High-power, widely tunable, green-pumped femtosecond BiB$_3$O$_6$ optical parametric oscillator

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We report on an efficient high-power, widely tunable femtosecond optical parametric oscillator in BiB$_3$O$_6$, synchronously pumped by a frequency-doubled mode-locked Yb:KGW laser at 515 nm. Using collinear type I (o → e + e) phase matching, a resonant wavelength range of 688–1057 nm at a 151-MHz repetition rate is demonstrated, with a tunable idler range of 1150–1900 nm. The output power at 705 nm is 1.09 W for 3.6 W pump power exceeding 30% conversion efficiency. Near-transform-limited pulses down to 71 fs are achieved by deploying extracavity dispersion compensation in a pair of SF$_6$ prisms. © 2016 Optical Society of America

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High-power, high-repetition-rate femtosecond pulses in the region of 700–1000 nm are of great interest for a variety of applications, such as biophotonics, time-resolved spectroscopy, and optical frequency combs [1–3]. Ti:sapphire laser, as the workhorse for so long [4,5], can generate more than 1 W average power, with broadband spectrum or tunable wavelength over 700–1000 nm; however, it costs a lot and produces sub-100 fs pulses only around 800 nm. Another attractive alternative approach that has been promoted recently is the femtosecond optical parametric oscillators (OPOs) synchronously pumped by the second harmonic generation (SHG) of Yb:KGW (Yb:KGW) laser, providing signals tuning over 780–940 nm with the maximum output power of 250 mW [6]. Based on a noncollinear BBO OPO pumped by the SHG of a femtosecond Yb:KGW laser at 525 nm, thin-disk oscillator, and four times larger than those of BBO and LBO, respectively.

Second, both the BBO and LBO crystal possess two couples large angular and spectral acceptance bandwidth, low spatial walk-off, and broadband angle tuning at room temperature. It is also not hygroscopic and is readily available in high optical
quality, in large size, and at low cost [12]. Up to now, several studies on nonlinear frequency conversion including femtosecond OPO, SHG, and optical parametric amplification have been reported [13–16].

In this Letter, we report on an efficient high-power femtosecond BIBO OPO pumped by a 515 nm femtosecond green source for the first time. Using 1-mm-long BIBO and deploying type I ($o \rightarrow e + e$) phase matching, we obtain widely tunable resonant pulses from 688 to 1057 nm at 151 MHz by angle tuning. The maximum output power is as high as 1.09 W with a fluctuationless less than 2% rms over 1 h for 3.6 W pump power. We use a pair of SF6 prisms for extracavity dispersion compensation and realize the near-transform-limited pulses with duration down to 71 fs. By replacing the output coupler with a flat high-reflectivity mirror, idlers across 1150 to 1900 nm with the maximum average power of 414 mW are also generated.

The schematic of the experimental setup is shown in Fig. 1. The pump source is a commercial Kerr-lens mode-locked Yb: KGW laser (Light Conversion, FLINT6.0) delivering 90 fs pulses at 1030 nm with up to 6.8 W average power. The repetition rate of the Yb:KGW laser is 75.57 MHz, corresponding to the linear cavity length of 198.35 mm. The fundamental wave is focused by a lens ($L_1$, $f = 75$ mm) into a 2.5-mm LBO crystal cut at $\theta = 90^\circ$ and $\varphi = 13.6^\circ$ for type I ($e \rightarrow o + o$) SHG, whose two surfaces are both antireflection coated at both 1030 and 515 nm wavelengths. A half wave plane (HWP) at 1030 nm was used to control the polarization of the fundamental wave. The generated second harmonic wave centered at 515 nm had as large as 4.1 W average power and was collimated with the second lens ($L_2$, $f = 150$ mm). The optical spectrum of the SHG pulses is also depicted in Fig. 1. We used four dichroic mirrors (DMs) to separate the second harmonic and the fundamental wave. To control the power and polarization of the second harmonic radiation, an attenuator consisting of two HWPs and a polarization beamsplitter (PBS) was used. The second harmonic wave was focused into the BIBO crystal using a lens ($L_3$, $f = 150$ mm). Due to the loss from the DMs and the lenses, the maximum power after $L_3$ was 3.6 W.

