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Generation of Femtosecond Laser Pulse at 1.43 GHz from an Optical Parametric Oscillator Based on LBO Crystal *

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A femtosecond LBO optical parametric oscillator (OPO) with widely adjustable repetition rate by fractionally decrement of the cavity length is demonstrated. The repetition rate of 755 MHz to 1.43 GHz at an interval of 75.5 MHz is realized, which is 10 to 19 times that of the pump laser. The properties of output signal at 750 nm at different repetition rates are studied. The power of signal decreases with increasing the repetition rate. The maximum power of 194 mW at the repetition rate of 755 MHz and the minimum power of 22 mW at repetition rate of 1.43 GHz for the signal at 750 nm are obtained for the pump power of 3 W.

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Broadly tunable femtosecond laser sources with repetition-rates up to several GHz have opened impact applications in the fields of precision spectroscopy, multi-photon fluorescence microscopy and optical telecommunications.[1−4] Synchronously pumped optical parametric oscillators (SPOPOs) can provide broadband wavelength range and short laser pulse duration, and can be locked with low noise level. In recent years, femtosecond OPOs with GHz mode spacing have been in demand for some particular applications such as astronomical spectrograph calibration, optical arbitrary waveform generation and optical coherence tomography.[5−7] However, generation of broadband ultrashort laser pulses at high repetition rate of GHz is of challenge, due to the fact that the peak power of the resonating signal radiation available to drive bandwidth-enhancing $\chi^{(2)}$ and $\chi^{(3)}$ nonlinear effects is decreased at higher repetition rates. At present, Ti:sapphire oscillators at high repetition rates are mature and commercial available, the tuning range and output power of SPOPOs are limited by that of Ti:sapphire lasers, especially in the near-infrared range 1000–2000 nm. For a given pump source at a low repetition rate, there are two methods to achieve OPO radiation at a high repetition rate: the first method is harmonically pumped OPO (i.e. the cavity length of the OPO is set to be N times shorter than that of the pump source), so the repetition rate of OPO is N times of pump source. In 1997, a harmonically pumped OPO was first reported by Reid *et al.*[8] The output power of 600 mW at 344 MHz was achieved, with the repetition rate of four times that of the pump laser. In 2000, Phillips *et al.* reported a 322-MHz femtosecond OPO pumped by an 80.5-MHz KLM Ti:sapphire oscillator, the average output power was 280 mW with the wavelength range of 1.00–1.14 µm.[9] In 2002, Jiang *et al.* reported a 1-GHz femtosecond OPO harmonically pumped by an 84-MHz Ti:sapphire oscillator.[10] Several years later, Balskus *et al.* demonstrated the first femtosecond OPO frequency comb harmonically pumped by a 333-MHz Ti:sapphire oscillator, in which a stabilized signal comb at 1-GHz mode spacing was realized.[11] However, due to the configuration of OPOs, length of an OPO cavity cannot be shortened infinitely. The second method is fractionally declining or increasing the length of the OPO cavity. When the cavity length of the OPO ($L_{\rm OPO}$) and pump source ($L_{\rm PUMP}$) satisfy the equation $M \times L_{\rm OPO} = N \times L_{\rm PUMP}$ ($M = 1, 2, 3,\ldots; N = 1, 2, 3,\ldots$), the OPO at a repetition rate of $MF_{\rm PUMP}$ ($F_{\rm PUMP}$ is the repetition rate of the pump laser) will be realized.[12] This method could get a high-repetition-rate OPO radiation based on a normal configuration of cavity. In 2002, fractionally increment of the OPO cavity length was first reported by Jiang *et al.*,[13] and the output power of 80 mW at 240 MHz, which was three times that of pump laser, was realized. In the next year, they reported a 400 MHz OPO using a PPLN crystal, with repetition rate of four times of the pump source and the maximum signal power of 65 mW.[14] In 2009, Kokabee *et al.* reported a 1 GHz OPO pumped by a 76 MHz Ti:sapphire oscillator with repetition rate of 14th harmonic of the pump laser.[15] For all the above-mentioned results, the Ti:sapphire

