Eur. Phys. J. Appl. Phys. **97**, 41 (2022)

https://doi.org/10.1051/epjap/2022210281

THE EUROPEAN PHYSICAL JOURNAL APPLIED PHYSICS

Regular Article

High power green picosecond laser and high efficiency ultraviolet femtosecond laser through second harmonic generation using $K_3B_6O_{10}Br$ crystal

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Received: 10 December 2021 / Received in final form: 19 February 2022 / Accepted: 17 May 2022

Abstract. We demonstrated high power green picosecond (ps) laser and high efficiency ultraviolet (UV) femtosecond (fs) laser through second harmonic generation (SHG) using type I phase-matched $K_3B_6O_{10}Br$ (KBOB) nonlinear optical crystals. The green ps laser was generated by using a homemade high power 1064 nm ps laser as the pump source. When the pump power was 28.2 W with a repetition rate of 800 kHz, 14.2 W ps green laser was obtained with the maximum optical conversion efficiency of 50.4%. When the pump power was 85.2 W with a repetition rate of 800 kHz, the maximum output power of 41.8 W of ps green laser was achieved with an optical conversion efficiency of 49.1%. During the UV fs laser generation, a 710 nm fs laser with a repetition rate of 1 kHz was used to pump the KBOB crystal. When the pump power of 710 nm laser was 54 mW, the 355 nm UV fs laser was obtained with output power of 18 mW and optical conversion efficiency of 33.3%. The experimental results show that the KBOB crystal is a highly qualified candidate for the application in generating high power ultrafast green and UV lasers.

1 Introduction

Ultrafast green and ultraviolet (UV) lasers can control the processing depth and precision more effectively because of their narrow pulse width, high peak power and smaller heat-affected zone [1–4]. Therefore, they have a very important application prospect in industrial processing and precision manufacturing. Frequency conversion based on nonlinear optical (NLO) crystals is a good method to obtain green and UV lasers. NLO crystal is a key factor in the research of frequency conversion.

In recent years, a novel NLO crystal $K_3B_6O_{10}Br$ (KBOB) has been researched. KBOB crystal has a wide transparency range, large NLO coefficients, high laser damage threshold and moderate birefringences [5,6]. At the same time, it is relatively easy to grow large size crystals and possesses superior mechanical properties and high chemical stability [7–8]. In the research of green ultrafast laser using KBOB crystal, Z.Y. Hou et al. researched 532 nm picosecond (ps) laser through second harmonic generation (SHG). The SHG conversion efficiency of KBOB crystal reached 57.3% using a 10 Hz, 25 ps 1064 nm ps laser source. And a 532 nm ps laser with the power of 11.86 W was generated using an 80 MHz, 10 ps 1064 nm laser [9], which is the highest power of 532 nm ps laser generated with KBOB crystal in recent years. In 2018, Meng et al. demonstrated a green ps laser based on KBOB NLO crystal. Through an intracavity frequency-doubling experiment, the average output power of 185 mW ps green laser was obtained with a repetition rate of 80 MHz and pulse width of 25.0 ps. Through an external frequency-doubling experiment, the average output power of 3.00 W green ps laser was generated with a repetition rate of 10 kHz and pulse width of 38.1 ps, which corresponding to the peak power of 7.89 MW and pulse energy of 0.30 mJ [10]. Some papers of ultrafast UV laser based on KBOB have been reported [11,12]. In 2018, Z.Y. Hou et al. obtained a ps UV laser at 355 nm based on a KBOB crystal and sum frequency generation between 1064 nm and 532 nm. The optical conversion efficiency of 30.8% was achieved using a 1064 nm laser with a repetition rate of 10 Hz and pulse width of 25 ps. The average output power

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of 5.3 W was obtained using a 35 W 10 ps laser at 1064 nm as the pump source with a repetition rate of 80 MHz [13]. Compared with the sum-frequency technology to get a 355 nm ultrafast UV laser, the SHG method is simpler, more compact. Generating 355 nm laser by sum frequency generation between 1064 nm and 532 nm laser has group velocity mismatch that causes a reduction in conversion efficiency, while generating 355 nm laser by SHG has no such problem. In 2020, our group reported a 355 nm femtosecond (fs) laser through the SHG method based on KBOB crystal. A 355 nm UV fs laser with the output power of 265 mW and the conversion efficiency of 18.8% was obtained with a pump of 1.408 W fs laser at 710 nm at a repetition rate of 80 MHz [14].

