1.9-W flash-lamp-pumped solid-state 266-nm ultraviolet laser

Zhen Xiang (项 震), Jianhong Ge (葛剑虹)*, Zhigang Zhao (赵智刚), Sha Wang (汪 莎), Chong Liu (刘 崇), and Jun Chen (陈 军)

State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China

**E-mail: jianhong@zju.edu.cn*

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Deep ultraviolet lasers have various applications in industries and scientific researches. For 266-nm ultraviolet (UV) laser generation, the good beam quality of 1064-nm laser and the elimination of gray-tracking effect of KTP crystal are two key factors. Using a dynamically stable resonator design, 1064-nm laser with an average power of 52 W is realized with repetition rate of 16 kHz. The measured M^2 factor characterizing the beam quality is 1.5. By the elimination of gray-tracking effect of KTP crystal, an 18-W green laser is realized with the M^2 factor of 1.6. Using a BBO crystal for the fourth harmonic generation, a 1.9-W 266-nm UV laser is achieved.

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Solid-state deep ultraviolet (UV) lasers have various applications in industries and scientific researches. Frequency conversion based on a neodymium doped solid state laser to generate fourth harmonic wave is an effective way to obtain UV lasers. The nonlinear crystals with high nonlinear coefficient and good quality are key factors for harmonic generation.

KTP crystals are widely used for second harmonic generation (SHG) of the near infrared laser radiation into the visible one due to high nonlinearity and good mechanical and optical properties. But with the increase of pump power, laser-induced damage in KTP crystal, termed gray-tracking, is severe which was observed during 1064-nm SHG[1,2]. The conversion efficiency and beam intensity distribution are deteriorated due to the gray-tracking effect.

CLBO crystals were reported these years for fourth harmonic generation (FHG)[3,4]. But the unstable physical properties of this crystal restrict its further applications. BBO crystals are still one of the best candidates for FHG due to high nonlinearity and high transmission in UV band[5,6]. BBO crystals have a low angle acceptance and large walk-off angle. Therefore, good beam quality and small divergence angle of the input laser are very important to achieve high conversion efficiency.

From the introduction above we know that the good beam quality of 1064-nm laser and the elimination of gray-tracking effect of KTP crystals are two key factors for the generation of 266-nm UV laser. In this letter, we reporte a flash-lamp-pumped solid-state laser system for UV generation. The 1064-nm laser is a lamp-pumped acoustic-optic Q-switched Nd:YAG laser. Up to several tens of kilowatt peak power is realized with fundamental mode operation.

Thermally induced stresses in the isotropic laser rod such as Nd:YAG creates birefringence[7]. A polarized laser beam transmitted by a laser rod with spatially varying birefringence is depolarized after the rod. This results in losses and, consequently, the decrease of efficiency. So compensation for the birefringence is necessary if one is constructing a high power Nd:YAG laser. Lü *et al.* proposed a refined concept of birefringence compensation with two identical pumped rods[8]. With a 90°-polarization rotator and a telescope imaging the principal planes of both rods, complete birefringence compensation can be achieved. This scheme was frequently employed these years [8−10].

Birefringence compensation is required but not enough for the high-power fundamental mode output. Appropriate resonator design is also important to ensure high extraction efficiency of fundamental mode. Magni *et al.* studied dynamically stable resonators (DSRs)[11,12], which satisfy the following requirements: 1) the mode size in the laser rod should be large enough to ensure a TEM_{00} mode output with high efficiency; 2) the resonator should be insensitive to mechanical perturbation or misalignment of the resonator mirrors; 3) the mode volume inside the rod should be insensitive to the fluctuations of the focal length of the thermal lens to avoid output power instability. Some general rules and some characteristics of a two-mirror DSR are also given in Refs. [11, 12].