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oscillators were employed as pump lasers, the output power was limited to hundreds of mW, and the tunable wavelength range was limited to 1.1–1.6 µm. With the development of ytterbium-doped (Yb-doped) fiber and solid-state oscillators, high power femtosecond Yb oscillators are a kind of very good candidates for pumping SPOPOs.[16−20] In 2016, we have demonstrated a high-repetition-rate OPO pumped by a fundamental frequency Yb:KGW fs laser. The repetition rate of 37.3 GHz was achieved by fractionally increasing the length of OPO cavity. The output power was 90 mW under 2 W pump power.[12] Nevertheless, high repetition rate OPO pumped by green laser is less reported. In a case of several hundreds of MHz up to a few GHz, high efficiency conversion compensates for the large cavity loss of the resonating signal radiation, which is favorable to improve repetition rate of a green pumped femtosecond OPO without sacrificing other parameters such as pulse duration or stability.

In this Letter, we demonstrate a GHz femtosecond LBO OPO system synchronously pumped by a femtosecond 515 nm laser. By decreasing the cavity length of $\Delta L = L_{\rm PUMP}/10$, the signal repetition of 755 MHz is achieved. Using a 5-mm-long LBO as the nonlinear crystal, the maximum signal power of the OPO is 194 mW at the central wavelength of 750 nm, corresponding to a pump to signal conversion efficiency of 6.5%. The signal pulse duration of 159 fs is measured at 750 nm. The signal powers have rms fluctuations of less than 1.6% over 30 min and the M^2 factors in the horizontal and vertical directions are 1.281 and 1.168, respectively. The signal repetition rate as high as 1.43 GHz is also achieved by decreasing the OPO cavity length of $\Delta L = L_{\rm PUMP}/19$.

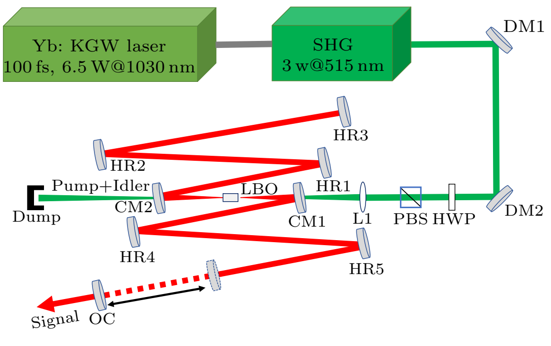

Fig. 1. Schematic of high-repetition-rate femtosecond OPO. HWP: half wave plate; PBS: polarizing beam splitter; DM1, DM2: dichroic mirror; L1: lens; CM1, CM2: concave spherical mirrors; HR1-HR5: plane mirrors; OC: 1% output coupler.

The experimental setup is shown in Fig. 1. The 515 nm pump source is generated from a frequency-doubled mode-locked Yb:KGW laser (Light Conversion, FLINT6.0) in a 2.5-mm-long LBO crystal. The repetition rate of 515 nm laser is 75.5 MHz with power of 3 W. A half wave plate (HWP) and a polarizing beam splitter (PBS) are employed as a variable attenuator to change the power of the 515 nm pump laser.[21] The pump laser is focused into the LBO crystal by a focal lens L1 with focal length of 100 mm. The configuration of the OPO is a Z-type cavity which consists of two concave mirrors (CM1 and CM2) with curvature radius of 100 mm, five plane mirrors (HR1-HR5), and an output coupler (OC). All mirrors are coated with high reflectivity for the signal in the range of 650–1020 nm. The concave mirrors CM1 and CM2 are also coated with high transmission ($T > 99.9\%$) for the pump source at 488–532 nm. To overcome large cavity loss of signal pulses, an OC with 1% transmission is used to increase power density inside the cavity. The OC is mounted on a translation stage, which can be used to finely control the length of the cavity to achieve synchronization with the pump pulse. A 5-mm-long LBO is used as the nonlinear crystal, which is cut at $\theta = 90^\circ$, $\varphi = 11.6^\circ$ for type-I($e \rightarrow o + o$) phase-matching condition in the X–Y plane, and coated with antireflection in wavelength ranges of 510–530 nm and 650–1050 nm. The beam waist radius of signal is about 17 µm in the LBO crystal, which is almost equal to that of the pump source.

