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Electro-optic comb pumped optical parametric oscillator with flexible repetition rate at GHz level

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We present a gigahertz (GHz)-repetition-rate optical parametric oscillator (OPO) pumped by an electro-optic (EO) comb at 1.03 μm , delivering sub-picosecond signal pulses across 1.5-1.7 μm from a MgO-doped periodically poled LiNbO₃ crystal. Using a pump power of 5 W at 14.2 GHz repetition rate, 378 mW of signal power is obtained at 1.52 μm from a subharmonic cavity, corresponding to a signal extraction efficiency of 7.6%. By cascading a Mach-Zehnder modulator, the pump pulse repetition rate can be divided by any integer number from 1 to 14, allowing the OPO to operate with flexible repetition rate from 1 to 14.2 GHz. Besides, a strategy leading to quasi-continuous repetition rate tunability of the OPO is also discussed. © 2021 Optical Society of America

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Electro-optic (EO) frequency combs are attracting more and more attentions as a new kind of ultrafast laser sources with GHz repetition rates [1–4]. Such high-repetition-rate lasers have great potentials in various fields, such as advanced material processing [5], ultrafast time-domain spectroscopy [6], free-space optical communication [7] and electron guns [8]. Compared to traditional mode-locked lasers, the repetition rate scaling of an EO comb in single-pass configuration is not bound to the cavity length of the laser, enabling easy repetition rate selection in a wide GHz range using a radiofrequency (RF) synthesizer. The naturally chirped pulses emerging from the EO combs also make it convenient to integrate with all-fiber chirped-pulse amplifiers (CPAs). Besides, the line spacing of an EO comb is inherently stable, and the carrier-envelope offset frequency is clearly defined by a single-frequency seed laser. Relying on mature single-frequency diode lasers, Yb- and Er-doped fiber amplifiers and commercially available EO modulators (EOMs), ultrafast GHz EO combs have been mainly demonstrated at ~ 1 and ~ 1.5 μm . Efforts on converting these EO combs to other wavelengths for maximizing their potentials are still rare. Regarding frequency up-conversion, a multi-GHz repetition rate deep ultraviolet source in burst mode derived from an EO comb

at 1.03 μm [9] and a broadband 30 GHz EO comb in the visible and near-infrared (near-IR) [10] have been reported. Regarding frequency down-conversion for mid-IR pulse generation, 10 GHz frequency combs covering 3.1-4.8 μm and 7-11 μm by intra-pulse difference-frequency generation (DFG) of a spectrally broadened EO comb centered at 1.55 μm have been demonstrated [11]. Besides, microresonators driven by EO combs have also shown potentials for harmonic generation at short wavelengths and optical parametric oscillation in the mid-IR [12]. Nevertheless, for generating powerful, high-beam-quality and ultrashort pulsed radiations tunable in the near- and mid-IR, synchronously pumped optical parametric oscillators (OPOs) based on bulk nonlinear crystals are still a promising approach.

Previously, synchronously pumped OPOs with high repetition rates of tens of GHz have been demonstrated [13–15]. However, such high-repetition-rate operation requires challenging cavity designs for the driving mode-locked lasers or very high order harmonic mode-locking technique [16], which are usually accompanied with multi-picosecond pulses. More often, multi-GHz repetition rates of synchronously pumped OPOs are achieved by using a conventional mode-locked laser at tens or hundreds of MHz repetition rate together with a harmonic OPO cavity whose length is proportional to the pump laser cavity length [17, 18]. Although this method could easily and flexibly extend the repetition rate up to multiple GHz, the uneven envelop of the output pulse train is always inevitable due to cavity loss of the resonant pulses in each round trip before being synchronized with the next pump pulse. This limit prevents its practicality for many applications.