The schematic of the DSR in our laser system is shown in Fig. 1. The system is flash-lamp pumped and operated in continuous-wave (CW) mode. The Nd:YAG rods with a diameter of 6 mm and length of 177.8 mm are doped with 1.1 at.-% Nd. The output coupler (OC) has a reflectivity of 60%. Both the OC and the high reflectivity (HR) mirror are flat. The imaging system

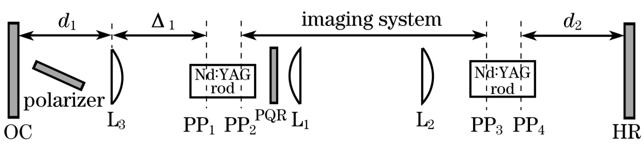

Fig. 1. Experimental setup of a DSR with two Nd:YAG rods. PP: principle plane of the thermal lens.

has a 1:1 telescope and a 90°-polarization quartz rotator (PQR) to achieve full birefringence compensation. A positive lens L_3 with focal length f_3= 75 mm was used to enlarge the TEM_{00} mode size. A Brewster plate was inserted close to the OC in order to get linearly polarized output. The cavity length parameters in Fig. 1 are as follows, d_1= 300 mm, Δ_1= 302.5 mm, and d_2= 370 mm.

The 61-W CW output is obtained from the laser system shown in Fig. 1. The measured M^2 factor is 1.5 using a M^2-200 beam analyzer from Spiricon Company. The beam intensity profile is nearly Gaussian distribution in the far field. But the M^2 factor cannot be reduced experimentally any more. We assume that the spherical aberration distorts the wave front of the mode and increases the divergence[13]. Through an acoustic-optic Q-switch, the laser works in pulsed operation with a pulse repetition rate in the range of 7.5−17.5 kHz. The pulse duration (full-width at half-maximum (FWHM)) varies from 120 to 270 ns for the considered range of repetition rate. The output power is related to the pulse repetition rate, as shown in Fig. 2, ranging from 47 to 52 W.

Using KTP crystals for SHG, gray-tracking effect should be avoided especially for the high-power and long-pulse laser system. A normal way to eliminate the gray-tracking effect is to use a weaker focal system, as shown in Fig. 3(a), i.e., to make the waist radius of 1064-nm laser beam inside the KTP crystal larger. Thus, the green laser beam radius becomes larger too. But in this way the conversion efficiency would decrease due to the decrease of power density. We present a simple way to eliminate the gray-tracking effect and maintain high conversion efficiency simultaneously. The principle of this method is shown in Fig. 3(b). It has been demonstrated that the gray-tracking effect is only related to the power density of green laser[2,14]. The power of green laser increases gradually along the KTP crystal with laser propagation. It has the minimum on the incident surface and achieves maximum on the output surface. Thus, the gray-tracking effect is only related to the green laser power density on the output surface. Therefore, we need not to increase the beam radii both on the incident and output surface, but to increase the beam radius only on the output surface. This idea allows us to use a strong focal system. As shown in Fig. 3(b), the focused laser beam is stronger than that in Fig. 3(a). The beam radius w_1' on the incident surface is nearly the same as w_1 in Fig. 3(a), which ensures high conversion efficiency. While the beam radius w_2' on the output surface becomes much larger than w_2 in Fig. 3(a), which decreases the power density of the green laser and hence eliminates the gray-tracking effect. The only disadvantage of this method is that the laser beam has a relatively large divergence angle inside the KTP crystal. Since the KTP crystal has a large angular acceptance for type II phase matching, the increase of divergence angle would not influence the conversion efficiency dramatically.

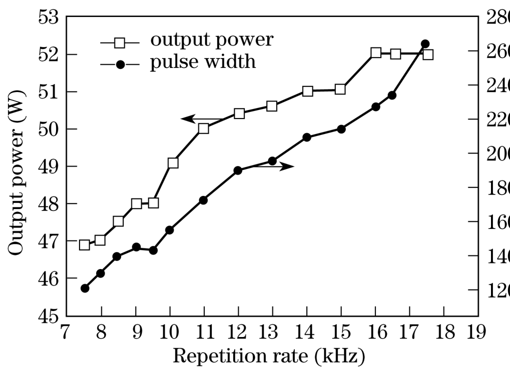

Fig. 2. Output power and pulse width versus pulse repetition rate.

