelihood of thermal fracture in the laser crystal for high intensity pumping and a reduction in the loss of pump power due to energy-transfer upconversion (ETU) [15–18]. A novel heatsink structure, in which thermally conductive silica gel was used as the bonding adhesive between laser crystal and copper heat sinks because of its thermal conductivity and flexibility, was proposed for further reducing thermal damage. Both surfaces of the laser crystal were coated with AR films at 808 and 1064 nm with the reflectivity of 1064 nm smaller than 0.1%.

The fiber-coupled laser diode modules of Jenoplik JOLD-45-CPXF-1L were applied as the pumping source in this experiment. The coupling fiber had a core diameter of 400 µm and a nominal numerical aperture (NA) of 0.22 (approximately 0.14 as measured). The temperature of the laser diode was controlled by temperature control unit, composed of temperature sensors and TEC, to obtain the best absorption. The 22.5 degree dichroic mirrors were antireflection coated at 808 nm and high reflection coated at 1064 nm. By adjusting the four-lens coupling-lenses system, the pump laser at 808 nm was focused into the crystal, and the mode radius and position in the crystal of the pump beam were optimized.

The quartz crystal, acoustic-optic Q-switch with the diffraction efficiency of about 80% and RF power of 20 W @ 40 MHz was utilized for intra-cavity Q-switching operation. The Q-switch was placed near the HR and set external trigger with adjustable duty cycle.

The HR mirror of the planar-planar cavity was a flat mirror with high reflector coated at the 1064 nm laser wave length and the output coupler used in the experimental system was also a flat mirror with a transmissivity of 38%.

To obtain high-average-power and high-beam-quality laser output, the cavity optics length of $L_1$ and $L_2$ is very important [19–22]. With the theory of resonant cavity [23], the cavity was optimized with $L_1 = 100$ mm and $L_2 = 150$ mm at full pump power. The laser mode radius varying with pump power presented by two axis-symmetrical U-shaped curves is shown in Fig. 2, from which we can see that, at full pump power of 90 W, the oscillator cavity operate close to the stability edge for the suppression of higher-order transverse mode oscillation.

The shape of two U-shape curves are determined by the longer one of the length of $L_1$ and $L_2$. The distance between two U-shape curves is dependent on the difference between $L_1$ and $L_2$ [24]. In the experiment, as the pump power was reduced, the laser no longer worked close to the edge of stable region. Considered $L_2 > L_1$, by the original optimum value, maintaining the length of $L_2 = 150$ mm $> L_1$ while increasing the length.

![Fig. 1. The schematics of the dual-end-pumped Nd:YVO$_4$ laser oscillator.](image1)

![Fig. 2. The laser mode radius varies with pump power in oscillator cavity.](image2)