1. INTRODUCTION

Laser diode (LD) end-pumped high efficiency intracavity frequency-doubled green laser has aroused more and more attention because it has a broad range of applications, such as medical treatment, spatial communication, laser displays, holography, underwater remote sensing and pump sources for other laser systems [1–4]. Intracavity second harmonic generation (SHG) of Nd-doped crystal laser is the most frequently used approach to obtain high efficiency green beams.

Due to Nd:YVO\(_4\) crystal is broad absorption bandwidth and high absorption coefficient at the pump wavelength of 808 nm, it is of great advantage to LD pumped lasers [5, 6]. Additionally, Nd:YVO\(_4\) crystal with larger stimulated emission cross sections, that it is nearly five times larger than that of Nd:YAG crystal, will make a contribution to raise the conversion efficiency of fundamental frequency light [7–10]. As a gain medium suitable for low and medium power lasers, Nd:YVO\(_4\) has attracted much attention. In recent years, highly efficient intracavity frequency-doubled Nd:YVO\(_4\) lasers have been reported [11–13]. KTiOPO\(_4\) (KTP) crystal is an excellent SHG crystal. The gray trace of the defects inside crystal along the optical path will be observed when it is applied to frequency-doubled of the higher power density 1064 nm laser. So, it is often replace KTP with LBO in the high power lasers. But recent years, high gray-tracking resistance KTP (GTR-KTP) crystal has been developed for high power laser generation [14].

This paper introduces a LD pumped high efficient intracavity frequency-doubled green laser using a GTR-KTP as the frequency-doubled crystal. In our experiment, we have made the comparison of two kinds of Nd:YVO\(_4\) crystal that are 0.1 and 0.3-at % doped Nd\(^{3+}\) ions, respectively. The average power of 13 W at 532 nm was achieved at a pulse repetition rate of 80 kHz, corresponding to the optical-to-optical efficiency of 47.3%. The peak power is up to 5.42 kW.

2. THE HIGH GRAY-TRACKING RESISTANCE KTP CRYSTAL

There are many second harmonic generation nonlinear crystals, such as BBO, LBO, BIBO, KTP, etc. Table 1 showed the comparison of the phase matching (PM) parameters of BBO, LBO, BIBO, and KTP. We can see that BBO, KTP, and BIBO have much larger \(d_{\text{eff}}\) than LBO, the \(d_{\text{eff}}\) of KTP is more than four times larger for that of LBO, but the walk-off angle of BBO and BIBO are much larger than that of LBO and KTP. In addition, BBO has weak deliquescence, BIBO is a uniaxial crystal that has the comparatively bad symmetrical characteristic. So the KTP crystal possesses...
larger effective nonlinear coefficient, wider permitted phase mismatch angle, smaller walk-off angle, easy to achieve higher frequency-doubled efficiency, etc. It is the most commonly used material for frequency-doubled and optical parametric oscillation, particularly used in frequency-doubled of 1064 nm Nd:YAG, Nd:YVO₄ and other Nd doped lasers [17–19]. However, whether KTP crystal is grown by hydrothermal method or molten salt method, when it is applied to frequency-doubled of the higher power density 1064 nm laser, the gray trace of the defects inside crystal along the optical path will be observed. In the formation of gray trace region, the laser absorption of the KTP crystal in the range of visible and near-infrared wave band has a obviously increase, which will lead to serious crystal heating and cause it permanent damage, finally the second harmonic conversion efficiency is seriously influenced [14].

The GTR-KTP crystal (Fujian ChuangXin Science and Technology Develops Co., Ltd.) used in our experiment was grown by the modified TSSG method. The experiment reported in reference [20] indicates that the KTP crystal grown by modified TSSG method has higher gray-track resistance than that grown by flux grown method. The Sellmeier equations of the GTR-KTP crystals at 30°C can be written as:

\[
\begin{align*}
    n_x^2 &= 2.98781 + \left[ \frac{0.04531}{\lambda^2} - 0.02766 \right] - 0.00791\lambda^2, \\
    n_y^2 &= 3.02211 + \left[ \frac{0.04362}{\lambda^2} - 0.04381 \right] - 0.01323\lambda^2, \\
    n_z^2 &= 3.31237 + \left[ \frac{0.06091}{\lambda^2} - 0.05056 \right] - 0.01711\lambda^2.
\end{align*}
\]

Through relational calculation, the phase matching angle for type II SHG at 1064 nm of GTR-KTP crystal is \(\theta = 90^\circ\) and \(\Phi = 24.40^\circ\). The calculated results show that the \(\Phi\) value of the high grey-tracking resistance KTP is larger than that of regular KTP grown by the TSSG method [21].

