

Harmonically pumped femtosecond optical parametric oscillator with multi-gigahertz repetition rate

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Abstract: We report a multi-gigahertz (GHz) repetition-rate femtosecond MgO:PPLN optical parametric oscillator (OPO) harmonically pumped by a 75.6 MHz Kerr-lens mode-locked Yb:KGW laser. By fractionally increasing the OPO cavity length, we obtained OPO operation up to the 493rd harmonic of the pump laser repetition rate, corresponding to a repetition rate as high as 37.3 GHz. Using a 1.5% output coupler, we are able to extract signal pulses with up to 260 mW average power at the 102nd harmonic (7.7 GHz) and 90 mW at the 493rd harmonic (37.3 GHz) under 2 W pump power. The measured relative standard deviations of the fundamental and the 102nd harmonic signal power were recorded to be 0.5% and 2.1%, respectively. The signal pulse durations at different harmonics were measured in the range of 160–230 fs.

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OCIS codes: (190.7110) Ultrafast nonlinear optics; (190.4970) Parametric oscillators and amplifiers; (190.4400) Nonlinear optics, materials.

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1. Introduction

Ultrafast lasers providing picosecond to femtosecond pulses are of demand in various application areas such as spectroscopy [1], precision measurement [2], biophotonics [3], etc. Particularly, ultrashort pulses around 1.5 μm are most attractive for fiber optical communication since they suffer the smallest loss in the fiber. Generally, sources of ultrashort pulses with gigahertz repetition rate in the 1.5 μm wavelength range are one of the key parts of optical time-division multiplexing for high-speed fiber optical communication. Thus, several techniques to generate such a laser source have been studied, such as mode-locked Er,Yb:glass lasers [4], rational harmonic mode-locked Er:glass lasers [5], and synchronously pumped optical parametric oscillator (SPOPO) [6]. Compared to the first three ways, SPOPO can provide not only broad wavelength coverage and short pulse duration, but also widely tunable signal wavelength, which benefits numbers of applications at gigahertz repetition rate, such as low-noise frequency combs [7], optical interconnects [8], lidar [9], high-speed asynchronous sampling [10] and analog to digital converters [11].

At present, there are mainly three methods to generate gigahertz repetition-rate SPOPOs. The first one allows a low-repetition-rate ultrafast laser to synchronously pump an OPO with an N times (N is an integer) shorter cavity length, resulting in N times the pump laser frequency. This method was firstly demonstrated by Reid et al. [12] in a femtosecond RTA OPO synchronously pumped by a Kerr-lens mode-locked (KLM) Ti:sapphire laser at 86 MHz, resulting in the fourth harmonic repetition rate. However, the repetition rate of the SPOPO is still determined by its cavity length, this method suffers from severe dimension restrictions and the corresponding rise in threshold. The highest repetition-rate of SPOPOs with this method is 1.334 GHz in a picosecond Nd:YVO₄ laser pumped KTA-OPO [13]. The second approach is so-called higher-order synchronous pumping, which required a very compact, high-repetition-rate ultrafast pump source, while the free spectra range (FSR) of the SPOPO could be several times of the pump laser. In this situation, the repetition rate of the SPOPO is defined by the pump's, which corresponding to that multiple pulses are circulating in the OPO cavity. Not only the dimension restrictions of the SPOPO for high repetition has been relieved with this method, but also all signal pulses have equal intensities compared to the first method. However, this approach is limited to the demands of high-repetition-rate ultrafast lasers with high average power as the pump source. In 2005, S. Lecomte et al. demonstrated the picosecond SPOPOs with repetition rate up to 39 GHz [14] and 81.8 GHz [15] in this way. The third manner is based on the cavity length difference between the OPO and the pump laser, which is firstly introduced by Jiang et al. [16, 17]. The way indicates that when the cavity lengths of the SPOPO (L_{SPOPO}) and its pump laser (L_{pump}) satisfy the following equation:

$$M \cdot L_{SPOPO} = N \cdot L_{pump} \quad M=1,2,3... \quad N=1,2,3...$$

The SPOPO with Nth harmonic of the pump repetition rate can be implemented. For $N = 1$ or $M = 1$, the equation is corresponding to the situations in the first or the second methods. For $M > N$, the OPO is shorter than the pump laser in cavity length, otherwise, the OPO is longer. With extended-cavity ($N > M$), O. Kokabee and A. Esteban-Martin realized 1GHz femtosecond SPOPO pumped by a 76 MHz Ti:sapphire laser with [18] and without [19] a prism pair for intracavity dispersion compensation, respectively. Most recently, O. Kimmelma et al. demonstrated a 7 GHz repetition-rate PPLN-OPO pumped by a 80 MHz picosecond Yb: fiber laser, corresponding to the 88th harmonic of pump repetition rate [20].

