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26W near diffraction limited Q-switched green laser based on a diode-end-pumped master oscillator power amplifier*

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An efficient acousto-optically Q-switched extracavity frequency-doubled 532nm laser based on a diode-end-pumped master oscillator power amplifier (MOPA) is demonstrated. With a type I non-critically phase-matched LBO, 26W of average power at 532nm in a near diffraction limited mode at a repetition rate of 30kHz was generated under 43W pump power of 1064nm Nd:YVO_4 laser, which correspond to a frequency-doubling conversion efficiency of 60%.

Keywords: frequency-doubling, diode end-pumped, green laser, master oscillator power amplifier
PACC: 4265K, 4260D

The generation of green laser light is very important in the applications of material processing, sensing, entertainment, pumping-sources etc. In particular, high power green laser with high beam quality is the ideal source for high-repetition-rate, non-linear frequency generation. For example, it is an ideal visible and ultra violet (UV) sources via harmonic generation and ideal Red Green Blue (RGB) and tunable infrared (IR) sources via parametric generation[1].With extra- or intracavity frequency doubling, laser diode (LD)-side-pumped configurations for 1064nm Nd: YAG or Nd: YVO_4 laser can generate high power 532nm laser, however, it was limited by low optical-to-optical efficiencies in TEM_{00} mode operation. End pumped geometries can provide much higher TEM_{00} efficiencies due to improved mode matching,[1−4] but scaling to higher power is difficult. Different designs have been investigated to obtain high output power and high beam quality generation of 532nm lasers.[2,4] By a dual Nd:YVO_4 rod, periodic resonator design and external frequency conversion, a 24W, TEM_{00} mode laser at 532nm was obtained.[2] In this paper, we designed a diode-end-pumped Nd:YVO_4 master oscillator power amplifier (MOPA) and with its efficient second harmonic generation (SHG) in nonlinear crystal LBO we obtained 26W near diffraction-limited quasi-continuous green laser. To the best of our knowledge, it is the highest output power in a near diffraction-limited mode for LD-end-pumped Q-switched 532nm laser.

The experimental setup for the green laser is shown in Fig.1. It consists of a MOPA and extracavity SHG system. The MOPA includes a master oscillator and two end-pumped amplifier stages. The pumping units of the oscillator and two amplifier stages were four fibre-coupled diode lasers with an output bundle of 0.4mm diameter and numerical aperture of less than 0.22. By controlling the temperature of the cooling water, we fixed the central wavelength of the emission at around 808nm.

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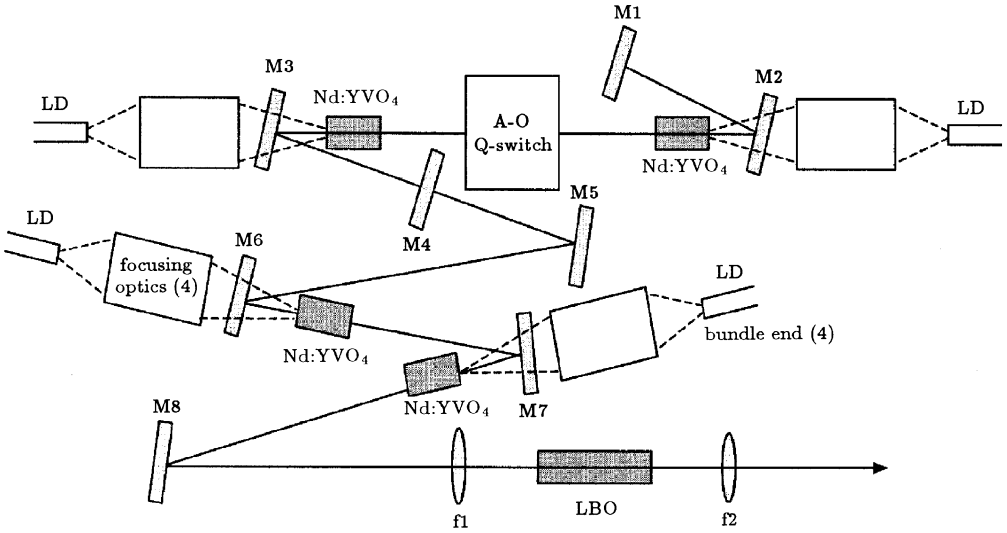


Fig.1. Configuration of the fibre coupled diode-end-pumped MOPA with external second harmonic generation in LBO. M2, M3, M6, M7 are dichroic mirrors (HT@808nm, HR@1064nm). M1, M5, M8 are high reflectors. M4 is output coupler. f1, f2 are focusing lenses.