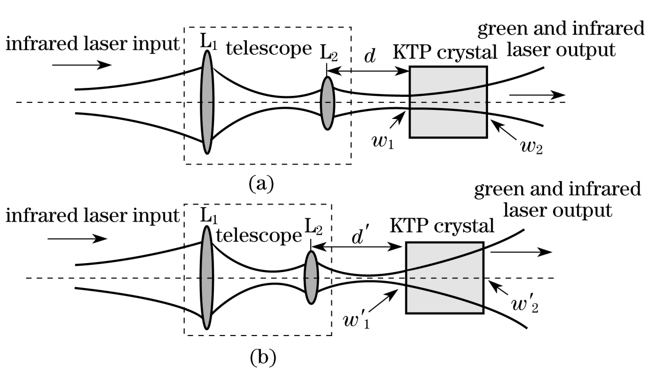

Fig. 3. Schematic of SHG using a KTP crystal. (a) With a weak focal system; (b) with a strong focal system.

Figure 4 shows the simulation results. In the calculation, the focal lengths of lens L_1 is fixed to be 200 mm. We change the focal length of lens L_2 to vary the focus ratio. Two focus ratios of 4:5 and 2:1 are calculated. The focal length of lens L_2 are 250 mm and 100 mm, respectively. The waist beam radius from the Nd:YAG laser is 0.2 mm in the experiment. Then the waist beam radii after the telescope are 0.25 and 0.1 mm respectively. The length of the KTP crystal is 15 mm. With the focus ratio of 4:5, the beam radii both on the incident surface and output surface of KTP crystal are nearly the same, i.e., 0.25 mm. But with a strong focal system of 2:1 focus ratio, if the distance from the KTP crystal to the focal system d' is selected properly (e.g., d' = 170 mm in Fig. 4), the beam radius on the output surface w_2' can be enlarged to 0.3 mm. The beam radius on the incident surface w_1' maintains 0.25 mm simultaneously, which ensures the high conversion efficiency.

From the analysis above, we know that in a strong focal system, the distance d' from the KTP crystal to the focal system has a great influence on the results of SHG. If d' is too long, the conversion efficiency becomes lower. If d'

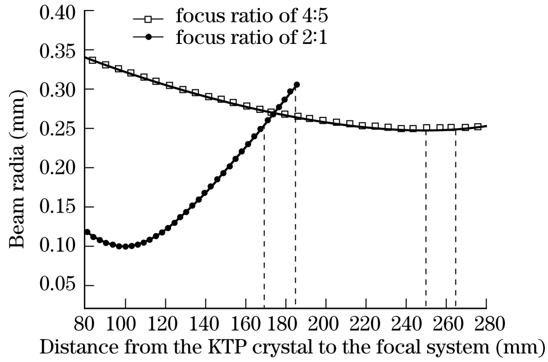

Fig. 4. Beam radii after the focal system with different focus ratios.

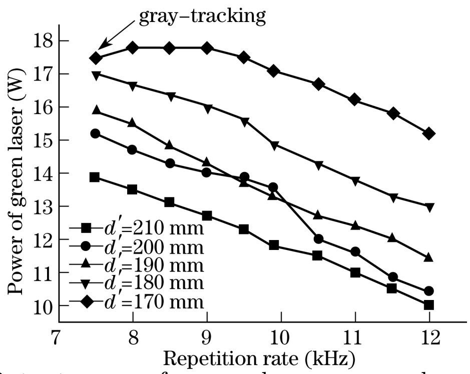

Fig. 5. Output power of a green laser versus pulse repetition rate under different d'.