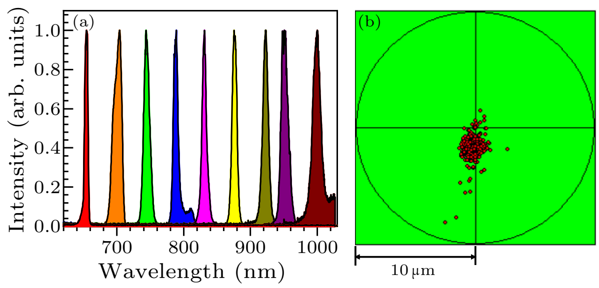

Fig. 2. (a) Signal output spectrum tunable by tuning the cavity length and rotating LBO crystal. (b) Signal beam pointing stability.

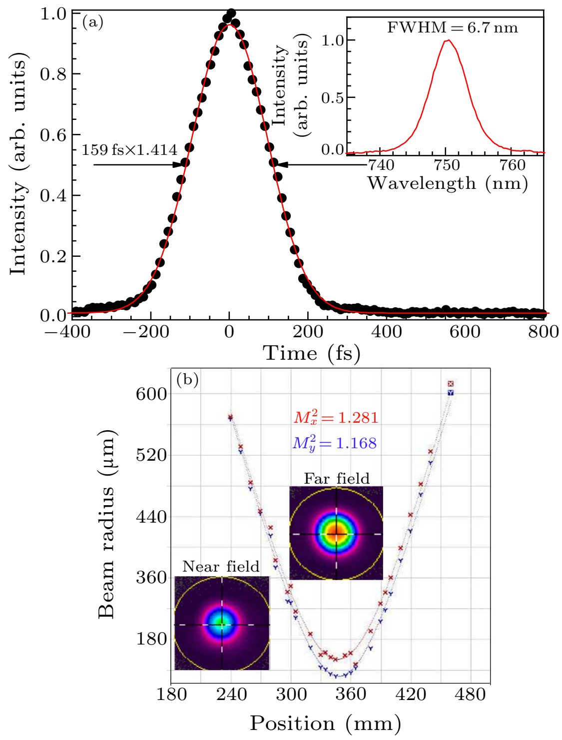

Fig. 3. (a) Typical intensity autocorrelation trace and spectrum at 750 nm. (b) Spatial profile of the signal beam.

The OPO works at 75.5 MHz, which is the same as that of the pump laser with cavity length of 1986 mm. The output signal is tuned from 650 nm to 1000 nm by optimization of the OPO cavity length and rotating the LBO phase matching angle, as shown in Fig. 2(a). In 5 min, the beam pointing stability of the output laser is also measured. As shown in Fig. 2(b), the maximum deviation is 8.5 µm, which corresponds to the maximum angle jitter of 28.3 µrad. We can obtain a much better beam pointing stability if we use fixed mirror mounts and active feedback loop to control the cavity. By decreasing the OPO cavity length of $\Delta L = L_{\rm PUMP}/10$, i.e. 19.8 cm, the signal repetition rate of 755 MHz is achieved. With 3 W pump power, the maximum output power is 194 mW at 750 nm, which corresponds to the pump-to-signal conversion efficiency of 6.5%. The pump threshold of the OPO at 755 MHz was increased to 1.5 W due to the incremental loss of multiple cavity round trips. The intensity autocorrelation trace is 224 fs at 750 nm, as shown in Fig. 3(a). Assuming a Gaussian pulse shape, the pulse duration is calculated to be 159 fs, which is very closed to the transform-limited pulse duration of 123 fs calculated from the measured signal spectrum as shown in the inset of Fig. 3(a). Figure 3(b) shows the beam quality M^2 of the output laser measured by a M^2 factor meter (Spiricon M2-200 s), which exhibits a Gaussian shape to a good approximation with only small ellipticity. The M^2 factors are 1.281 and 1.168 in the horizontal and vertical directions, respectively. This beam quality is better than that of the output at 75.5 MHz (usually >1.3). The reason of good beam quality at higher repetition rate is that the pulses in the cavity experience more tremendous loss under the condition of high-repetition-rate operation, and only the signal with good spatial coupling with the pump laser in the crystal could be amplified.