The master oscillator utilizes a dual-end-pumped 'Z' resonator structure and its gain media are two Nd:YVO_4 crystals with 0.3 at% doping concentration and a size of 3mm×3mm×15mm. The effective thermal focal length of the laser crystal is given by[5]

$$f = \frac{\pi K_c^2 w_p^2}{P_h(\mathrm{d}n/\mathrm{d}t)}\left(\frac{1}{1-\exp(-\alpha L)}\right), \qquad (1)$$

where K_c is the thermal conductivity (W/(cm·K)); P_h is the fraction of pump power that results in heating; $\mathrm{d}n/\mathrm{d}t$ is the temperature derivative of index; w_p is the pump spot radius; α is the effective absorption coefficient and L is the length of the laser crystal. The heat generated by pump process P_h is mainly determined by the quantum defect and by nonradiative transitions from the upper laser level. Typically, for 1064nm generation, about 28% of the absorbed pump power P_{abs} is transferred into heat.[4] For 0.3 at% doped Nd:YVO_4 crystal, K_c=0.052W/(cm·K), $\mathrm{d}n/\mathrm{d}t$=3.0×10^{-6}/K, w_p=0.4mm, α=14/cm, L=15mm, we compared two symmetric flat–flat resonators with one and two Nd:YVO_4 crystals. In order to get high beam quality, we make the diameter of the Gaussian beam in the cavity a little smaller than the diameter of the pumping laser. Both resonators have a total cavity length of 600mm and the gain crystals absorb about 85% pump power. Figure 2 depicts the design of two resonators and the calculated Gaussian beam diameter in the Nd:YVO_4 as a function of pump power. From Fig.2 we can see that the symmetric resonators with two Nd:YVO_4 crystals have a larger stable range of pump power than that with one crystal. In addition, the configurations with two gain crystals can obviously decrease the possibility of thermally induced fracture.

In the experiment, two fibre-coupled laser beams are imaged into two Nd:YVO_4 crystals through two dichroic input mirrors M2 and M3 respectively as shown in Fig.1. An acousto-optic modulator with high diffraction loss was set between the two crystals to generate the repetition range from 1kHz to 50 kHz. The output coupler M4 has a transmission T= 60%. With configurations of this type we obtained high power and high beam quality 1064nm laser in a large range of pump power.