The signal single resonant OPO was a linear standing wave cavity with five mirrors, whose repetition rate was set to be 151 MHz, corresponding to twice of that of the pump laser. $C_1$ was a concave mirror with 150 mm radius of curvature (ROC), coated with high reflectively over 620–1080 nm ($R > 99.9\%$), and high transmittance around 488–532 nm ($R < 5\%$). A concave mirror with ROC of 100 mm ($C_2$) and two flat mirrors ($HR_1$ and $HR_2$) were not only coated with high reflectivity over 620–1120 nm ($R > 99.9\%$) but were also group delay (GD) optimized. The output coupler (OC), which was mounted on a translation stage for finely tuning the cavity length, had 11% transmittance at the range of 640–1050 nm and was GD dispersion optimized. The BIBO crystal was cut at $\theta = 174^\circ$ and $\varphi = 90^\circ$ for type I ($o \rightarrow e + e$) phase matching in the $y - z$ plane and coated with high transmittance in both the 510–530 and 700–1040 nm regions. Taking the material dispersion and the group velocity mismatching between pump and signals of the BIBO crystal into consideration, here we used a 1-mm-long BIBO crystal. The beam waist radius in the center of the BIBO was calculated to be 23 $\mu$m based on the ABCD matrix. The corresponding spatial walk-off length and the maximum incident angle for such 1-mm-long BIBO crystals were 11.79 $\mu$m and 9.3 mrad, respectively, which were much smaller than the waist diameter of both signal and pump as well as the acceptable angular of 33.2 mrad. Therefore, they would have little effect on the OPO performance. In addition, the average temporal walk-off between the signals from 650 to 1030 nm and pump of 515 nm for 1-mm-long BIBO crystal was 134 fs. While this would have some implications on the pulse duration of signal pulses, a pair of prisms (SF6) was employed to compensate the dispersion outside the cavity. The extracavity dispersion compensation would also reduce the difficulty for pre-alignment of the cavity over intracavity dispersion compensation using a prism pair.

The OPO cavity was aligned with the green laser easily, and then the parametric oscillation was achieved by finely tuning the cavity length to meet the synchronous pumping condition. After fine alignment, the maximum output power of 1.09 W at the fundamental transverse mode (TEM$_{00}$) for 3.6 W pump power was obtained when the pump laser was normally incident into the BIBO crystal, resulting in the maximum gain and minimum loss. The corresponding signal was 705 nm. Figure 2 shows the dependence between the output power and the pump power.

![Fig. 1. Sketch for the experimental setup of the femtosecond OPO based on a BIBO. HWP: half wave plate; DM1–DM4: dichroic mirrors; PBS: polarization beamsplitter; L1–L3: lenses; HR1–HR2: high-reflectivity flat mirrors; OC: output coupler; C1 and C2: concave mirrors; SF6: prism. Inset: optical spectrum of the SHG pulses.](image)

![Fig. 2. Output power (black) and the corresponding conversion efficiency (blue) of the femtosecond OPO based on BIBO. Inset: beam profile at the maximum output power.](image)
It is obviously to see that the output power was linearly increasing with the pump power, and the maximum conversion efficiency was about 30%. The beam quality ($M^2$) at the maximum output power was also measured with a commercial $M^2$ factor meter (Spiricon $M^2$−200 s), resulting in the $M^2_X$ and $M^2_Y$ being equal to 1.33 and 1.37, respectively. The beam quality factor was higher than that of the pump pulses ($M^2_X = 1.19$ and $M^2_Y = 1.10$), which originated from the astigmatism caused by two folded concave mirrors. The inset in Fig. 2 is the near-field beam profile at the maximum output power.

Then we performed the output stability by measuring the long-term average power fluctuation. For the fixed pump power of 3.6 W, the recorded power stability in 1 h is shown in Fig. 3. It can be seen that the output power was naturally stable with a fluctuation of 2% rms over 1 h. For comparison, we also give the corresponding power stability of pump power with only 0.2% rms fluctuation in 1 h, as inserted in Fig. 3. The dropping of power stability was believed to be derived from the ambient temperature fluctuation, air flow, and mechanical vibration, which can be effectively suppressed by isolation and active feedback control.