The output pulse trains of signal are detected by a high speed photodiode and a 26 GHz spectrum analyzer (R&S FSW26). Figure 4(a) shows the 755 MHz radio-frequency (rf) spectrum with a span of 2 GHz and span of 100 kHz, respectively. The perfect rf spectrum indicates that the cavity length of the OPO is well matched with that of the pump source. The other harmonic frequencies besides the 755-MHz repetition frequency are also detected, due to the periodic modulation of the signals at the repetition rate of 75.5 MHz, which is equal to that of the pump laser. As shown in Fig. 4(c), the signal pulse trains at the 10th harmonic of the input repetition rate are detected by a fast photodiode and recorded by an oscilloscope with 1-GHz bandwidth (DPO5104B, Tektronix). There are 10 progressively increasing signal pulses in one pump period. This is due to the fact that the prior signal pulses suffer one more cavity loss in one pump period. The signal pulse train indicates that the OPO works with a high stability.

The signal repetition rate from 755 MHz to 1.43 GHz at an interval of 75.5 MHz is achieved by decreasing the cavity length of $\Delta L = L_{\rm PUMP}/N$ ($N =$ 10, 11, 12,..., 19). The detailed information of the 12th and 15th harmonic repetition rates is recorded by an oscilloscope, as shown by Figs. 5(b) and 5(c). We also measure the rf spectrum of the signal pulse trains at the repetition rate of 1.43 GHz, as shown in Fig. 5(c) .

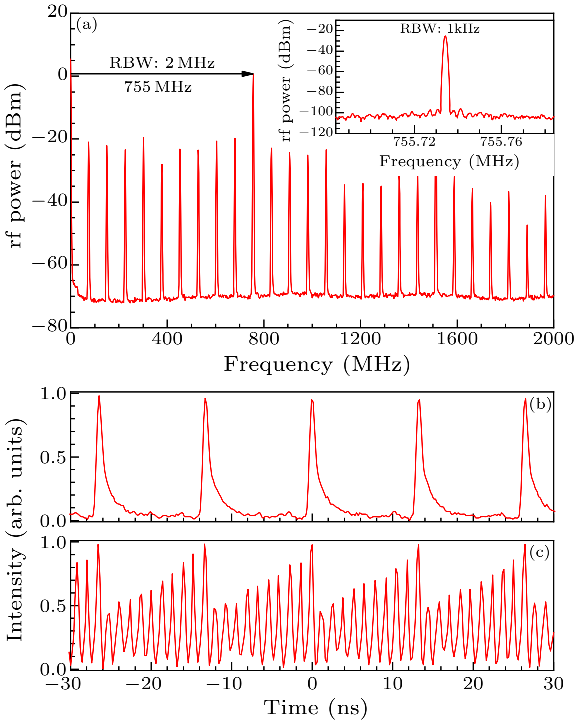

Fig. 4. (a) Typical radio-frequency spectrum of 755 MHz from 0 Hz to 2 GHz with 2 MHz resolution. Inset: radio-frequency spectrum spanning 100 kHz with 1 kHz resolution. (b) and (c) Pulse train of the pump laser and 755 MHz signals.

