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Ling Zhang, Yun Long, Min Zhang, Chunyong Li, Ying Wang, Shilie Pan, Xingwang Zhang, Xin Zhang, "Femtosecond green and ultraviolet lasers generated using second-harmonic generation based on $K_3B_6O_{10}Br$ nonlinear optical crystals," *Opt. Eng.* **59**(5), 056107 (2020), doi: 10.1117/1.OE.59.5.056107

# Femtosecond green and ultraviolet lasers generated using second-harmonic generation based on $K_3B_6O_{10}Br$ nonlinear optical crystals

**Ling Zhang,[a,b] Yun Long,[c] Min Zhang,[d] Chunyong Li,[c,*] Ying Wang,[d] Shilie Pan,[d] Xingwang Zhang,[a,b] and Xin Zhang[e]**

[a]Chinese Academy of Sciences, Institute of Semiconductors, Key Laboratory of Semiconductor Materials Science, Beijing, China

[b]University of Chinese Academy of Sciences, Center of Materials Science and Optoelectronics Engineering, Beijing, China

[c]Durham University, Department of Physics, Durham, United Kingdom

[d]Chinese Academy of Sciences, Xinjiang Technical Institute of Physics and Chemistry, Key Laboratory of Functional Materials and Devices for Special Environments, Urumqi, China

[e]Wuyi University, Joint Lab of Digital Optical Chip, Jiangmen, China

**Abstract.** We demonstrate the output of femtosecond (fs) green and ultraviolet (UV) lasers through second-harmonic generation using type-I phase-matched $K_3B_6O_{10}Br$ (KBOB) nonlinear optical (NLO) crystals. The wavelengths of the fs green and UV lasers are 515 and 400 nm, respectively. The 1030-nm fs laser is used to pump the KBOB crystal to generate the green output. When the laser pump power reached 880 mW with a repetition rate of 1 kHz, an output power of 235 mW was obtained from the green laser with an optical conversion efficiency of 26.7%. When a pump power of 5.87 W was attained with repetition rate of 10 kHz, a green output power of 1.03 W was generated. The fs UV laser is pumped by an 800-nm fs laser, with 132-mW output power achieved when the pump power was 470 mW with an optical conversion efficiency of 28.1%. The experimental results indicate that the KBOB crystal is a promising NLO crystal for generating fs green and UV lasers because of its excellent NLO properties.  [DOI: 10.1117/1.OE.59.5.056107]

**Keywords:** femtosecond laser; second-harmonic generation; nonlinear optical crystal.

Paper 191700 received Dec. 8, 2019; accepted for publication May 4, 2020; published online May 14, 2020.

## 1 Introduction

In recent years, solid-state femtosecond (fs) green and ultraviolet (UV) lasers have attracted a lot of attention in the fields of physical chemistry, biomedicine, and ultra-precision micromachining owing to the advantages of short pulse width and small heat-affected zones.[1–3] Second-harmonic generation (SHG) or frequency doubling is an effective method used in generating fs green and UV lasers; therein, the nonlinear optical (NLO) crystals play one of the most important roles in the process of promoting the development of laser technology. Up to now, the most commonly used NLO crystals are $KTiOPO_4$, $LiB_3O_5$, and $\beta$-$BaB_2O_4$.[4–6] The increasing demands for scientific and technological development urge researchers to constantly develop new types of NLO crystals and promote the development of laser technology to a higher level.

Recently, a new NLO crystal $K_3B_6O_{10}Br$ (KBOB) has been reported. The crystal has a wide transparency range, moderate birefringence, and relatively large SHG coefficients, and also possesses beneficial chemical and mechanical properties.[7–11] Al-Ama et al.[12] investigated the NLO properties of powdered samples of KBOB that synthesized through hydrothermal techniques in 2006. Zhang et al.[13] further investigated KBOB and first obtained the sizable single crystal via top seeded solution growth method. Then a complete research of linear and NLO properties,

*Address all correspondence to Chunyong Li, E-mail: chunyong.li@durham.ac.uk

0091-3286/2020/$28.00 

both in experiments and theory, was conducted. Xu et al.[14] reported a nanosecond 355-nm laser by third-harmonic generation of an Nd:YAG laser with a 4 mm × 4 mm × 13.3 mm type-I cut KBOB crystal, for which an average power of 19.3 W was achieved. Meng et al.[15] demonstrated a picosecond (ps) green laser based on KBOB NLO crystal, and the average output power of 3-W ps green laser was generated with a repetition rate of 10 kHz and pulse width of 38.1 ps, which corresponds to a pulse energy of 0.30 mJ and a peak power 7.89 MW, respectively. To the best of our knowledge, fs SHG based on KBOB crystal has not been reported.