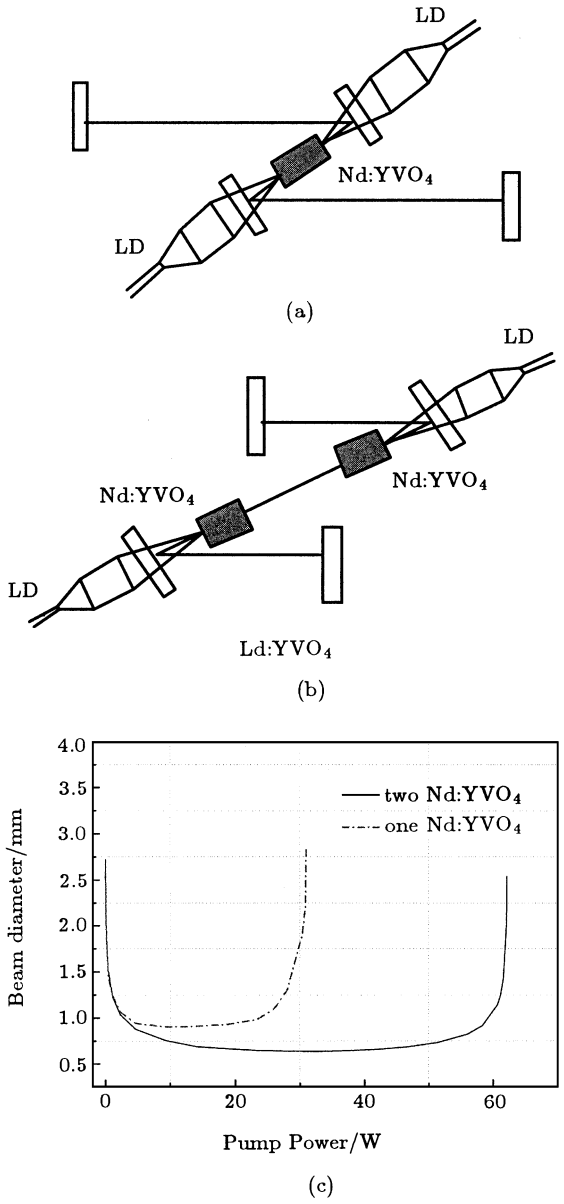


Fig.2. Calculated Gaussian beam diameter in the crystal as a function of pump power for two symmetric flat–flat resonators: (a), (b) the configurations of two oscillators with one and two Nd:YVO_4 crystals, respectively; (c) the calculated Gaussian beam diameter in the crystal as a function of pump power for two resonators. Both resonators have a total cavity length of 600mm and pump spot diameter of 0.8mm.

The output power of the master oscillator was measured by a power meter and the laser beam quality factor M^2 was determined by Laser Beam Analyser (model: M2-200-ACC-BB, Spiricon Inc.). Figure 3 depicts the oscillator's average output power as a function of the pump power at different repetition rates. The cw output power is also shown in Fig.3 for comparison. When the repetition rate was 30kHz and the pump power was 45.8W, we obtained an average output power of 19.8W with M^2 ~1.1 and a pulse width of about 22ns.

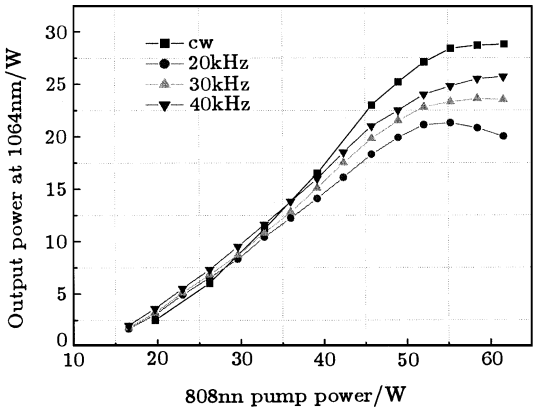


Fig.3. Cw output power and Q-switched average output power at 1064nm as a function of pump power at different repetition rates for the master oscillator.

The Q-switched master oscillator seeded two amplifier stages to increase the output power of 1064nm fundamental laser. The gain media of each amplifier stage was a Nd:YVO_4 crystal which was end pumped by a fibre-coupled LD. The strongly aberrated thermal lenses of the Nd:YVO_4 crystal will greatly affect the laser beam quality in the amplifier stages.[6–8] With one transmission through the lens, the beam quality factor M^2 after the lens is evaluated[9–11] by

$$M^2 = \sqrt{1 + M_{\mathrm{ab}}^2}, \tag{2}$$

and deterioration of the beam quality by aberration is determined by

$$M_{\mathrm{ab}}^2 = \frac{3\sqrt{2}\beta\gamma}{\lambda} P_{\mathrm{abs}} \left(\frac{w_{00}}{w_{\mathrm{p}}}\right)^4. \tag{3}$$

Here w_{00} is the radius of calculated Gaussian mode, w_{p} is the radius of pump spot. The thermal lens coefficient β is 0.08μm/W for Nd:YVO_4 crystals. To maintain beam quality factor M^2, the condition of $M^2 < 1.1$ leads to a requirement for the fill factor:

$$\left(\frac{w_{00}}{w_{\mathrm{p}}}\right)^4 < \frac{0.05\lambda}{\beta P_{\mathrm{abs}}\gamma}. \tag{4}$$