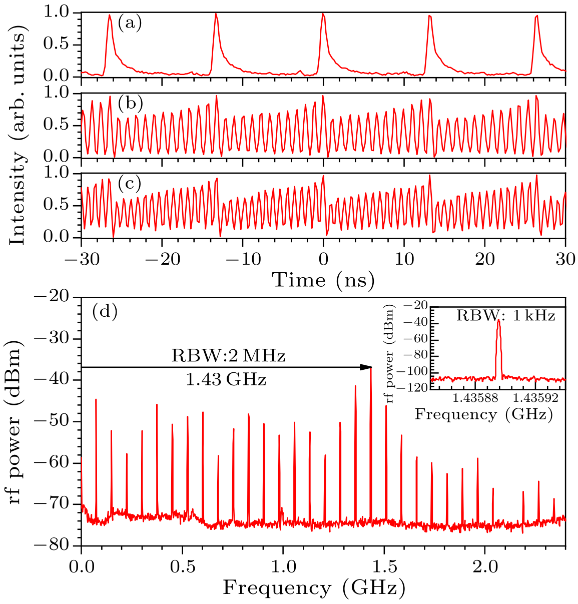

Fig. 5. Oscilloscope traces of high-repetition-rate signal pulse train and typical radio-frequency spectrum of 1.43 GHz. (a) Pump laser trace, (b) and (c) 906 MHz and 1.13 GHz, respectively, (d) rf-spectrum of 1.43 GHz signal with span of 2.4 GHz. Inset: rf-spectrum spanning 100 kHz with resolution of 1 kHz.

The pump threshold and output power at different repetition rates are investigated as shown in Fig. 6(a). With the increasing harmonic orders of signal, the signal power decreases and the pump threshold increases. This is due to the increment of cavity loss for higher number of signal round trips in the absence of gain.[22] The maximum signal power is 194 mW at 750 nm at the repetition rate of 755 MHz under 3 W pump power. The power stability of the signal laser at 750 nm at the repetition rate of 755 MHz was measured, as shown in the inset of Fig. 6(a), to be <1.6% average power drift in 30 min. Using the active feedback control can effectively improve the power stability.

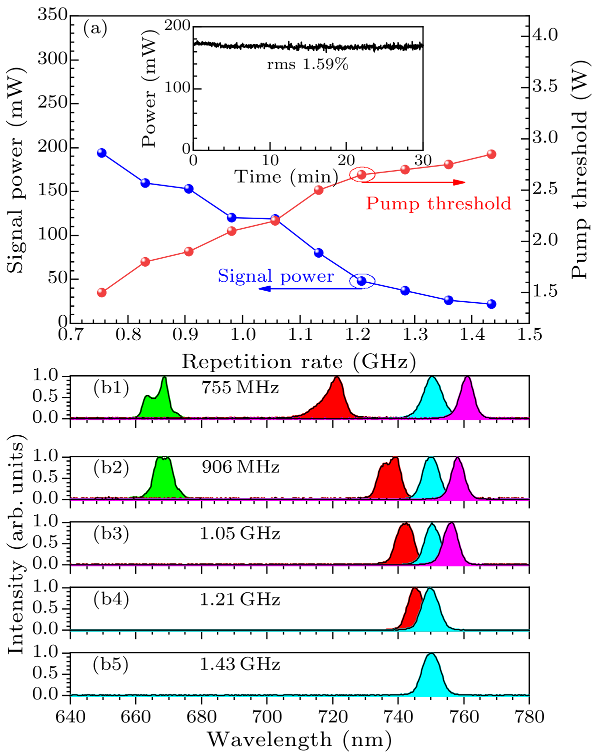

Fig. 6. (a) GHz OPO output power and pump threshold versus harmonic number. Inset: the long-term average power stability of the signal at 755 MHz. (b) Signal spectra tunable just by finely tuning the cavity length near 750 nm: (b1) 755 MHz, (b2) 906 MHz, (b3) 1.05 GHz, (b4) 1.21 GHz, (b5) 1.43 GHz.

Figure 6(b) shows the signal spectrum versus cavity length detuning ($\Delta L_{\rm OPO}$), the regulation of cavity length leads to signal wavelength shift, which is attributed to positive intra-cavity GDD. When the cavity length increases, the wavelength of signal is shifted to a longer wavelength to keep to be synchronous with the pump pulse. Similarly, a shorter signal wavelength oscillates at a shorter cavity length.[23] By only changing the OPO cavity length, the signal wavelength can be tuned from 720 nm to 761 nm at the repetition rate of 755 MHz, and 665 nm also could be generated due to the dual wavelength property of the LBO crystal, the signals at 665 nm and 760 nm have the same phase match angle under 515 nm pump laser. As the repetition rate increases, the cavity length detuning ($\Delta L_{\rm OPO}$) is decreased, so the wavelength tuning range becomes narrower. The signal wavelength will be fixed by changing the cavity length when the OPO running at higher than 1.28 GHz i.e. 17th-harmonic of pump source. It is worth noting that this tunable signal wavelength is only realized by changing the OPO cavity length, while a larger spectral tunability can be realized by finely rotation of the LBO crystal angle.