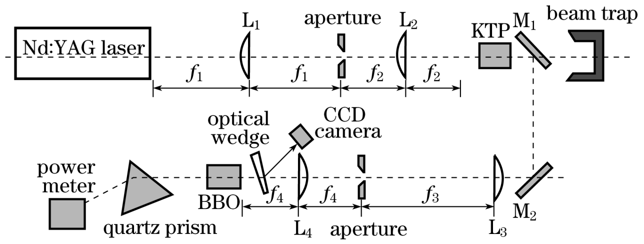

Fig. 6. Schematic of UV laser generation with a BBO crystal.

is too short, gray-tracking effect occurs. Figure 5 shows the output power of a green laser versus pulse repetition rate with different d'. The dimension of the KTP crystal in the experiment is 5×5×15 (mm). The focus ratio of telescope in the experiment is selected to be 2:1. It is obvious in Fig. 5 that the power of green laser increases with the decrease of d'. When $d' = 170$ mm, the maximum conversion efficiency is obtained. A 18-W green laser is achieved with pulse repetition rate of 9 kHz. The intensity is nearly Gaussian-shaped distribution. The measured M^2 factor of the green laser is 1.6. We can see in Fig. 5 that gray-tracking effect occurs with the pulse repetition rate up to 7.5 kHz. When d' goes shorter than 170 mm, the gray-tracking effect becomes more serious. From Fig. 4, we can see that the beam radius on the output surface of KTP crystal is 0.3 mm when $d' = 170$ mm. With the pulse repetition rate of 7.5 kHz, the power of green laser is 17.5 W with pulse width of 120 ns. The calculated threshold of gray-tracking effect is 6.9 MW/cm^2.

The high beam quality of green laser is a key factor for FHG using a BBO crystal. The experimental setup of FHG is shown in Fig. 6. The 1064-nm laser is focused into a KTP crystal using a strong focal system. The output green laser is separated by a dichroic mirror M_1 (HR@532 nm, HT@1064 nm) and then reflected by mirror M_2 (HR@532 nm). The green laser beam is focused into a BBO crystal by a focal system. The output laser beam propagates through a quartz prism and thus the 266-nm UV laser is separated. The BBO crystal used in the experiment has a dimension of 5×5×7 (mm) and a cut-angle of θ=47.6° and $\phi = 90°$ used for type I phase matching. The lens L_3 has a focal length of 300 mm. We change the focal length of lens L_4 to vary the divergence angle of the input green laser. An aperture is inserted between lens L_3 and L_4 for spatial filtering. An optical wedge is used before the BBO crystal for beam intensity profile measurement.

It is found that strong focal systems are not suitable for BBO crystals because the conversion efficiency will decrease due to phase mismatching and there is a best focal condition. A weaker focus ratio also decreases the conversion efficiency due to the lower power density. In our experiment, the optimum focus ratio is 3:2. The average UV laser power increases with the decrease of pulse repetition rate due to the increase of peak power of every single pulse. The maximum UV laser power of 1.9 W is demonstrated with the pulse repetition rate of 7.5 kHz. Due to the reflection of the optical wedge and the spatial filtering by the aperture, the incident power of the green laser is 15.2 W before the BBO crystal. The calculated conversion efficiency is 12.5% from the green laser to the UV laser.

In conclusion, a 1.9-W flash-lamp-pumped solid-state 266-nm UV laser is reported. The good beam quality of 1064-nm laser and the elimination of gray-tracking effect of KTP crystal are the two key factors for 266-nm UV laser generation. Using a dynamically stable resonator design, average power of 52 W is realized with repetition rate of 16 kHz. A strong focal system is suitable for SHG using a KTP crystal. Green laser power of 18 W is demonstrated in 9-kHz repetition rate with beam quality factor M^2=1.6. Using a BBO crystal for fourth harmonic generation, a 1.9-W 266-nm UV laser is realized experimentally. The conversion efficiency from green to UV in the experiment is not high enough as expected because the pulse width is relative long due to the long resonator length. To optimize the resonator length and increase the pulse peak power is our further study goals.

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