High power Nd:YAG lasers operating at 1.3 μm wave band

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Abstract

The laser properties of 1.3 μm spectral region in Nd:YAG crystal and their simultaneous dual wavelength threshold condition are investigated. Three types of high power 1.3-μm Nd:YAG quasi continuous wave (QCW) lasers, which operate at 1.319 μm or 1.338 μm single wavelength, 1.319 μm and 1.338 μm simultaneous dual wavelength, are achieved with a maximum average output power of 138 W, 132 W and 120 W, respectively.

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1. Introduction

High power lasers in the 1.3 μm spectral region are of great interest in the fields of medical applications and fiber optics, their advantages are not only low loss and dispersion in the quartz fiber, but also good absorption of water molecules and very good capability of blood hemostasis [1,2]. On the other hand, the frequency doubling of a 1.3 μm laser is also an attractive alternative for generating a red light or pumping tunable lasers such as Cr:LiSAF [3]. In addition, 1.3-μm multi-wavelength lasers are useful for the newly developed THz wave generation based on nonlinear optical difference frequency method [2].

The laser emissions at 1.3 μm wave band come from the 4F3/2–4I13/2 transitions of Nd3+ ion mainly, and it is well known that Nd:YAG crystal is the most common laser gain medium for its excellent laser characteristics physical, and chemical properties so far. The ratio of simulated-emission cross sections between 1.319 μm and 1.338 μm transitions is approximately unit as well as their branching ratios. As the strongest emission line of Nd3+ ion is 1.064 μm, it is rather difficult for both 1.319 μm and 1.338 μm wavelengths to obtain high power coherent radiation at single wavelength or simultaneous dual wavelength.

Many previous works were investigated on this field. A 122 W of CW output power at 1.319 μm from a diode-side-pumped Nd:YAG laser was reported in Ref. [3], transition lines other than 1.319 μm were suppressed by using a solid etalon. In Ref. [4], a diode-end-pumped simultaneous CW dual wavelength laser operating at 1.319 μm and 1.338 μm in a Nd:YAG crystal has been demonstrated, which achieved a total output power of 6.3 W at an absorbed pump power of 15 W with a slope efficiency of 43.5%. Additionally, in our previous work [5], a single wavelength 1338 nm Nd:YAG laser pumped with a Kr-lamp achieved a 102 W of average output power. In Ref. [6], a Nd:YAG rod was pumped by a laser diode-side-pumping module, and as high as 131 W and 109 W CW lasers at 1319 nm single wavelength and 1319 nm and 1338 nm simultaneous dual wavelength, respectively, were achieved at the pumping power of 555 W. Flash-lamp-pumped or diode-pumped, pulsed or CW multi-wavelength laser operations in Nd3+ doped materials, such as Nd:YAG [4–6,8], Nd:YLF [9], Nd:YVO4 [10,11], (Er, Nd); YAG [12], (Ho, Nd); YAG [13], Nd:GdVO4 [14], and Nd:YAP [15,16], have been previously reported. In this paper, through calculating the simultaneous dual wavelength threshold...
condition, coating the laser cavity at different wavelengths precisely and increasing Nd$^{3+}$ ions doping level and the length of Nd:YAG rod, we successfully developed three types of high power 1.3 $\mu$m wave band Nd:YAG quasi continuous wave (QCW) lasers pumped with a Kr-lamp. Among these lasers, 1.319 $\mu$m and 1.338 $\mu$m simultaneous dual wavelength lasers achieved an average output power of 120 W, and 1.319 $\mu$m together with 1.338 $\mu$m single wavelength lasers achieved 138 W and 132 W, respectively.