Though 1-GHz-repetition-rate femtosecond SPOPOs have been demonstrated in all these methods, multi-GHz repetition-rate is not available yet directly from the femtosecond SPOPOs. In this paper, we demonstrated a multi-GHz repetition-rate femtosecond OPO synchronously pumped by a KLM Yb:KGW femtosecond laser with the third method. By fractionally increasing the OPO cavity length, signal pulses with repetition rate scaling from 7.7 GHz to 37.3 GHz were generated. As high as 260 mW and 90 mW average powers were obtained at the 102nd harmonic (7.7 GHz) and 493rd harmonic (37.3 GHz) for 2 W pump power, respectively. The measured relative standard deviations of the fundamental and the 102nd harmonic signal power were recorded to be 0.5% and 2.1%, respectively. To the best of our knowledge, this is the highest repetition rate from a femtosecond OPO, providing a new solution for high-power multi-GHz-repetition-rate femtosecond sources.

2. Experimental setup

The pump source is a commercial KLM Yb:KGW laser (Light Conversion, FLINT6.0) delivering 90 fs pulses at 1030 nm with up to 7 W average power. The repetition rate of the Yb:KGW laser is 75.6 MHz, corresponding to the linear cavity length of 1984 mm. The nonlinear crystal is a 3-mm-long, 5 mol% MgO doped PPLN with seven grating periods from 28.5 μm to 31.5 μm in steps of 0.5 μm , among which the grating period of 30 μm was employed in this work. The crystal is anti-reflection-coated around 1020-1080 nm and 1200-2100 nm on both surfaces. To eliminate the harmful influence on the Yb:KGW laser from reflected pump, the pump laser was firstly passed through an isolator comprising an half-wave-plate (HWP), a polarization beam splitter (PBS) and an Faraday rotator (FR). The combination of the HWP and PBS also acted as a power attenuator, keeping the pump power focused on the PPLN less than 2 W to avoid damage on the PPLN. A second HWP after the FR was used to adjust the pump polarization relative to the crystal orientation. The pump beam was focused to a waist diameter of 44 μm by a lens (L) with 100 mm focus length. The pulse duration of the pump pulse was stretched to 120 fs passing through the isolator system.

Figure 1 is the schematic of the experimental setup. The single signal resonant OPO was a linear standing wave cavity with six fused silica mirrors. C1 and C2 are concave mirrors with 100 mm radius of curvature (ROC), coated with high reflectivity over 1400-1800 nm ($R > 99.9\%$) and high transmittance at 1030 nm ($R < 2\%$) and around 3-4 μm ($R < 5\%$). The beam waist radius of the OPO cavity is 32 μm x 32 μm based on the ABCD matrix. Two GTI mirrors with 99.8% reflectivity covering 1400-1800 nm were used to intra-cavity dispersion compensation, introducing -400 fs^2 group delay dispersion (GDD) around 1500 nm. A high-reflectivity (HR) flat mirror with 99.9% reflectivity from 1410 nm to 1830 nm was used as a folded mirror. The output coupler (OC) had a 1.5% transmittance in the range of 1220-1740 nm. One of the GTI mirrors was mounted on a translation stage for finely tuning the cavity length. The maximum detuning length of the translation stage is 25 mm.

