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High average power Q-switched green beam generation by intracavity frequency doubling of diode-side-pumped Nd:YAG/HGTR-KTP laser

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ABSTRACT

To obtain high power and high beam quality second harmonic generation, a Q-switched system has been demonstrated by intracavity frequency doubling of two diode-side-pumped Nd:YAG modules with double AO-modulators in an astigmatism compensated cavity geometry. A maximum average frequency doubled power of 185 W is obtained when the pumping power is 600 W for each module. The corresponding optical-to-optical conversion efficiency is 15.4% and the pulse width is 180 ns at a repetition rate of 10 kHz. An instability of 2.5% was measured over a period of 2 h and the beam quality factors were measured to be $M_x^2 = 9.52$, $M_y^2 = 9.86$ the maximum output power.

1. Introduction

In recent years, the development of high power green lasers with more than 100-W average powers has attracted great attention due to their numerous applications in many areas, such as a processing tool for high reflectivity materials, in medical equipment, as a pumping source of Ti: sapphire lasers, and as a light source for laser displays [1–7]. Up to now, intracavity frequency doubling of dual acoustic-optically Q-switched diode-side-pumped Nd:YAG laser has proved to be one of the most effective methods for obtaining high power green beams with high repetition rate and low instability [8]. For instance, Geng et al. used a diode-side-pumped Nd:YAG laser with a dual-V-shaped configuration to output power of 121 W with a beam quality factor $M^2 = 20$ [9]. Konno et al presented a diode-side-pumped Q-switched laser based on an L-shaped resonator to obtain an output power of 127 W with $M^2 < 9$ [10].

Generally, two factors must be taken into account for improving the frequency conversion efficiency, a large fundamental mode volume within the laser gain medium and a relatively small spot size at the nonlinear crystal [11]. On the one hand, having a large spot size at the end of the crystal rod is beneficial to make full use of the laser active medium. On the other hand, the output power of frequency doubled beam is inversely proportional to the beam radius of fundamental wave, so having a small beam size at the frequency doubler is advantageous in increasing the efficiency of second harmonic generation. For the purpose above, V-shaped folded cavities should be the better choice for second harmonic generation. In addition, the folded resonator can also enable the double passing of the frequency doubler, provide a single-ended output and also prevent the green laser beam entering the laser medium. Furthermore the structure can avoid the absorption of the green beam in the Nd:YAG rod.

In this letter, in order to get high power and high beam quality second harmonic generation, a V-shaped system is designed which can compensate for astigmatism by adopting the appropriate fold angle. An average power of 185 W is obtained at 532 nm with a pulse width of 180 ns and a repetition rate of 10 kHz. The optical-to-optical conversion efficiency is 15.4%. At the maximal power, beam quality factors $M_x^2 = 9.52$, $M_y^2 = 9.86$ are measured, and the instability is less than 2.55% over a period of 2 h.

2. Experimental setup

The laser system is shown in Fig. 1, which is a simple three-mirror folded cavity. One end mirror M_3 is a plano–plano mirror with high-reflectivity (HR) at 1064 nm. The other end mirror, M_2, is a plano–concave mirror with a radius of curvature of 100 cm. The concave surface has dual wavelength high-reflective coatings at 1064 and 532 nm. The folding mirror M_1 is also a plano–concave mirror with the concave surface coated for high reflectance at 1064 nm and high transmittance at 532 nm, while the plano

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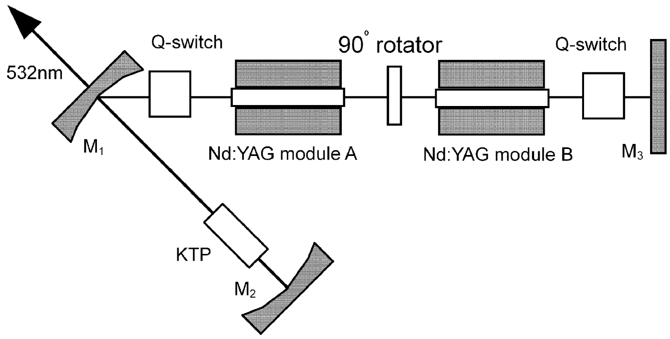

Fig. 1. Schematic drawing of the cavity configuration.

surface is coated for anti-reflectance (AR) at 532 nm to extract the green beam from the resonator. The radius of curvature of M_1 is 40 cm, two laser modules with the same geometry (CEO, Inc.) are placed in one arm of the cavity, each module consisting of 30 20-W laser diodes and an Nd:YAG rod ($\phi 5.0\times 105$ mm, Nd^{3+} doping of 0.6%) coated with an antireflective film at 1064 nm on the two end faces. A 90° quartz rotator is inserted between the two modules to compensate for thermal birefringence, allowing the output power and beam quality to be improved. In addition, two acousto-optic modulators are placed orthogonally on the sides of the two rods to achieve higher diffraction loss, which is beneficial for nonlinear frequency conversion and high pulse power generation. A $5\times 5\times 15\,\mathrm{mm}^3$ HGTR-KTP crystal (RAICOL Crystal Inc., Israel) cut for type-II critical phase matching ($\theta = 90°$, $\phi = 23.8°$) is employed as the frequency doubler in the second arm. Both the surfaces are anti-reflection coated at 1064 and 532 nm to reduce intracavity reflection losses. The temperature of the KTP crystal is kept constant for purpose of decreasing the thermal lens effect and compensating for the phase mismatching, thus improving the frequency conversion.