We investigated fs green and UV lasers via SHG using type-I phase-matched (PM) KBOB crystal. The fs frequency-doubling lasers were successfully generated from two fs lasers (1030 and 800 nm, respectively). These experimental results show that the KBOB crystal is a promising nonlinear crystal for the generation of fs green and UV lasers.

## 2 Experimental Setup

The schematic experimental setup is shown in Fig. 1. The output from the fs laser pumps KBOB crystal to generate the SHG, while two second-harmonic separators ($M_1$ and $M_2$) were used to separate the SHG output from the fundamental pump. The powers of the pump and SHG are monitored by Thorlabs S302C thermal power sensor and PM100D compact power meter console.

For generation of the fs green laser, we use Lightconversion Pharos (1030 nm, 180 fs) as the pump laser, which can be run at different repetition rates; here we chose 1 and 10 kHz. The frequency-doubling crystal KBOB was a type-I PM cut with $\theta = 36.1$ deg, $\varphi = 30$ deg, and dimensions of 7 mm × 7 mm × 1 mm. Compared with commercial UV NLO crystals, KBOB has superior optical properties, namely, large SHG coefficients, short UV cutoff edge (182 nm), and high laser damage threshold (∼64 $\mathrm{GW/cm^2}$ at 1064 nm, 30 ps, 10 Hz). Based on the effective nonlinearity ($d_{\mathrm{eff}}$) equations of crystal with 3 m point group, the $d_{\mathrm{eff}}$ of KBOB crystal for type-I PM at 1030 and 800 nm fundamental wavelength is 0.66 and 0.56 pm/V, respectively.[11] The entrance and exit surfaces of the KBOB crystal were uncoated to avoid damage at high power density. Two second-harmonic separators ($M_1$ and $M_2$) were coated for high reflection (HR) at 515 nm and high transmission (HT) at 1030 nm at the incident angle of 45 deg to separate the residual 1030-nm beam from the output at 515 nm.

In the experiment of fs UV laser, the pump laser used was from Coherent Legend (800 nm, 53 fs, 1 kHz). The frequency-doubling crystal KBOB was type-I PM cut with $\theta = 47.6$ deg, $\varphi = 30$ deg, and dimension 7 mm × 7 mm × 1 mm. The entrance and exit faces of the KBOB crystal were also uncoated. Here, the two second-harmonic separators ($M_1$ and $M_2$) coated for HR at 400 nm and HT at 800 nm at the incident angle of 45 deg were used to separate the residual 800-nm beam from the output at 400 nm.

## 3 Results and Discussion

The fs green laser experiment was carried out first. The beam diameter ($1/e^2$ full width) from the KBOB crystal was 3.93 mm. The output power and conversion efficiency of 515 nm fs laser were shown as a function of 1030-nm pump power in Fig. 2. When the pump power was 880 mW with the repetition rate of 1 kHz, the power density is calculated to be 40.3 $\mathrm{GW/cm^2}$.