2. Analysis of dual wavelength threshold condition

In Ref. [15], the possibilities of simultaneous multiple wavelength lasing in various Nd host crystals have been analyzed first, and the simultaneous multiple wavelength lasing in a CW Nd:YAP laser at both 1.079 $\mu$m and 1.341 $\mu$m has been achieved for the first time. Further, Shen studied the operating condition of continuous wave simultaneous dual wavelength laser (SDWL) in neodymium host crystal based on the single longitudinal mode rat equation after considering the spatial hole-burning effects, and came to a conclusion that the thresholds of rat equation after considering the spatial hole-burning in $\mu$A will be achieved, otherwise, only $\lambda_1$ or $\lambda_2$ will lase. If all conditions given in Eq. (1) are satisfied, the simultaneous dual wavelength laser will be achieved, otherwise, only $\lambda_1$ or $\lambda_2$ will lase if only the left- or right-hand side of Eq. (1) is satisfied.

As for Nd:YAG crystal, the strongest emission line of Nd$^{3+}$ ion is 1.064 $\mu$m, the values of 1.319 $\mu$m and 1.338 $\mu$m stimulated-mission cross section are very close to each other and only 1/5 of that of 1.064 $\mu$m line. Some basic parameters of Nd:YAG crystal are listed in Table 1 [18–20].

<table>
<thead>
<tr>
<th>Wavelength $\lambda$ (nm)</th>
<th>1.319</th>
<th>1.338</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy level</td>
<td>$4I_{3/2}^{3/2} - 4I_{13/2} (R_2 - X_1)$</td>
<td>$4I_{3/2}^{3/2} - 4I_{13/2} (R_2 - X_3)$</td>
</tr>
<tr>
<td>Simulated-mission cross section $\sigma$ ($10^{-19}$ cm$^2$)</td>
<td>0.92</td>
<td>0.9</td>
</tr>
<tr>
<td>Frequency $v$ ($10^{14}$ Hz)</td>
<td>2.27</td>
<td>2.24</td>
</tr>
<tr>
<td>Cavity loss</td>
<td>0.151</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 1. The calculated corresponding reflectivities in Nd:YAG crystal according to Eq. (1), $R_1$ for 1.319 $\mu$m reflectivity and $R_2$ for 1.338 $\mu$m reflectivity.](image)

Shen et al. considered the situation of $P_{in} = 1.3 P_{th1}$ for operating condition of continuous wave SDWL [16], but the pump energy was set to be nearly twice that of the threshold energy in the computational model of Q-switch Nd:YAlO$_3$ dual wavelength laser in Ref. [17]. When focused on 1.3 $\mu$m Nd:YAG lasers operating in the state of quasi continuous wave (QCW), $P_{in}/P_{th1}$ is set to 2 in this work. According to Eq. (1) and Table 1, the reflectivity conditions for achieving single line or simultaneous dual-line laser of 1.319 $\mu$m and 1.338 $\mu$m can be calculated after restraining the 1.064 $\mu$m strong line. The calculated results are shown in Fig. 1. When the reflectivity conditions are set above Curve 1 or below Curve 2 in Fig. 1, the 1.319 $\mu$m or the 1.338 $\mu$m single line will lase, respectively. If the region of the selected reflectivity values locates between Curve 1 and Curve 2, the 1.319 $\mu$m and 1.338 $\mu$m dual wavelength lasing will appear simultaneously, which makes an important indication for the design of coatings.

3. Experiments and results

The experimental sketch of the 1.3 $\mu$m wave band Nd:YAG laser pumped with a Kr-lamp is shown in Fig. 2. The laser cavity consists of two plane mirrors, all-reflective mirror $M_1$ and output mirror $M_2$. The length of the cavity is 30 cm. The all-reflective mirror $M_1$ was coated...
with high reflectivity (HR, \( R > 99.6\% \)) coatings at 1.319 \( \mu \)m and 1.338 \( \mu \)m wavelengths and assumed the reflectivity of 100\%, hence the laser cavity reflectivities, which are the products of reflectivity values of \( M_1 \) and \( M_2 \) at different wavelengths, are actually those of output mirror \( M_2 \).

Based on the results depicted in Fig. 1, the output mirror \( M_2 \) was coated with different reflectivity coatings at corresponding wavelengths (1.064 \( \mu \)m, 1.319 \( \mu \)m and 1.338 \( \mu \)m) in order to obtain the corresponding single lines and simultaneous dual wavelength Nd:YAG lasers at 1.3 \( \mu \)m band, whose reflectivity values are tabulated in Table 2.

