Study on 660-nm quasi-continuous-wave intracavity frequency-doubled Nd:YAG laser

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A quasi-continuous-wave intracavity frequency-doubled Nd:YAG laser which operates at 660 nm is studied. By using a flat-flat laser cavity, 2 Kr-lamps, KTP crystal and an acousto-optically Q-switch, 2-W output power at 660 nm is obtained. The relationship between laser cavity length and output power is analyzed.

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As one of the tricolor, red light at 660 nm has applications in many areas, such as laser display, laser full-color film, laser therapy and scientific experiment. It can be got by using intracavity frequency-doubled Nd: YAG laser with KTP crystal. At the present time, the literatures about 660-nm red light lasers interiorly are few.

In this paper, we report a quasi-continuous-wave intracavity frequency-doubled Nd:YAG laser, which uses a KTP crystal as the nonlinear optical material with 660-nm laser output. The maximum stable outputs of 2 W from one end and 2.5 W from both ends are obtained.

First, the optimum design of the laser cavity should be made. As we all know, most of the solid-state lasers can be treated as symmetric confocal cavity[1]. When the Fresnel $N \to \infty$, the Laguerre-Gassian function of the self-consistent mode is[2]

$$V_{mn}(r,\varphi) = C_{mn}\left(\sqrt{2}\frac{r}{\omega_{oos}}\right)^m L_n^m\left(2\frac{r^2}{\omega_{oos}^2}\right) \times \exp\left(-\frac{r^2}{\omega_{oos}^2}\right)\exp(-im\varphi), \quad (1)$$

where (r,φ) is the polar coordinates on the mirror, C_{mn} is the normalization constant, $\omega_{oos} = \sqrt{L\lambda/\pi}$ is the fundamental mode radius on the mirror and L is the length of the cavity.

The equations of the radius of curvature and far-field divergence angle are[2]

$$\omega_{mn,z} = \omega_{mn,0}\sqrt{1+\left(\frac{\lambda z}{\pi\omega_{mn,0}^2}\right)^2 K^4},$$

$$R_{mn,z} = Z\left[1+\left(\frac{\pi\omega_{mn,0}^2}{\lambda Z}\right)^2\left(\frac{1}{K^4}\right)\right],$$

$$\theta = \left(\frac{\lambda}{\pi\omega_{mn,0}}\right)K^2 \quad \left(Z \gg \frac{\pi\omega_{mn,0}^2}{\lambda}\right), \quad (2)$$

where K is the multimode efficient which is a general parameter of the mixing modes containing the fundamental mode. K meets

$$K = \frac{\omega_{mn,0}}{\omega_{00,0}} = \frac{\omega_{mn,z}}{\omega_{00,z}}. \quad (3)$$

From the equation above, we can see that the beam of lower order mixing mode may be regarded as a fundamental mode Gassian beam which is expanded by K times. In the analysis, thermal lens of the Nd:YAG crystal is as a thin lens with focal length f_1 shown in Fig. 1.

From Eq. (2), we get

$$d_2 = \frac{f_1\left(\frac{\pi\omega_{m,01}^2}{\lambda k^2}\right)^2 + f_1 d_1^2 - f_1^2 d_1}{f_1 - 2d_1 f_1 + d_1^2 + \left(\frac{\pi\omega_{m,01}^2}{\lambda k^2}\right)}$$

$$\omega_{m,02} = \frac{1}{\sqrt{\left(1-\frac{d_1}{f_1}\right)^2 + \left(\frac{\pi\omega_{m,01}^2}{\lambda f_1 k^2}\right)^2}}, \quad (4)$$

where $\omega_{m,01}$ and $\omega_{m,02}$ are the multimode radius on the two mirrors. L is the cavity length (it should be the difference between the real cavity length and the length of crystal YAG). Assuming $d_1 = d_2 = L/2$, for the

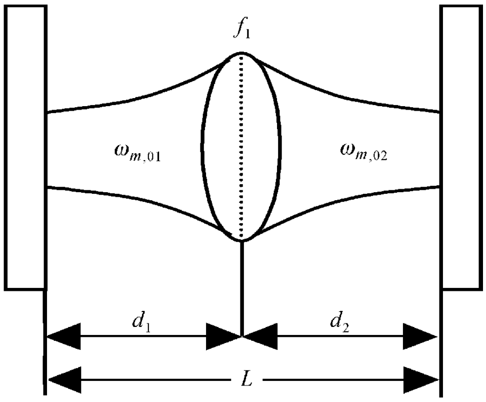

Fig. 1. Schematic of Nd:YAG laser cavity.