In conclusion, we have demonstrated a femtosecond OPO at repetition rate of GHz pumped by a femtosecond 515 nm laser. Fractional decrement of the OPO cavity length is used to increase the repetition rate of signal. The repetition rates from 755 MHz to 1.43 GHz at an interval of 75.5 MHz are achieved at 750 nm. The maximum signal power of 194 mW at the repetition rate of 755 MHz with the minimum power of 22 mW at 1.43 GHz at the same wavelength of 750 nm are achieved with pump power of 3 W. The pulse duration is 159 fs at 750 nm at the repetition rate of 755 MHz, and the stability of signal power is less than 1.6% in 30 min.

References

[1] Bartels A, Dekorsy T and Kurz H 1999 *Opt. Lett.* **24** 996
[2] Vainio M, Merimaa M, Halonen L and Vodopyanov K 2012 *Opt. Lett.* **37** 4561
[3] Chen I H, Chu S W, Sun C K, Cheng P C and Lin B L 2002 *Opt. Quantum Electron.* **34** 1251
[4] Marandi A, Leindecker N, Pervak V, Byer R L and Vodopyanov K L 2012 *Opt. Express* **20** 7255
[5] Wilken T, Curto G L, Probst R A, Steinmetz T, Manescau A, Pasquini L, Hernández J I G, Rebolo R, Hänsch T W, Udem T and Holzwarth R 2012 *Nature* **485** 611
[6] Cundiff S T and Weiner A M 2010 *Nat. Photon.* **4** 760
[7] Hee M R, Izatt J A, Jacobson J M, Fujimoto J G and Swanson E A 1993 *Opt. Lett.* **18** 950
[8] Reid D T, McGowan C, Sleat W, Ebrahimzadeh M and Sibbett W 1997 *Opt. Lett.* **22** 525
[9] Phillips P, Das S and Ebrahimzadeh M 2000 *Appl. Phys. Lett.* **77** 469
[10] Jiang J and Hasama T 2002 *Appl. Phys. B* **74** 313
[11] Balskus K, Leitch S, Zhang Z, McCracken R and Reid D T 2015 *Opt. Express* **23** 1283
[12] Tian W L, Wang Z H, Zhu J F and Wei Z Y 2016 *Opt. Express* **24** 29814
[13] Jiang J and Hasama T 2002 *Opt. Commun.* **211** 295
[14] Jiang H and Hasama T 2003 *Opt. Commun.* **220** 193
[15] Kokabee O, Esteban M A and Ebrahim Z M 2009 *Opt. Express* **17** 15635
[16] Gu C L, Hu M L, Fan J T, Song Y J, Liu B W and Wang C Y 2014 *Opt. Lett.* **39** 3896
[17] Chaitanya K S, Agnesi A, Dallocchio P, Pirzio F, Reali G, Zawilski K T, Schunemann P G and Ebrahim Z M 2011 *Opt. Lett.* **36** 3236
[18] Chaitanya K S, Krauth J, Steinmann A, Zawilski K T, Schunemann P G, Giessen H and Ebrahim Z M 2015 *Opt. Lett.* **40** 1398
[19] Coluccelli N, Viola D, Kumare V, Perri A, Marangoni M, Cerullo G and Polli D 2017 *Opt. Lett.* **42** 4545
[20] Lang T, Binhammer T, Rausch S, Palmer G, Emons M, Schultze M, Harth A and Morgner U 2012 *Opt. Express* **20** 912
[21] Meng X H, Wang Z H, Jiang J W, Tian W L, Fang S B and Wei Z Y 2018 *J. Opt. Soc. Am. B* **35** 967
[22] Esteban M A, Kokabee O, Moutzouris K and Ebrahim Z M 2009 *Opt. Lett.* **34** 428
[23] Hebling J, Zhang X P, Giessen H, Kuhl J and Seres J 2000 *Opt. Lett.* **25** 1055