3. Results and discussion

The folded cavity, also called an astigmatic resonator, usually brings astigmatism to the oscillator beam since the folded mirror is placed off-axis. However, astigmatism can cause the beam radius and curvature radius of equiphase-surfaces to be unequal at the tangential and sagittal planes, respectively, which influences the laser beam quality and doubling frequency conversion efficiency. Therefore, the incorporation of astigmatism compensation in the design of resonators is essential to obtain a high output power with good beam quality and stability.

The different focal lengths of the tangential and the sagittal beams are expressed as follows:

$$f_t = \frac{R\cos\alpha}{2},\quad f_s = \frac{R}{2\cos\alpha} \tag{1}$$

where R is the radius of the concave surface of the folded mirror, α is the folded angle (half angle), and the subscripts t and s represent tangential and sagittal planes, respectively.

For the V-shaped cavity, when the mirror M_3 serves as the reference plane, the round-trip propagation matrix M is given by:

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = [\boldsymbol{d_1}][\boldsymbol{M_r}][\boldsymbol{d_2}][\boldsymbol{M_r}][\boldsymbol{d_3}][\boldsymbol{M_{R1}}]_{s,t}[\boldsymbol{d_4}] \times[\boldsymbol{M_{R2}}][\boldsymbol{d_4}][\boldsymbol{M_{R1}}]_{s,t}[\boldsymbol{d_3}][\boldsymbol{M_R}][\boldsymbol{d_2}][\boldsymbol{M_R}][\boldsymbol{d_1}][\boldsymbol{M_{R3}}] \tag{2}$$

where $[\boldsymbol{d_1}]$, $[\boldsymbol{d_2}]$, $[\boldsymbol{d_3}]$, $[\boldsymbol{d_4}]$ are the ray propagation matrices for the distance from the mirror M_3 to the principal plane of the YAG rod B, between the two rod principal planes, from the principal plane of the rod A to the mirror M_1, and from the mirror M_1 to the mirror M_2, respectively. $[\boldsymbol{M_{R1}}]$, $[\boldsymbol{M_{R2}}]$, and $[\boldsymbol{M_{R3}}]$ represent those at three mirrors.

The matrix of the gain medium $[\boldsymbol{M_r}]$ is [12]

$$\boldsymbol{M_r} = \begin{bmatrix} 1+\gamma L_0^2 & 1/n_0 \\ 2\gamma n_0 L_0 & 1+\gamma L_0^2 \end{bmatrix} \tag{3}$$

where n is the refractive index of the gain medium and $n = n_0(1+\gamma r^2)$. γ is the thermal lens coefficient and L is the length of the gain medium

According to the *ABCD* law, only when both tangential and sagittal laser beam oscillate in the stable zone simultaneously, the resonator can be regarded as a stable one. That is

$$\left|\frac{A_{t/s}+D_{t/s}}{2}\right| \leqslant 1 \tag{4}$$

The relationship between the q parameters of the TEM_{00} Gaussian mode and every element of the round trip matrix is

$$\frac{1}{q_{t/s}} = \frac{D_{t/s}-A_{t/s}}{2B_{t/s}} - \mathrm{i}\frac{\sqrt{1-[(A_{t/s}+D_{t/s})/2]^2}}{B_{t/s}} = \frac{1}{R_{t/s}} - \mathrm{i}\frac{\lambda}{\pi\omega_{t/s}^2} \tag{5}$$

So the beam waist of the Gaussian mode in the mirror M_3 is

$$\omega_{t/s} = \sqrt{\frac{\lambda\cdot B_{t/s}}{\pi}\cdot\left[1-\left(\frac{A_{t/s}+D_{t/s}}{2}\right)^2\right]^{-1/2}} \tag{6}$$

The laser spot size anywhere in the resonator can be obtained by changing the inceptive reference place of the round trip matrix. The laser beam distribution may be calculated at any position within the cavity.

As mentioned above, it is necessary to compensate for astigmatism in order to get good beam quality and high frequency conversion efficiency, which can be implemented by means of appropriate choice of folded angle and the distances between the optical components. In the process of numerical simulation and calculation, it can be seen that when the total cavity length is designed to be 60 cm (the folded arm is 17.5 cm, the distance from M_1 to the left end face of the Nd:YAG rod A is 6.7 cm, and that from the right end face of the Nd:YAG rod B to M_3 is 7.8 cm) and the folded angle (half angle) is 12.5°, and the fundamental spot sizes on the folded mirror in the tangential and sagittal plane are different scarcely when the incident pumping power changes from 275 to 695 W. We depicted the change law, which is shown in Fig. 2.

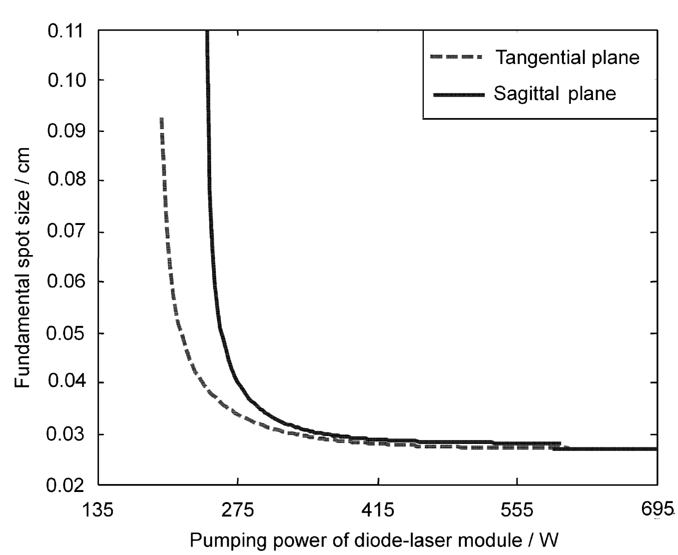

Fig. 2. Variation of fundamental spot size on folded mirror with pumping power.