In this paper, we investigated ultrafast green and UV lasers using type I phase-matched KBOB NLO crystals. The KBOB crystals were grown under the new improved growth process, and the optical quality has been greatly improved. And we obtained high output power ultrafast green laser and high conversion efficiency of ultrafast UV laser only through the SHG method. During ultrafast green laser generation, we used a home-made 8.3 ps 1064 nm laser with adjustable repetition rate as the fundamental laser source. When the 1064 nm pump power was 85.2 W with a repetition rate of 800 kHz, we obtained a 532 nm green ps laser with the maximum output power of 41.8 W and the conversion efficiency of 49.1%. The output power and conversion efficiency of 532 nm ultrafast laser that our experimentally obtained are much higher than that of the 532 nm ultrafast laser generated by using KBOB crystals ever reported. During the fs UV laser generation, a ∽85 fs 710 nm laser with a repetition rate of 1 kHz was used as the pump source, and the 355 nm fs UV laser was successfully generated with an optical conversion efficiency of 33.3%, which is much higher than the 18.8% we previously reported. We generated green ps laser with higher output power and UV fs laser with higher conversion efficiency, further strongly demonstrated the application potential of KBOB crystals in generating high power laser, and provided ideas for generating ultrafast lasers with high power and high conversion efficiency based on these crystals.

2 Experimental setup

The schematic experimental setup of SHG based on KBOB crystal is illustrated in Figure 1. In the experiment of the high power ps green laser generation, we used a home-made high power 1064 nm 8.3 ps laser with adjustable repetition rate as the pump laser. The laser beam was collimated to 1.5 mm using a lens group consisting of a convex lens and a concave lens, and then passed through the KBOB crystal. These two lenses were coated for high transmission (HT) at 1064 nm laser. Two type-I phase-matched KBOB crystals with different lengths were used in the experiment. The dimensions of the short KBOB crystal are 4 mm × 4 mm × 5 mm and the dimensions of long KBOB crystal are 4 mm × 4 mm × 13 mm. According to the Sellmeier equations of NLO crystal KBOB, they were cut along $\theta = 34.7°$, $\varphi = 30°$. The entrance and exit surfaces of KBOB crystal were uncoated to avoid damage at high power density. Two second harmonic separators coated for high reflection (HR) at 532 nm and HT at 1064 nm at the incident angle of 45° were used to separate the 1064 nm laser and the output laser at 532 nm. The power of the 532 nm green ps laser was measured using a power meter (Laserpoint A-200-D60-USB).

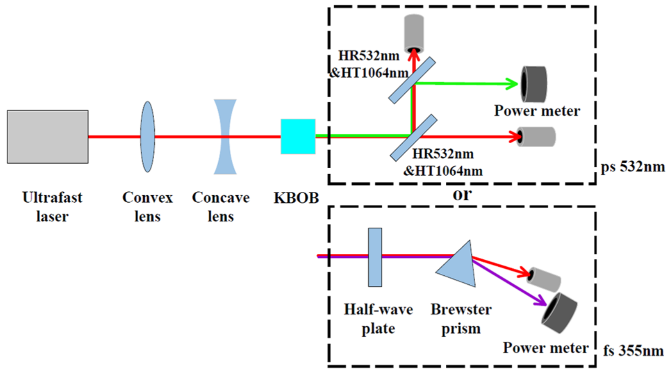

Fig. 1. The experimental setup of SHG based on KBOB crystal.

In the frequency doubling experiment of high efficiency UV fs laser generation, the pump laser was 710 nm fs laser (repetition rate of 1 kHz, pulse width of ∽85 fs). The laser beam was shaped by the lens group. The lens group consisted of a convex lens with a focal length of 150.2 mm and a concave lens with a focal length of –50.8 mm. These two lenses were coated for HT at 680–1080 nm laser. The frequency doubling crystal was a type-I phase-matched KBOB crystal with dimensions of 5 mm × 5 mm × 3.5 mm, and the phase-matching angles were $\theta = 54.05°$ and $\varphi = 0°$. The entrance and exit surfaces of the KBOB crystal were uncoated. The Brewster prism was employed in order to separate 710 nm laser and the frequency doubled 355 nm laser. The 710 nm laser source we used is horizontally polarized, so the polarization direction of the 355 nm UV laser is vertically polarized. In order to reduce the power loss of the Brewster prism on the 355 nm laser, a half-wave plate at 355 nm was used to change the polarization of the 355 nm fs laser to horizontal polarization. The power of the 355 nm UV fs laser was measured using a power meter (Physcience Opto-electronics Co. LPE-1A).

