A high polarization microchip green laser with dual Nd:YVO\textsubscript{4} crystal

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1. Introduction

Recent developments in compact diode-pumped solid-state green/blue laser sources are motivated by potential applications such as high-density optical data storage, display and printing technology, and replacement of the gas lasers. Specifically, a diode-pumped intracavity frequency-doubled Nd:YVO\textsubscript{4} crystal laser has attracted attention [1–4]. This device permits the efficient generation of green coherent light owing to the presence of a high-intensity light confined in the laser resonator. However, stable CW emission seems to be difficult to achieve, owing to the so-called green problem, which leads to large amplitude fluctuations in the frequency-doubled emission [5].

1. Theoretical analysis

In a common LD-pumped Nd:YVO\textsubscript{4}/KTP laser, since there are $\pi$- and $\sigma$-emission cross-sections in Nd:YVO\textsubscript{4} crystal, and $\pi$-emission cross-section is 4.2 times the $\sigma$-emission cross-section, the fundamental frequency light (1064 nm) has a good linear $\pi$-polarization. However, the degree of polarization of frequency-doubled green laser is very small, which is less than 1.5:1. Based on the theoretical analysis, there are two main reasons that lead to low polarization of green light.

For the fundamental frequency light, KTP crystal acts as a waveplate, which leads to depolarization of the fundamental frequency light. When the fundamental frequency light comes through KTP crystal, it will always be divided into o-light (perpendicular to the optical axis of the KTP crystal) and e-light (parallel to the optical axis of the KTP crystal). The o-light and e-light merge into a linearly-polarized green light along the optical axis, and the ratio of the o-light and e-light only affect the frequency-doubled efficiency, and does not affect the polarization of green light.

In our work, a technique of stabilizing high polarization states has been developed for CW intracavity frequency-doubled laser that not only provides high polarization, but is also easy to adjust. The method uses two identical Nd:YVO\textsubscript{4} gain crystal, which were rotated 90° from each other as gain medium, which eliminate the depolarization effect of single Nd:YVO\textsubscript{4} crystal, the high polarization green laser is obtained, and the polarization ratio is more than 110:1.
total reflection coating at 1064 nm and 532 nm and anti-reflection coating at 808 nm. When the fundamental frequency light is reflected from the output mirror, second harmonic will happen in the KTP crystal, and a reverse polarized SHG (second harmonic generation) green laser is produced, which is divided into o-light and e-light in Nd:YVO₄ crystal. Since Nd:YVO₄ crystal has two different refractive indices to green light, the polarization of green light becomes worse after coming through the Nd:YVO₄ crystal. When the green light is reflected by the mirror near the pump source and comes through Nd:YVO₄ crystal again, the polarization of green light will be further reduced, and the original linearly-polarized SHG green light becomes elliptically-polarized light. Therefore, the depolarization of Nd:YVO₄ crystal is the main reason for low polarization of green laser.

As described above, two identical crossed Nd:YVO₄ gain crystals are used in the cavity to eliminate the depolarization effect of single Nd:YVO₄ crystal. A simple mathematical model using the round-trip Jones matrix describes the high polarization of green laser. The Jones matrix $M$ for a cavity with two Nd:YVO₄ gain crystals is given in Eq. (2) below, where $C(x)$ is the matrix for the birefringence, $\delta_1 = -\delta_2 = \delta$ are the birefringent values for two crossed, equally sized Nd:YVO₄ gain crystals, and $E_i$ and $n_i$ present the eigenvectors and eigenvalues of the polarization states, respectively:

$$C(x) = \begin{bmatrix} \exp[i(x/2)] & 0 \\ 0 & \exp[-i(x/2)] \end{bmatrix}. \quad (1)$$

$$M = C(\delta_1)C(\delta_2)C(\delta)C(\delta), \quad (2)$$

$$= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \quad (3)$$

$$E_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad n_1 = 1, \quad E_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad n_2 = 1 \quad (4)$$

With the design described above, the Jones matrix becomes the unit matrix (Eq. (4)), which means that the crossed Nd:YVO₄ crystal configuration completely eliminates the influence of the depolarization of the single Nd:YVO₄ gain crystal. Therefore the stable and high polarization emission is obtained.

3. Experimental results and discussions

3.1. Temperature effect of Nd:YVO₄ crystal for the polarization

Fig. 1 shows the sketch of common Nd:YVO₄/KTP crystal green laser. The temperature of Nd:YVO₄ crystal is controlled by a Peltier TEC module, and it is measured by a temperature detector (0.1 °C accuracy). Fig. 2(a) shows that the green laser power changes periodically as the temperature of Nd:YVO₄ crystal changes, since the refractive index of Nd:YVO₄ crystal changes periodically with temperature. With the temperature further rising, green light power decreases significantly because of the thermal effect of Nd:YVO₄ crystal. Fig. 2(b) shows that the polarization of green light also changes periodically as temperature of Nd:YVO₄ crystal changes. These results demonstrate that the depolarization of Nd:YVO₄ crystal is the main reason for low polarization of green light.