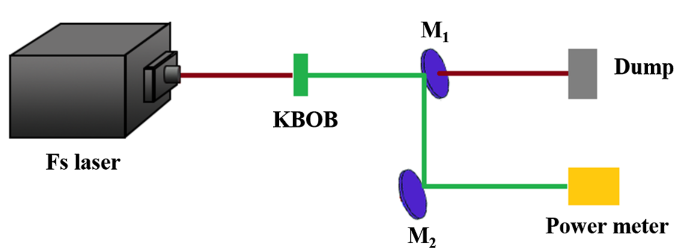


**Fig. 1** The experimental setup of fs SHG green and UV lasers using KBOB as an NLO crystal.

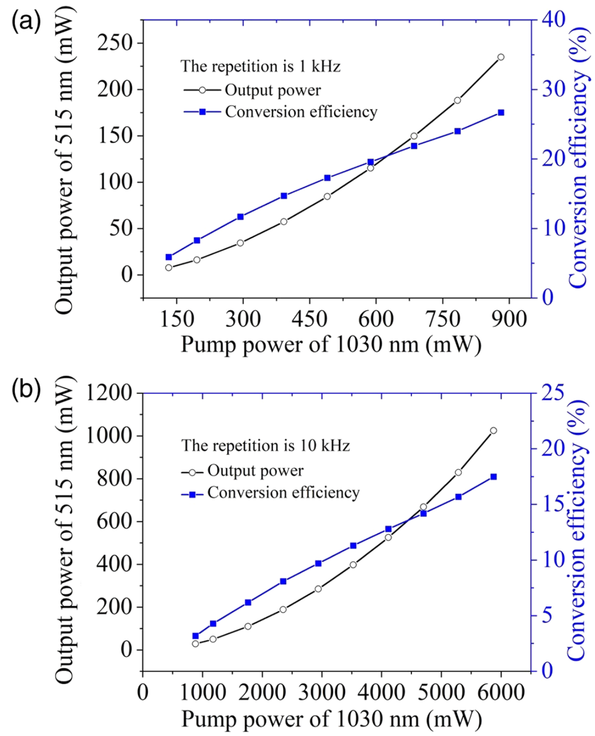


**Fig. 2** (a) The output power and conversion efficiency of 515-nm fs laser as a function of 1030-nm input pump power with the repetition rate of 1 kHz. (b) The output power and conversion efficiency of 515-nm fs laser as a function of the pump power of the 1030-nm laser with the repetition rate of 10 kHz.

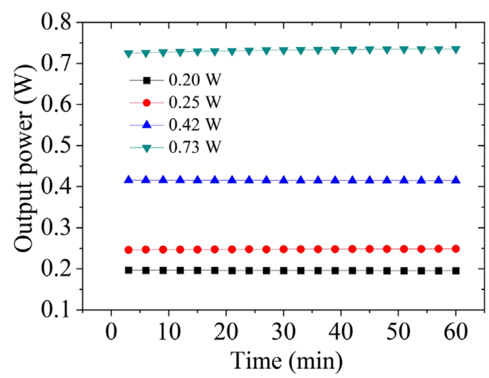


**Fig. 3** Power stability of 515-nm fs laser at different output power.

The SHG output power at 515 nm was 235 mW with an optical conversion efficiency of 26.7%. The pulse width of the green laser was measured to be 132 fs by a home-built autocorrelator, and the single pulse energy and peak power of 515-nm fs green laser were 235 $\mu$J and 1.78 GW, respectively. When the pump power was 5.87 W with a repetition rate of 10 kHz, the power density is calculated to be 26.9 GW/cm$^2$. An fs green laser was generated at 1.03 W with the optical conversion efficiency of 17.5%. As is shown in Fig. 3, the stability of the fs green laser was measured when the output power was 0.20, 0.25, 0.42, and 0.73 W, respectively. In this experiment, the output power of frequency-doubling fs laser was very stable, although the temperature controller of KBOB was not used.

In the experiment of fs UV laser, the pumping laser was operating at 800 nm with the repetition rate of 1 kHz. The output power and conversion efficiency of 400-nm fs laser as function of 800-nm pump laser were shown in Fig. 4. When the output power of fs UV laser was 87 mW,

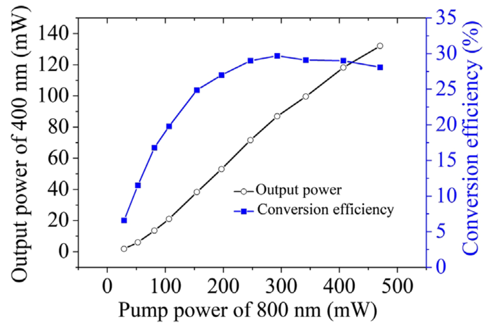


**Fig. 4** The output power and conversion efficiency of the 400-nm fs laser as a function of pump power at 800 nm.

the maximal optical conversion efficiency of 29.7% was obtained. The average output power of 132-mW fs UV laser was achieved when the pump power was 470 mW and the optical conversion efficiency was 28.1%.