3 Experimental results and discussion

In the experiment of the high power green ps laser, a high power 1064 nm laser with a pulse width of 8.3 ps and adjustable repetition rate was used as the pump source. Figure 2a shows the 532 nm power as a function of the repetition rate for the short KBOB crystal. Figure 2b shows the 532 nm power as a function of 1064 nm pump power for the long KBOB crystal. As shown in Figure 2a, for the short KBOB crystal (4 mm × 4 mm × 5 mm), the power of 532 nm laser decreases with the increasing of the repetition rate it means the power of 532 nm increased with the increasing of the peak power. As shown in Figure 2b, for the long KBOB crystal, the 532 nm power at 800 kHz is higher than that at 1000 kHz, but the 532 nm power at 400 kHz is lower than that at 800 kHz. We think that laser experimental results of the long KBOB crystal were more

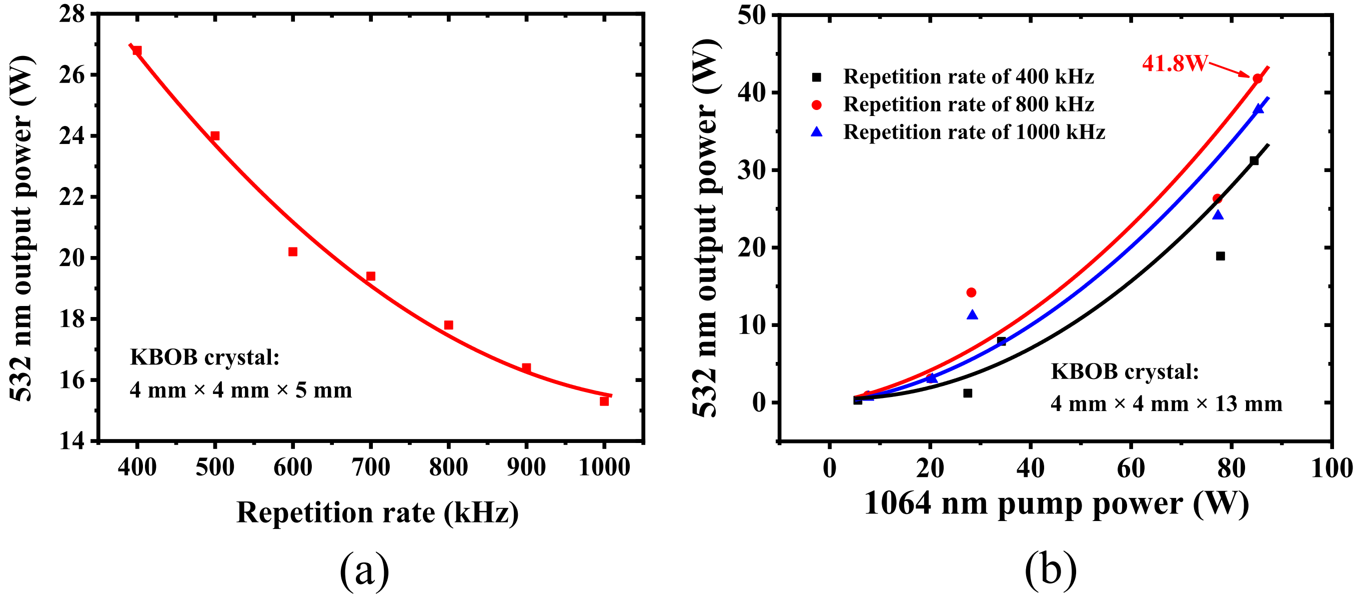

Fig. 2. (a) The 532 nm power as a function of the repetition rate for the short KBOB crystal. (b) The 532 nm power as a function of 1064 nm pump power for the long KBOB crystal.

susceptible to thermal effects under the same experimental conditions during the frequency conversion. At the repetition rate of 400 kHz, the thermal effect was too great in the long KBOB crystal, which affected the effective output of the 532 nm laser. Therefore, in Figure 2b, it occures that the 532 nm power at 400 kHz is lower than that at 800 kHz. When the repetition rate was 800 kHz, 14.2 W green ps laser was obtained with the maximum optical conversion efficiency of 50.4% and the pump power of 28.2 W. The maximum output power of 41.8 W of green ps laser was achieved with the pump power of 85.2 W and the corresponding optical conversion efficiency of 49.1%. The output power and conversion efficiency of 532 nm ultrafast laser that our experimentally obtained are much higher than those generated by using KBOB crystal ever reported. The diameter of the pump laser incident on the KBOB crystal was 1.5 mm. When the pump power was 85.2 W with a repetition rate of 800 kHz, the power density is calculated to be 0.73 GW/cm^2. There is some Fresnel loss at the entrance and exit surfaces of the frequency doubling crystal as the two transmission surfaces of the KBOB crystal are not coated with HT at fundamental laser and second-harmonic laser. The Fresnel loss at 1064 nm laser on each transmitting surface of the KBOB crystal is calculated to be 4.96%. As shown in Figure 3, the stability of the 532 nm ps green laser was measured when the output power was 41.5 W. The root mean square (RMS) power instability in 60 minutes is smaller than 1.0%.