By changing the angle of BIBO, resonant pulses from 688 to 1057 nm were obtained, and their spectra were measured with a commercial optical spectrum analyzer (YOKOGAWA, AQ6370C), as shown in Fig. 4. It should be noticed that the resonant wavelength is beyond the signal wavelength limit (1030 nm), which can be attributed to the wider reflection coating range. The shortest wavelength of 688 nm in our experiment was limited by the phase-matching condition of the BIBO on the $y-z$ plane, and the longest wavelength of 1057 nm was limited by the coating of the C1 mirror (high reflectivity over 620–1080 nm). The maximum average powers at different resonant wavelengths are also depicted in Fig. 4. All the maximum average powers of the resonant pulses across the tuning range were above 450 mW.

For extracavity dispersion compensation, a pair of SF6 prisms with the tip–tip distance between the two prisms of 370 mm was employed. Fine dispersion control was managed by changing the insert length of the second prism. The pulse duration with dispersion compensation was in the range of 71 to 122 fs, measured by a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.). Figure 5 shows the typical intensity autocorrelation trace and optical spectrum for signal at 850 nm. The full width at half-maximum (FWHM) bandwidth of the spectrum at 850 nm was 15 nm, and the corresponding transform-limited (TL) pulse duration was 52 fs, calculated by Fourier transforming the spectrum without dispersion. The autocorrelation width of the TL pulse was 79 fs, which was close to the measured value of 109 fs as shown in Fig. 5.

The idler performance was also characterized by replacing the output coupler with a flat high-reflectivity mirror and extracting the idlers directly from the behind of C2. The idler spectra were recorded from 1150 to 1900 nm with a commercial wavelength meter (WaveScan, A. P. E GmbH), as shown in Fig. 6. Figure 6 also depicts the output powers crossing the idler range. Because the surface of C2 was not coated with high transmittance in the idler range, the maximum average power of the idler was 414 mW with a rapid drop of power near
1150 nm. This is because it is close to the edge of the coating of the C2 mirrors with high reflectivity over 620–1120 nm. The idler spectra seem to be a smooth Gaussian shape since they were single passing through the BIBO. The pulse durations over the tunable idler range were in the range of 94 to 223 fs, if hyperbolic secant shape pulses were assumed, measured by a commercial autocorrelator (PulseCheck-50, A. P. E. GmbH). Shown in Fig. 7 is the typical intensity autocorrelation trace of the 1670 nm idler whose spectrum is displayed in Fig. 6; the corresponding pulse duration is 94 fs.

In conclusion, we have reported on a femtosecond BIBO OPO synchronously pumped by the SHG of a Kerr-lens mode-locked Yb:KGW laser. Using an OC with 11% transmittance, the maximum output power of 1.09 W at 705 nm has been obtained, with a long-term average power fluctuation of 2% rms in 1 h. The signal conversion efficiency is 30%, and the total efficiency including the idler is 41.4%. By rotating the angle of the 1-mm-long BIBO, resonant wavelength covering from 688 to 1057 nm was realized, with the average power more than 450 mW for 3.6 W pump power. Using a pair of SF6 prisms for extracavity dispersion compensation, the shortest pulse duration was compressed down to 71 fs at 850 nm. Moreover, we have characterized the idler performance by replacing the OC with a high-reflective mirror. Idlers from 1150 to 1900 nm were obtained with the maximum output power of 414 mW. The typical pulse duration of the idler at 1670 nm was as short as 94 fs. Compared to previous works with BBO or LBO crystals [6–10], here we not only obtain the widest tunable pulses range from 688 to 1900 nm but also realize the highest parametric conversion efficient of 30% from pump to signal power. Future work will be focused on increasing the output power by refocusing the residual pump power and extending the operating wavelength by intracavity SHG and SFG processes. Such a high-power 100-fs widely tunable NIR femtosecond source is believed to be attractive in various applications such as time-domain spectroscopy and frequency metrology.

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**REFERENCES**