### 3. EXPERIMENTAL SETUP

The experimental setup of the frequency-doubled green laser is illustrated in Fig. 1. The pump source is a 27 W fibre-coupled laser diode array at 808 nm wavelength with a core diameter of 200 \(\mu\)m and a numerical aperture of 0.22. Pumping laser through two plane-convex lens with the respective focal length of 30 and 60 mm was focused into the Nd:YVO₄ crystal. The output characteristics of 532 nm green light generated by using of two Nd:YVO₄ crystals (3 \(\times\) 3 \(\times\) 10 mm³) with 0.3 and 0.1-at % doped Nd³⁺ ions were compared in this experiment. The endfaces of both crystals are plane-parallel and well polished. One surface of them was coated with high transmission (HT, \(T > 95\%\)) at 808 nm and high reflection (HR, \(R > 99.9\%\)) at 1064 nm as the incident facet of the pumping laser and one resonator mirror of the laser cavity, which is available to reduce the insertion loss and shorten the cavity length. The other facets of the crystals were coated with 1064 and 808 nm antireflection (AR) film. The Nd:YVO₄ crystal was set on the focus point of the lens. The crystal was wrapped with indium foil and mounted in a copper block which was kept at about 20°C by a thermoelectric cooler. Acoustic-optic Q-switched (AOS, from Gooch & Housego Co.) with high transmission at 1064 nm was fixed in an adjustable mount. The mirror M2 is a second harmonic

<table>
<thead>
<tr>
<th>Crystal</th>
<th>PM type</th>
<th>(d_{\text{eff}}, \text{pm/V})</th>
<th>PM directions ((\theta, \Phi))</th>
<th>Walk-off angle, mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBO</td>
<td>o + o → e</td>
<td>2.01</td>
<td>(22.9°, 0°)</td>
<td>55.85 (for 532 nm)</td>
</tr>
<tr>
<td>LBO</td>
<td>o + o → e</td>
<td>0.832</td>
<td>(90°, 11.3°)</td>
<td>6.88 (for 532 nm)</td>
</tr>
<tr>
<td>BIBO</td>
<td>e + e → o</td>
<td>2.96</td>
<td>(168.9°, 90°)</td>
<td>25.6 (for 1064 nm)</td>
</tr>
<tr>
<td>KTP</td>
<td>e + o → e</td>
<td>3.58</td>
<td>(90°, 23.5°)</td>
<td>3.16 (for 1064 nm)</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental configuration for intracavity frequency-doubled Nd:YVO₄ laser using GTP-KTP.
reflective mirror coated with 532 nm HR \((R > 99\% )\) and 1064 nm HT film \((T > 99.5\% )\). Output mirror M1 is coated with 532 nm HT \((T = 95\% )\) and 1064 nm HR \((R > 99.9\% )\) film. The output couplers with plane mirror and concave mirror \((300 \text{ mm radius of curvature})\) have been experimentally investigated for comparison. The nonlinear crystal is KTP with II-type phase matched \((\theta = 90^\circ , \Phi = 24.4^\circ )\) cut for 1064 nm. The size of KTP crystal is \(3.5 \times 4.5 \times 8.0 \text{ mm}^3\) with polished plane-parallel endfaces and its both surfaces were AR \((T > 99.8\% )\) coated at 532 and 1064 nm. The length of the cavity should be as short as possible and the full cavity length is 10 cm in this experiment. The distance of M1 to M2 is 2.5 cm. The experimental setup was shown in Fig. 1.

4. EXPERIMENTAL RESULTS

The output characteristics of 532 nm green laser were experimentally investigated. The output characteristics of 532 nm green laser using different doping concentrations and cavity configurations were compared. The relationship between 532 nm average output power and 808 nm incidents pump power at 80 kHz repetition rate was shown in Fig. 2. It can be seen from it that the highest average power of 532 nm laser output is 13 W and the optical-to-optical efficiency is 47.3\% when using Nd:YVO\(_4\) crystal with 0.3-at \% of doping concentration and flat-flat cavity at the maximum 808 nm pumping power of 27.5 W. The corresponding slope efficiency is 51.1\%. Whereas if using Nd:YVO\(_4\) crystal with 0.1-at \% of doping concentration and plano-concave cavity, the output green laser power is the lowest. However, the lowest threshold of 532 nm output is 0.9 W using the configuration of plano-concave cavity and 0.3-at \% doped Nd:YVO\(_4\) crystal. The detail results of the experiment are listed in Table 2.