Then the SHG experiment of high conversion efficiency UV fs laser was conducted. The pump laser was shaped by the lens group. In our experiment, the polarization direction of the fundamental 710 nm laser is horizontal. The polarization direction of the frequency doubled 355 nm laser is vertical. The vertically polarized laser has greater power loss when it passes through the Brewster prism than that of the horizontally polarized laser. Therefore, we used a half-wave plate of 355 nm laser in front of the Brewster prism to change the polarization of the UV fs laser to be horizontal.

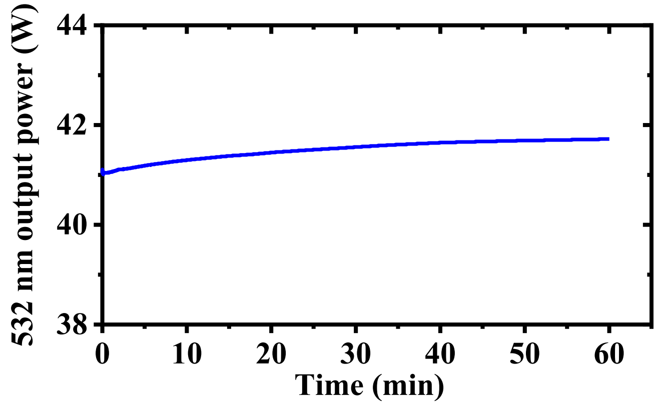

Fig. 3. Power stability of 532 nm ps laser at an output power of 41.5 W.

The output power and conversion efficiency of 355 nm fs laser as a function of 710 nm pump laser was shown in Figure 4. From Figure 4, we can see that the output power and optical conversion efficiency of 355 nm UV fs laser were increased with the increasing of pump power. When the 710 nm laser pump power was 54 mW, a UV laser was generated with the output power of 11 mW and the repetition rate of 1 kHz. The optical conversion efficiency from 710 nm laser to 355 nm laser was 20.4%. In order to obtain higher output power and conversion efficiency of a UV fs laser, we used a convex lens with the focal length of 150.2 mm to replace the lens group to obtain a higher peak power density when the pump laser passed through KBOB crystal. As shown in Figure 5, a UV fs laser with the output power of 18 mW and the repetition rate of 1 kHz was obtained when the 710 nm laser pump power was 54 mW. The optical conversion efficiency from 710 nm to 355 nm was increased to

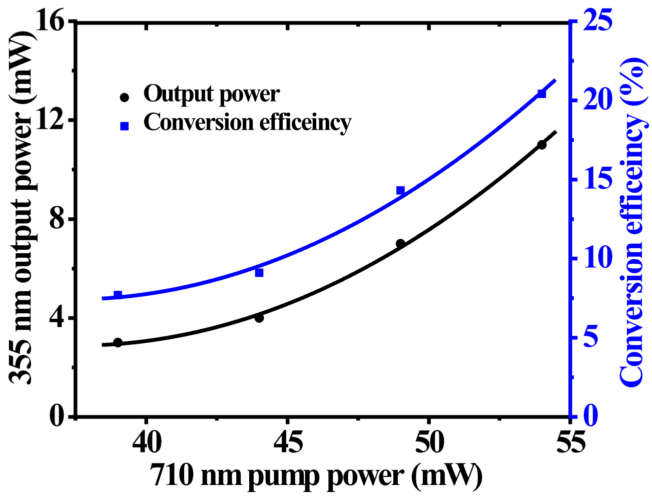

Fig. 4. The output power and conversion efficiency of 355 nm fs laser as a function of 710 nm pump laser (pump laser shaped by the lens group).