The Nd:YAG rod, with 1.1 at.% Nd\(^{3+}\) ions doping level and coated with a broadband antireflective film at both of end surfaces, is 6 mm in diameter and 120 mm in length. The Kr-lamp ignited by a power source with the pumping repetition rate of 100 Hz is 8 mm in diameter and 100 mm in the distance between the electrodes.

The output power was measured by LPM-100 power meter. In order to detect the wavelength of output lasers, the lasing beam was reflected by a beam splitter \( M_3 \) and absorbed by a Ge diode detector, which was set at the output end of the grating monochromator (Model 44W) for the determination of the laser wavelength.

The relationships between pumping power and output power of 1.3-\( \mu \)m Nd:YAG lasers are described in Fig. 3, and the experimental results are listed in Table 3.

The output pulses captured by TDS3052B (500 MHz) oscilloscope at pumping power of 2630 W are shown in Fig. 4. It can be known that the full width at half maximum (FWHM) of each pulse are about 0.75 and 0.76 ms, respectively, in Fig. 4a and b.

The spectrum of generation with 1.319 \( \mu \)m and 1.338 \( \mu \)m was detected by using the Model 44W grating monochromator sensitive in the IR region (above 1000 nm) at the maximum pumping power of 7243 W. The measured results are depicted in Fig. 5, in which the intensity ratio of 1.319 \( \mu \)m and 1.338 \( \mu \)m wavelength is 41:37, and the center wavelength is 1318.8 nm for 1.319 \( \mu \)m wavelength, however the value changes to 1338.2 nm for 1.338 \( \mu \)m wavelength.

4. Conclusion

Based on the calculated results of the simultaneous dual wavelength threshold condition, three types of high power Nd:YAG QCW lasers operating at 1.319 \( \mu \)m or 1.338 \( \mu \)m

<table>
<thead>
<tr>
<th>Lasers</th>
<th>Maximum output power (W)</th>
<th>Overall efficiency (%)</th>
<th>Slope efficiency (%)</th>
<th>Instability of output power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.319 ( \mu )m</td>
<td>138 W</td>
<td>1.90</td>
<td>1.98</td>
<td>(&lt;5)</td>
</tr>
<tr>
<td>1.338 ( \mu )m</td>
<td>132 W</td>
<td>1.83</td>
<td>2.04</td>
<td>(&lt;5)</td>
</tr>
<tr>
<td>1.319 ( \mu )m and 1.338 ( \mu )m dual line</td>
<td>120 W</td>
<td>1.64</td>
<td>1.61</td>
<td>(&lt;5)</td>
</tr>
</tbody>
</table>

Table 2
Reflectivity values of \( M_2 \) for 1.3 \( \mu \)m wave band Nd:YAG lasers

<table>
<thead>
<tr>
<th>Lasers</th>
<th>Reflectivity values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 1.064 ( \mu )m</td>
</tr>
<tr>
<td>1.319 ( \mu )m</td>
<td>&lt;40</td>
</tr>
<tr>
<td>1.338 ( \mu )m</td>
<td>&lt;40</td>
</tr>
<tr>
<td>1.319 ( \mu )m and 1.338 ( \mu )m dual line</td>
<td>&lt;40</td>
</tr>
</tbody>
</table>

Table 3
Experimental results of 1.3 \( \mu \)m wave band Nd:YAG lasers

Fig. 3. The relationships between the pumping power and output power of 1.3 \( \mu \)m wave band Nd:YAG lasers. (a) Output power of 1.319 \( \mu \)m laser versus pumping power. (b) Output power of 1.338 \( \mu \)m laser versus pumping power. (c) Output power of 1.319 \( \mu \)m and 1.338 \( \mu \)m dual wavelength laser versus pumping power.
single wavelength, 1.319 μm and 1.338 μm simultaneous dual wavelength are developed, and have achieved a maximum average output power of 138 W, 132 W and 120 W, respectively. The experimental results show good agreements with those of theoretical analysis.

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References