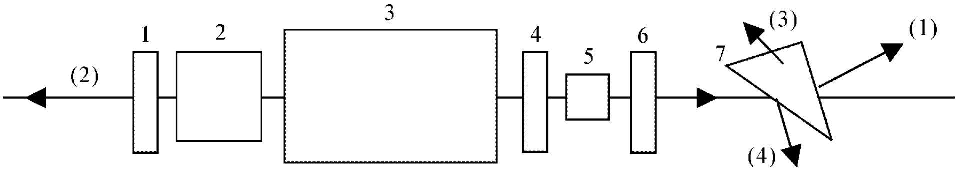

Fig. 2. Schematic of intracavity frequency-doubled Nd:YAG laser. 1: reflector; 2: acousto-optically Q-switch; 3: Nd:YAG crystal; 4: harmonic wave reflecting mirror; 5: KTP crystal; 6: output coupler; 7: prism for testing. (1), (3) and (4): three beam paths of the red laser outgoing from the prism; (2): one-end output when the red laser 660-nm output from both ends.

beam self-consistency in the resonant cavity, we have $\omega_{m,01}=\omega_{m,02}=\omega_{m,0}$. From Eq. (4), we get

$$\left(1-\frac{d_1}{f_1}\right)^2+\left(\frac{\pi\omega_{m,0}^2}{\lambda f_1 k^2}\right)^2=1,$$

or

$$\frac{\omega_{m,0}}{k}=4\sqrt{\frac{\lambda^2}{\pi^2}L\left(f_1-\frac{L}{4}\right)},$$

$$\theta=\frac{\omega_{m,0}}{f_1\sqrt{L\left(1-\frac{d_1^2}{f_1}\right)^2}}=\frac{\omega_{m,0}}{\sqrt{(2f_1-d_1)d_1}}. \qquad (5)$$

In order to get bigger mode volume for a certain value of pump power and a constant f_1, $\omega_{m,0}/k$ should have the maximum value. It is nearly a fundamental mode operation which indicate the optimum laser cavity. In the experiment, higher output power can be achieved with shorter cavity length and it is in agreement with the theoretical analysis.

Flat-flat cavity was used in this system in order to obtain bigger mode volume and better beam quality.

Figure 2 shows the setup of the 660-nm laser. A 110-mm long Nd:YAG crystal with diameter of 6 mm was used. Both faces of the crystal were AR coated at 1319 and 660 nm. The phase match angle of KTP crystal at 1319 nm is $\theta = 60.7°$ and $\phi = 0°$ by calculation[1]. The size of the KTP crystal is $8 \times 8 \times 8$ mm^3. Both ends of KTP are antireflection-coated at 1319 and 660 nm.

It is important to inhibit the resonant of 1064 nm for the 660-nm laser. So the input coupler had high reflectivity at 1319 nm and was AR coated at 1064 nm. The output coupler was AR coated at 660 nm and had high reflectivity at 1319 nm. The harmonic wave reflecting mirror was AR coated at 1319 nm and had high reflectivity at 660 nm.

In this system, the carriers of the reflector, the harmonic mirror, the output coupler and the frequency-doubled crystal are all fabricated with new style patented invention. They were adjusted from the radial instead of the traditional axial direction with a shorter cavity length as shown in Fig. 3[3].

In this system, we used two Kr-lamps for pumping with the maximum current of 26 A and the maximum voltage of 360 V[4]. The electrode connection with crossing link instead of vertical link shortened the cavity length. Finally the cavity length is 390 mm.