Figure 3 shows a scatter diagram of 532 nm output power versus AO Q-switch modulation frequency. With the increase of repetition rate, the trend of the diagram is a parabola. The optimum modulation frequency is about 80 kHz. In addition, the relationships between the pulse width of 532 nm output laser and repetition rate were also reported in Fig. 3. It can be seen from it that the pulse width of 532 nm output laser increases with the increase of the repetition rate. When the repetition rate is 80 kHz and 808 nm pumping power is 27.5 W, the output power of 532 nm green laser is up to 13 W. Its single pulse energy is 162.5 \(\mu\)J with the pulse half-height width of 30 ns and the peak

![](image1.png)

**Fig. 2.** Variation in the 532 nm green laser output power against the incident pump power.

![](image2.png)

**Fig. 3.** Average output power at 532 nm and pulse width versus pulse repetition rate.

<table>
<thead>
<tr>
<th>Doping concentrations</th>
<th>Cavity configurations</th>
<th>Average output, W</th>
<th>Optical-to-optical efficiency, %</th>
<th>Thresholds, W</th>
<th>Slope efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-at %</td>
<td>plano-concave</td>
<td>7.7</td>
<td>28</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>flat-flat</td>
<td>9.8</td>
<td>35.6</td>
<td>3.3</td>
<td>42.5</td>
</tr>
<tr>
<td>0.3-at %</td>
<td>plano-concave</td>
<td>11.5</td>
<td>41.8</td>
<td>0.9</td>
<td>44.1</td>
</tr>
<tr>
<td></td>
<td>flat-flat</td>
<td>13</td>
<td>47.3</td>
<td>1.9</td>
<td>51.1</td>
</tr>
</tbody>
</table>
Efficient 532-nm laser power is 5.42 kW. The temporal pulse profile of 532 nm light received by a PIN photodiode and displayed by a Model TDS3052B (500 MHz) dual-line oscilloscope was shown in Fig. 4.

Through compared experiments, we found that the influence of the doping concentrations of Nd\(^{3+}\) ions on the 532 nm output power is more important than that of the cavity configurations. No matter which configuration of cavity was adopted, the 532 nm average output powers obtained by 0.3-at % doped Nd:YVO\(_4\) crystal are higher than that obtained by 0.1-at % doped one. But the threshold power of the former is lower than the latter. Moreover, if the doping concentration of Nd:YVO\(_4\) crystal is the same, the 532 nm average output power obtained by using flat-flat cavity is higher than that using plano-concave cavity.

In addition, in order to make comparison, we take the KTP crystal away and use a plane output mirror with the transmission optimized for 1064 nm output (\(T = 13\%\) at 1064 nm) replaced the output mirror M2 in the previous experiment. With an input pump power of 27.5 W, the maximum average output power of 14.7 W at 1064 nm was obtained at a pulse repetition rate of 80 kHz. The optical-to-optical efficiency was about 54.5%. The average output power increases almost linearly with the pumping power, which is in favor of the 532 nm green light.

5. CONCLUSIONS

A LD end-pumped acoustic-optic Q-switched intracavity frequency-doubled Nd:YVO\(_4\) laser using a GTR-KTP as nonlinear optical crystal was demonstrated. The compared experiments of 532 nm green laser using a GTR-KTP and different doping concentrations laser crystals and cavity configurations were carried out. The average power of 13 W for 532 nm light with the optical-to-optical efficiency of 47.3% for 808 nm pump power to 532 nm was obtained by using a straight flat-flat cavity, 0.3-at % doped Nd:YVO\(_4\) crystal, and a GTR-KTP. The single energy pulse of 162.5 \(\mu\)J with half-height width of 30 ns, and the peak power of 5.42 kW was achieved. Under the same experimental conditions, the average power of 14.7 W 1064 nm light with the optical-to-optical efficiency of 53.5% was achieved when 808 nm incident pump power is 27.5 W. The results of the relationship between output power and pulse width and repetition rate were given in this experiment. This work is a significant exploration for using a GTR-KTP crystal to generate highly efficient SHG green laser.

ACKNOWLEDGMENTS

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REFERENCES