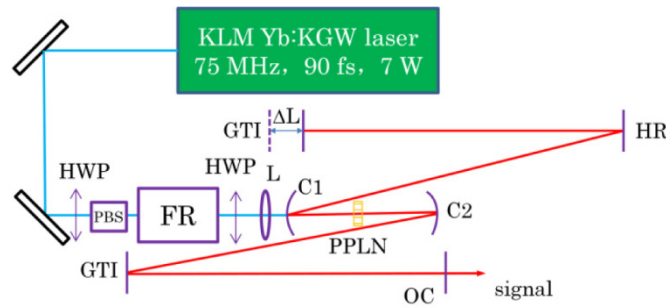


Fig. 1. Experimental setup for ultrahigh-repetition-rate femtosecond SPOPO. HWP: half wave plate; PBS: polarization beam splitter; FR: Faraday rotator; L: lens; C1 and C2: concave mirrors; HR: high reflective mirror; GTI: Gires-Tournois interference mirror; OC: output coupler.

3. Experimental results and discussion

At first, the OPO cavity length was set to be equal to the pump cavity length ($\Delta L = 0$), generating signal pulses at 75.6 MHz repetition rate with 450 mW average power for 2 W pump power, corresponding to 22.5% conversion efficiency. The threshold for the SPOPO was only 56 mW. To achieve pulse repetition-rate multiplication from the input 75.6 MHz to several GHz at the output, the OPO cavity length was extended by translating the GTI mirror. Extending the OPO cavity length to $L = L_{\text{pump}} / Q$ could operate the femtosecond OPO at Q^{th} harmonic of the pump repetition-rate. Thus, at specific values of ΔL (from 4.02 mm to 19.45 mm), we are able to obtain signal pulses at the corresponding harmonics of the pump laser frequency covered from 7.7 GHz to 37.3 GHz. Figure 2 shows an example of the generated OPO signal pulse train at the 102nd harmonic of the input repetition-rate, recorded by an oscilloscope with 8 GHz bandwidth (DPO70804C, Tektronix) and a high-speed photodetector with a bandwidth of 25 GHz (New Focus 1437). For the 102nd harmonic, the GTI mirror was detuned by 19.45 mm from the fundamental position, being 1/102 of the synchronized cavity length.

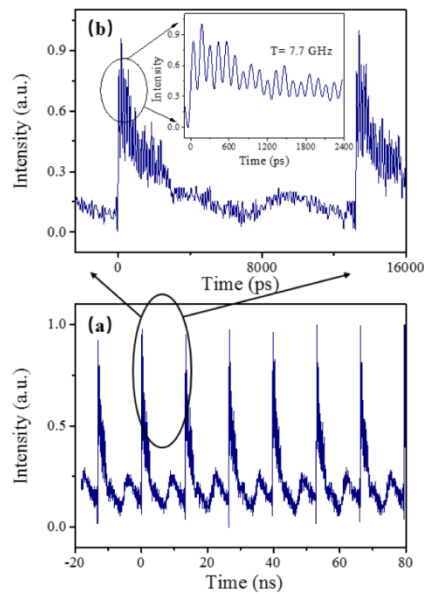


Fig. 2. (a) Oscilloscope traces of the signal pulses at the 102nd harmonic of the input repetition-rate (7.7 GHz). (b) Details of the fine structure.

To measure the output pulse repetition-rate at higher frequencies and for various values of ΔL , a radio frequency (RF) spectrum analyzer with maximum measurable RF frequency of 26.5 GHz (ROHDE&SCHWARZ, FSW26) was used. Figure 3(a) and 3(b) reveal typical examples of the RF spectra of the SPOPO signal pulses at 7.7 GHz and 16.85 GHz, respectively. These frequencies correspond to the 102nd and 223rd harmonics of the 75.6 MHz pump repetition-rate, and were realized at the positions of $\Delta L = 19.45$ and 8.89 mm, respectively. In the RF spectra, it is clear to see the main peaks at the selected harmonic of the pump repetition-rate and the corresponding subsequent harmonic, with fine substructure formed by the spectral lines separated by 75.6 MHz, corresponding to the fundamental pump laser repetition-rate.