The acousto-optically Q-switch had the max output power of 125 W with the adjustable repetition rate of 0 – 20 kHz. In this device, the cavity, YAG crystal, KTP crystal, and the acousto-optically Q-switch were all cooled by a water cooler with cooling power of 5 kW[5], circulating water-flow of 3 m^3 and output water temperature of 10 – 30 °C.

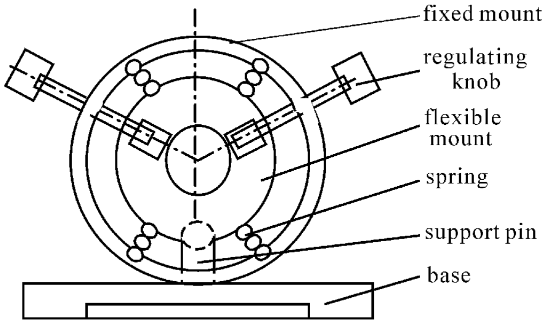

Fig. 3. A new kind of optical lens radial position adjustment.

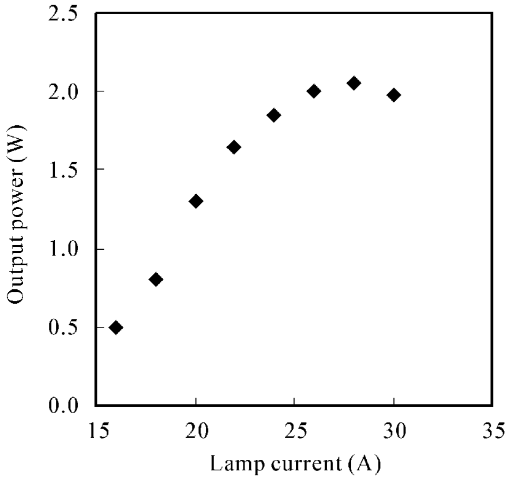

Fig. 4. The experimental curve of the laser input-output.

In Fig. 4, the laser output as a function of the pump input is shown. The output power of the 660-nm red laser was 2 W when the voltage was 250 V, the current was 26 A, the acousto-optically Q-switch output power was 50 W and the repetition rate was 9 kHz. The output power was stable. At the distance of 200 mm from the output mirror, the diameter of laser beam was 3.5 mm. In the same condition, when the cavity length increases to 420 mm, the output power decreased to 1.8 W, which showed agreement with the tendency of theoretical analysis.

If changing the 660-nm output coupler with the reflectivity of 3.74% at 1319 nm, output power of 40 W at 1319 nm can be obtained without KTP. The conversion efficiency of fundamental wave to harmonic is estimated to be 2.6%.

When the current increased to 28.5 A, the output power was 2.2 W. But it was not stable. When the current increased further, the output power decreased, which was mainly for the reason of the thermal effects in the crystal.

The acousto-optically Q-switch was important to the output power, mainly because it can increase the peak power density of 1319 nm and thus increase the harmonic efficiency. When the repetition rate was 9.9 kHz, the output was maximum. The output power of the Q-switch had the optimum value to the corresponding output power of 660 nm. For example, when the output power of the red laser at 660 nm was 1.5 W, the optimum value of the Q-switch was 41 W.

If changing the reflector at 660 nm with the output mirror and taking away the harmonic reflector, the 660-nm output of one end of KTP (the main end) was 1.8 W and the other end was 0.7 W. Altogether the two-end output is 2.5 W.

When the current was 23 A and the repetition rate of Q-switch was 8.6 kHz, we used a prism to test the reality of the red laser output. With the prism on the output (the main end), three arms output is absorbed at 660 nm. The outputs are 1.6, 0.4, 0.2 and 0.1 W, respectively.

In a word, the scheme of the quasi-cw intracavity frequency-doubled Nd:YAG laser is rational and feasible. The output power was 2 W. The beam and output were stable and the system worked steadily. The radial adjusted carriers shortened the cavity length effectively and increased the output power correspondingly, which was in agreement with the tendency of the theoretical analysis. The acousto-optically Q-switch is important to the output power. When the repetition rate was 9.9 kHz, the output power was maximum.

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