The spectra of fundamental and SHG lasers were measured by spectrometer. The spectral widths (FWHM) of 1030-nm laser and 515-nm laser were ∼10 and ∼3.8 nm, respectively. The spectral widths of 800-nm laser and 400-nm laser were ∼30 and ∼2.1 nm, respectively. In this experiment, the group velocity mismatch of 1030-nm laser and 515-nm laser in KBOB crystal is 102.64 fs. The group velocity mismatch of 800-nm laser and 400-nm laser in KBOB crystal is 144.17 fs. In the experiments, there is some Fresnel loss at the entrance and exit surfaces of the crystal as the two transmission surfaces of the KBOB crystal are not coated with antireflective (AR). In the experiment of the fs green laser, the Fresnel loss at each transmitting surface of KBOB crystal[16] is about 4.97%. Similarly, in the experiment of the fs UV laser, the Fresnel loss at each transmitting surface of KBOB crystal is about 4.85%. If the KBOB crystals have AR coatings both at the fundamental laser and the frequency-doubling laser on both surfaces of the crystals, higher output power and conversion efficiency of fs green laser and UV laser are expected.

## 4 Conclusions

In conclusion, we demonstrated the effective generation of fs green and UV lasers using a type-I PM KBOB crystal. The fs frequency-doubling lasers were successfully generated from two types of fs lasers with one operated at 1030 nm and the other at 800 nm. Using pump power of 880 mW at 1030 nm and 1 kHz repetition rate, the SHG output power at 515 nm was 235 mW. A 515-nm fs green laser of 1.03 W was obtained with the 1030-nm pump power of 5.87 W at repetition rate of 10 kHz. The average output power of 132 mW was achieved for an fs UV laser operating at 400 nm with pump power of 470 mW. This work indicates that the KBOB crystal is a highly qualified candidate for the application in generating fs green and UV lasers.

## Acknowledgments

This work has been supported by the Guangdong Provincial Science and Technology Program (Grant No. 2018B090904002), Science and Technology Project of Urumqi (Grant No. P161010003), and the Youth Innovation Promotion Association of Chinese Academy of Sciences (Grant No. 2020429).

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**Ling Zhang** received her PhD from the Institute of Physics, Chinese Academy of Sciences (CAS), Beijing, in 2006. Currently, she is an associate professor at the Institute of Semiconductors, CAS. Her research interests include ultrafast lasers and their frequency conversion. She has authored and coauthored more than 80 journal and conference publications.

**Yun Long** received her BA and MSc degrees in natural sciences (physics) from the University of Cambridge, United Kingdom, in 2012. She received an MSc degree in photonic and optoelectronics devices and her PhD in organic semiconductor photophysics from the University of St. Andrews. She then carried out postdoctoral research in organic materials at the University of Durham, United Kingdom, and is now a research associate in ultrafast spectroscopy at Rutherford Appleton Laboratory in Didcot.

**Min Zhang** is a professor at Xinjiang Technical Institute of Physics and Chemistry, CAS, China. He received his PhD from the University of Chinese Academy of Sciences (UCAS) in 2012 and promoted to professor in 2019. His research interest focuses on optical crystals.

**Chunyong Li** received his BS degree in physics from Peking University, Beijing, China, in 1999 and his PhD in optics from the Institute of Physics, CAS, Beijing, China, in 2004. Currently, he is working as the laser science experimental officer in the Department of Physics, Durham University. His research interests include solid-state lasers and ultrafast spectroscopies.

**Ying Wang** received his PhD in material physics and chemistry at the UCAS in 2015. In the same year, he started his independent career as an assistant professor at Xinjiang Technical Institute of Physics and Chemistry of CAS, and promoted to associate professor in 2017. Currently, he is an associate professor at Hebei University, China. His current research interest focuses on nonlinear optical (NLO) materials.

**Shilie Pan** is a professor at Xinjiang Technical Institute of Physics and Chemistry, CAS, China. He received his PhD from the University of Science and Technology of China in 2002. He had conducted postdoctoral studies both in China and USA from 2002 to 2007. His research interest focuses on NLO material. He has published over 400 papers in international journals.

**Xingwang Zhang** received his bachelor and PhD degrees in physics from Lanzhou University in 1994 and 1999, respectively. He worked in succession as a postdoctoral and as a Humboldt Research fellow at the Chinese University of Hong Kong and University of Ulm, Germany, from 1999 to 2004. Then he joined the Institute of Semiconductors, CAS as a full professor. His current research interests include two-dimensional atomic crystals, photovoltaic materials and devices.

**Xin Zhang** received his MS degree from the University of Electro-Communications, Japan, in 2001, and his PhD from Harbin Engineering University, China, in 2007. Currently, he is a professor at Wuyi University. His research interest focuses on communication technology.