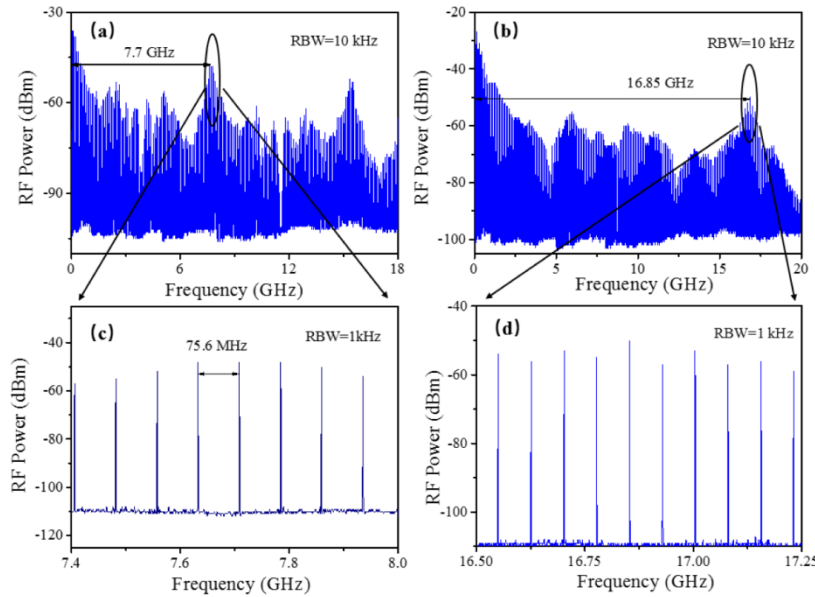


Fig. 3. RF spectra of the signal pulses with (a) 7.7 GHz and (b) 16.85 GHz repetition-rates. The corresponding fine substructures around the main peak at (c) 7.7 GHz and (d) 16.85 GHz.

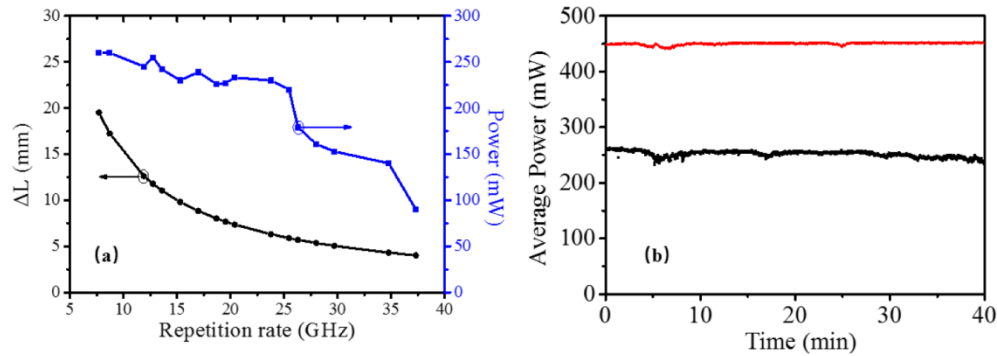


Fig. 4. (a) OPO signal power as a function of the repetition rate (blue square) and the respective mirror displacement related to the fundamental mirror position (black circle). (b) Power stability over 40 min for fundamental (red) and 102nd harmonic (black).

The behavior of the signal average output power as a function of the measured repetition rates is presented in Fig. 4(a), where it can be clearly seen that power drops as the repetition-rate increases. Due to the limitations of the high-speed photo-detector (25 GHz bandwidth) and the RF spectrum analyzer, the highest repetition-rate directly deduced from the RF spectrum analyzer was restricted to 25 GHz. For higher repetition-rates, the frequencies were deduced by measuring the displacement of the GTI mirror, ΔL , on the micrometer scale and recording the corresponding power. At 7.7 GHz repetition rate, as high as 260 mW output signal power was obtained, while it dropped to 90 mW for 37.3 GHz repetition rate. Higher repetition-rate was not achieved due to the increasing pump threshold beyond 2 W. The power stability of the output signal at the fundamental repetition-rate and 102nd harmonic recorded over 40 min. are shown in Fig. 4(b). The relative standard deviations for the fundamental and 102nd harmonic are 0.5% and 2.1%, respectively. As evident from Fig. 4, OPO operating at higher harmonic is less stable and with lower power, which is due to higher loss.

We determined the spectra of the output signal pulses at several repetition rates including 7.7 GHz, 16.85 GHz, 26.3 GHz and 37.3 GHz, with an optical spectrum analyzer (YOKOGAWA, AQ6370C) of 20 GHz resolution, as shown in Fig. 5(a). The signal pulses at different repetition rate were centered at 1515 nm, corresponding to S band wavelength. The frequencies representing the 102nd, 223rd, 348th and 493rd harmonics of the pump repetition-rate were obtained by detuning the GTI mirror with $\Delta L = 19.45$ mm, 8.89 mm, 5.7 mm and 4.02 mm, respectively. It is clear to see the comb structures on the spectra, when the repetition-rate is above 20 GHz.