3.2. The experiment of dual crossed Nd:YVO₄/KTP laser

The schematic diagram of the dual gain single cavity Nd:YVO₄/KTP laser and micro-chip configuration are shown in Figs. 3 and 4, respectively. A single 100-μm-stripe, 2 W laser diode supplies the longitudinal end pump of the microchip. The wavelength of the maximum emission at 25 °C is 809.0 nm, and the FWHM spectral width is 1.2 nm. The micro-chip consists of two 3 mm × 3 mm × 1 mm, 3 at% Nd³⁺-doping Nd:YVO₄ crystals with their c-axes orthogonal to each other, which are bonded to an 3 mm × 3 mm × 2 mm KTP crystal. One surface S1 of the Nd:YVO₄ crystal is coated with high reflection at 1064 nm and 532 nm (HR at 1064 nm and 532 nm), and anti-reflection coating at 808 nm (AR at 808 nm). The KTP crystal is cut with $\theta=90^\circ, \phi=23.5^\circ$ for type II phase matching of 1064 nm wavelength. One surface S2 of the KTP crystal is coated with high reflection at 1064 nm (R > 99.8%) and high transmission coating at 532 nm (T > 95%), which acts as the cavity output mirror. In order to
improve the laser output power and its stability, the optical bond between the components and the temperature controller are used. The laser operation temperature is controlled at 25.0 ± 0.1 °C by the Peltier TEC module. The 1064 nm filter and the polarizer combination are used to analyze the state of polarization of the output laser beam. The transmitted beam from the polarizer is detected with the help of a photo-diode (PD) after attenuation and displayed on a digital storage oscilloscope.

Fig. 5 shows the light–light conversion efficiency curves for only C1 (crystal 1) or C2 (crystal 2). The outputs from C1 and C2 could be measured separately. Before optically gluing C1 and C2, the output of green laser1 (only C1) is measured, then instead of C1, the output of green laser2 (only C2) is measured. The threshold of absorbed pump power using C1 is 200 mW, with nearly 15.9% light–light conversion efficiency. The laser using C2 showed 3.8% light–light conversion efficiency with the absorbed pump power at the threshold of 215 mW. From Fig. 5, it can be seen that the light–light conversion efficiency of laser using C2 is much lower, compared to the laser using C1. The reason is that there are π- and σ-emission cross-sections in Nd:YVO₄ crystal relative to the pump light, and the σ-emission cross-section is 4.2 times the π-emission cross-section and the thresholds of laser using C1 and C2 are little different. The main reason is the similar intra-cavity losses with equal crystals in the cavity.

Fig. 6 shows the light–light conversion efficiency curves for the dual gain Nd:YVO₄ crystal laser. The output power is measured with the help of a power meter. The absorbed pump power at the threshold is estimated by a linear fit to the experimental data. This configuration shows a slope efficiency of 20.3% at 532 nm with 220 mW absorbed pump power at the threshold. The threshold and efficiency values suggest that the performance of the cavity is optimized. The maximum output power obtained is 366 mW for 1.8 W absorbed pump power. It can be seen from Fig. 6 that the output power from the dual orthogonal gain crystals is always higher than the sum of the individual laser powers. The higher extraction efficiency for laser oscillation in our configuration arises because longitudinal modes in solid-state lasers with birefringent intra-cavity elements are split into two orthogonal polarization modes [10], which are preferentially amplified by one of the dual crystals. The residual gain in one crystal will therefore be extracted by the laser beam from the other crystal. Even if the gain in one of the crystals is kept below the threshold, the increase in output power is still observed. Fig. 7 shows the stability of the output power of green laser. When LD pump power is 1.8 W and the temperature of microchip is controlled at 25.0 ± 0.1 °C by the Peltier TEC module, the output power of green laser is 364 ± 5 mW, which was measured once per minute for an hour. The stability of green laser is less than 1%.

Polarization state of the output laser beam from this dual gain laser is analyzed with the help of a filter at 1064 nm and a polarizer. The latter has an extinction coefficient of ~10⁻⁵ in crossed condition. On rotating the polarizer, the maximum and
minimum powers of the output laser beam are measured. Fig. 8 shows that the polarization ratio of green laser increased with increasing pump power. However, when pump power is more than 1.4 W, the polarization ratio of green laser increased slowly. The possible reason is little longitudinal mode coupled in the intracavity. From Figs. 8 and 9, when LD pump power is 1.8 W, the polarization ratio of green light is about 110:1, which is 100 times that of the single gain crystal green laser, and when the temperature of microchip is changed from 10°C to 42°C, the polarization ratio is almost above 110:1, whose stability is better than that of single Nd:YVO4/KTP laser.

4. Conclusion

In conclusion, without changing the structure of single Nd:YVO4/KTP cavity and its produce process, a high polarization green laser is realized using two optical axis orthogonal Nd:YVO4 crystals as gain medium. These results demonstrate that this method is a simple and efficient way to improve the polarization of green laser, which has a very high practical value in actual production.

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References