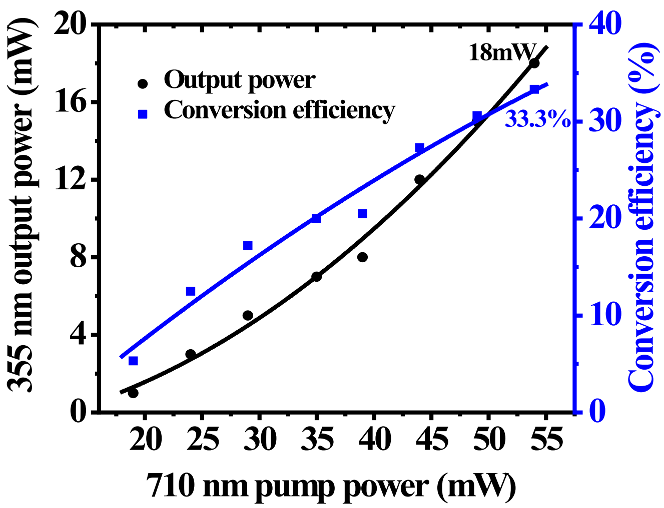

Fig. 5. The output power and conversion efficiency of 355 nm fs laser as a function of 710 nm pump laser (pump laser shaped by the focusing lens).

33.3%. The conversion efficiency of 33.3% is much higher than the 18.8% we previously reported. The spectrum of 355 nm UV fs laser was measured by a spectrometer (Ocean optics MayaPro2000), as shown in Figure 6.

If both surfaces of the KBOB crystals are coated for HT at the fundamental laser and the second-harmonic laser in the above experiments, the output power and conversion efficiency of UV fs laser and green ps laser are expected to increase.

4 Conclusions

In conclusion, we investigated 532 nm ps laser and 355 nm fs laser only through the SHG method using type I phase-matched KBOB NLO crystals. In high power green ps laser, the maximum output power of 41.8 W of 532 nm green ps laser with 800 kHz repetition rate was obtained with the pump power of 85.2 W. The 532 nm ultrafast laser power we obtained by using KBOB crystal is higher than all the results that reported before. In high efficiency UV fs laser experiment, a 355 nm UV fs laser with 18 mW output power and 1 kHz repetition rate was successfully generated. The conversion efficiency of 33.3% is much higher than the 18.8% we previously reported. If both surfaces of the KBOB crystals have HT coatings at the fundamental laser and the second-harmonic laser, higher output power and conversion efficiency of ultrafast UV and green lasers are expected. The experimental results further demonstrated the application potential of KBOB crystals to output high power ultrafast laser, and provided ideas for generating ultrafast lasers with high power and high conversion efficiency based on these crystals.

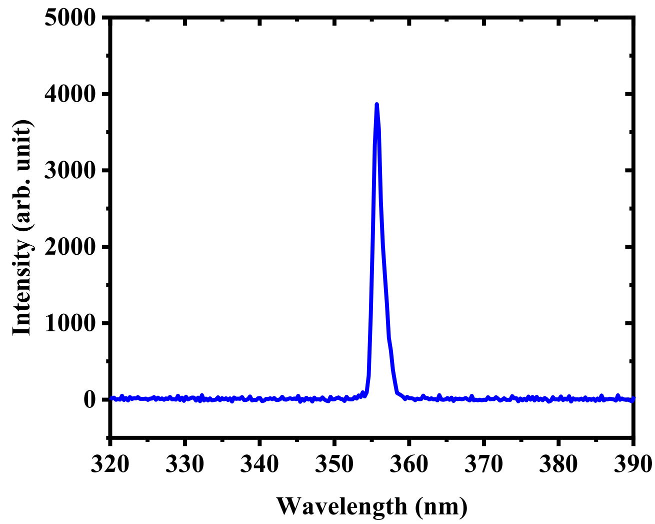

Fig. 6. The spectrum of 355 nm UV fs laser.

This work has been supported by Cross training plan for high level talents in Beijing, Beijing Municipal Science & Technology Commission, Administrative Commission of Zhongguancun Science Park (No. Z211100004821006) and the Youth Innovation Promotion Association of CAS (2020429).

Author contribution statement

Guangxin Tang and Xin Yan did the experiment. Min Zhang solved the problem in the experiment. Zhihao Luan and Hongfeng Li participated in experimental data processing. Qiulin Zhang discussed the experimental results. Ling Zhang wrote the first version of the manuscript. Lirong Wang wrote the final version of the manuscript.

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Cite this article as: Guangxin Tang, Xin Yan, Min Zhang, Zhihao Luan, Hongfeng Li, Qiulin Zhang, Ling Zhang, Lirong Wang, High power green picosecond laser and high efficiency ultraviolet femtosecond laser through second harmonic generation using $K_3B_6O_{10}Br$ crystal, Eur. Phys. J. Appl. Phys. **97**, 41 (2022)