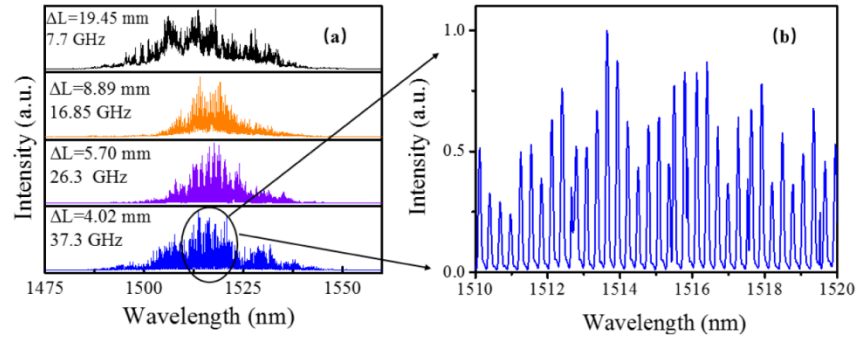


Fig. 5. (a) Optical spectra of the output signal pulses at several random repetition-rates. (b) Detail of the spectrum between 1510 nm and 1520 nm of signal pulses at 37.3 GHz.

The temporal characteristics of the OPO signals at different repetition-rates from 7.7 GHz to 37.3 GHz were measured utilizing a commercial intensity autocorrelator (FR-103XL, Femtochrome Research, Inc.) and presented in Fig. 6, where it can be seen clearly that the pulse durations of signals were in the range of 160-230 fs. Insert in Fig. 6 is an example of the intensity autocorrelation trace of the signal pulse at the highest repetition rate, whose half maximum full width (HMF_W) is 251 fs, representing a pulse duration of 163 fs, if the sech^2 -pulse-shape was assumed.

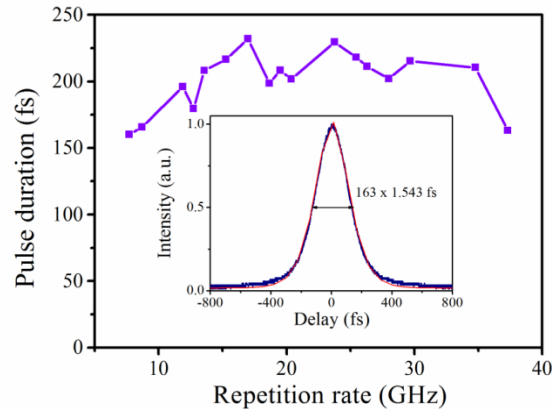


Fig. 6. Pulse durations of OPO signals at different repetition rates from 7.7 GHz to 37.3 GHz. Inset: Intensity autocorrelation trace of the signal pulse at 37.3 GHz.

4. Conclusions

In conclusion, we have demonstrated a femtosecond MgO:PPLN OPO operated at multi-gigahertz repetition rates scaling from 7.7 GHz to 37.3 GHz, by fractionally increasing the OPO cavity length. Using an OC with 1.5% transmittance, 7.7 GHz and 37.3 GHz pulses with as high as 260 mW and 90 mW average output powers were obtained for 2 W pump power,

respectively. Higher repetition-rate even up to hundreds of GHz will be readily attainable, by further increasing the pump power as well as optimizing the mirror reflectivity and the output coupling. It is believed that the multi-GHz repetition-rate femtosecond OPO with considerable average power will be a suitable tool in various applications in the near to mid-IR.

Funding

The National Key Basic Research Program of China (2013CB922402); The National Key Scientific Instruments Development Program of China (2012YQ120047); The National Natural Science Foundation of China (11174361, 61575217 and 61205130); The CAS key deployment project (KJZD-EW-L11-03); and The Open Research Fund of the State Key Laboratory of Pulsed Power Laser Technology, Electronic Engineering Institute, Hefei, China (Grant No. SKL2015KF02).