For pump profile shape factor γ of 0.1, Eq.(4) indicates that the beam radius w_{00} has to be 0.71 times the pump spot radius. In the experiment, we choose w_{p}=1.1mm and w_{00}=0.8 mm by appropriately imaging the laser beam and diode pumped beam. We obtained an amplified 1064nm laser with high beam quality. Table 1 shows the output power of amplifier stages at a repetition of 30kHz and a total output power of 43W was obtained for the MOPA with M^2 ~1.2 and a pulse width of 22ns.

Table 1. Output power of oscillator and amplifier stage from 1 to 2.

	oscillator	amplifier1 stage 1	amplifier stage 2
Pump power/W	45.8	29.8	28.5
Output power/W	19.8@30kHz	32	43

LBO crystal is frequently chosen as the SHG nonlinear crystal, but its conversion efficiency is limited by low effective nonlinear coefficient and short length. In this paper, the LBO crystal was cut for type I non-critically phase matching (θ=90°, ϕ=0°), so the walk-off angle was zero and we can use a long LBO (l=40mm) to improve the SHG conversion efficiency. Lens f1 with focal length of 75mm was used for focusing the pump beam into LBO crystal with a beam waist of around 51μm. We measured the output power of 532nm laser at different repetition rates and obtained a maximum output power of 26W at 30kHz for the 43W 1064nm fundamental laser, which corresponds to a high conversion efficiency of 60%. Figure 4 presents output power at 532nm as a function of repetition rate. At the maximum output power of 26W with the repetition rate of 30kHz, we measured the beam quality factor M^2 and the pulses width of 532nm laser. The beam quality factor M^2 was about 1.3. The pulse profile of 532nm laser was shown in Fig.5, from which we can see the pulse width was about 20.5ns.

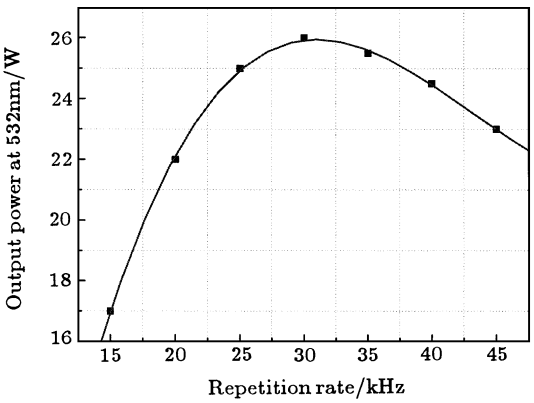


Fig.4. Output power of 532nm laser as a function of repetition rate.

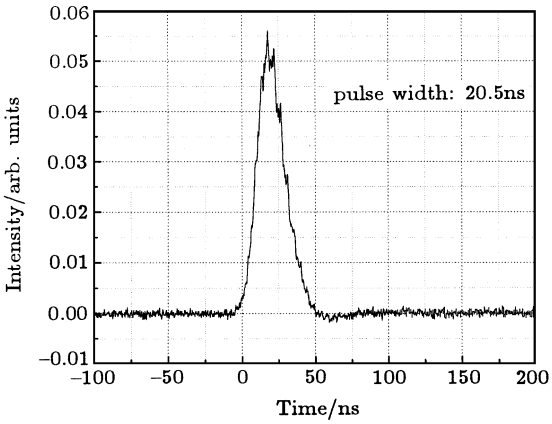


Fig.5. Q-switched pulse profile of 532nm obtained at 30kHz.

In conclusion, with a dual end-pumped two Nd: YVO_4 crystals maser oscillator and two appropriate mode matched amplifiers, we have developed an end-pumped MOPA that generates 43W high beam quality 1064nm laser. With a 40mm long type I non-critically phase-matched LBO, we obtained a 26W, near diffraction limited 532nm laser by extracavity frequency doubling. This is the highest power in a near diffraction-limited mode for Q-switched diode-end-pumped 532nm solid-state laser.

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