In this letter, based on recent development of EO combs, we demonstrate an ultrafast EO comb pumped OPO delivering multi-GHz pulses. The 1.03- μm EO comb system delivers 5 W of average power and 1.16 ps de-chirped pulses at 14.2 GHz repetition rate. The comb pumped OPO generates sub-picosecond signal pulses up to 378 mW at 1.52 μm with the capability of covering the 1.5-1.7 μm spectral band by crystal temperature tuning. An additional Mach-Zehnder Modulator (MZM) is further used as a divider to realize flexible repetition rate operation from 1 to 14.2 GHz. Furthermore, a strategy for obtaining quasi-

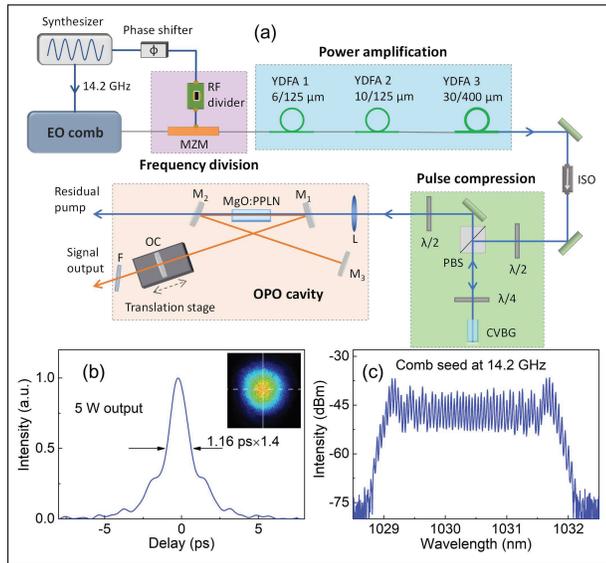


Fig. 1. (a) Experimental setup of the EO comb pumped OPO with multi-GHz repetition rates. MZM, Mach-Zehnder Modulator; YDFA, Yb-doped fiber amplifier; ISO, isolator; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; PBS, polarizing-beam splitter; CVBG, chirped volume Bragg grating; L, lens; M, mirror; OC, output coupler; F, filter. (b) Autocorrelation of the EO comb at 5 W after compression. Inset: Beam profile of the EO comb at 5 W after compression. (c) Measured spectrum of the EO comb seed at 14.2 GHz.

continuous repetition rate tunability is also discussed.

The experimental setup for the EO comb pumped OPO with multi-GHz repetition rates is shown in Fig. 1(a). The EO comb originating from a continuous-wave single-frequency diode laser at $1.03 \mu\text{m}$ consists of two phase EOMs for spectral broadening and a MZM for pulse formation and linear chirp selection, as detailed in [2]. Another MZM sharing the same RF synthesizer is further used to divide the pulse repetition rate. Frequency division by any integer number from 1 to 14 is enabled by using a binary-controlled RF divider. The power of the divided pulses varies from 1 mW to 38 mW, depending on the division factor, and is boosted by three cascaded Yb-doped fiber amplifiers (YDFAs). The first stage is a core-pumped YDFA ($6/125 \mu\text{m}$), providing 50-102 mW output power correspondingly. The second and final stages are cladding-pumped YDFAs ($10/125 \mu\text{m}$ and $30/250 \mu\text{m}$), providing ~ 800 mW and >7 W output powers, respectively. The amplified comb is collimated to free space and guided through an isolator to prevent optical feedback. Then we employ a chirped volume Bragg grating (CVBG) based compressor to de-chirp the comb pulses. In the compressor, a half and quarter-wave plate together with a polarizing-beam splitter (PBS) are used to inject the comb pulses into the CVBG and then extract the reflected beam for pumping the OPO. Since the compressor only provides a fixed dispersion, we adjust the driving RF frequency of the EO comb and thus the chirp amount in the modulated pulses to find the RF frequency where the compressor perfectly cancels the chirp of the comb pulses. By monitoring the autocorrelation (AC) of the compressed pulses, we confirm the optimal frequency to be around 14.2 GHz. Considering the compressor efficiency of $\sim 80\%$ and optical loss in the isolator, ~ 5 W of comb power are available to drive the OPO.

In the frequency conversion part, the EO comb is corrected

to vertical polarization and focused into a 10-mm-long MgO-doped periodically poled LiNbO₃ (MgO:PPLN) crystal with a beam waist radius of $\sim 49 \mu\text{m}$ for achieving phase matching and cavity mode matching. The MgO:PPLN crystal housed in an oven contains five different grating periods with $29.98 \mu\text{m}$ and $30.49 \mu\text{m}$ used for the OPO. We use an X-cavity with a length of ~ 590 mm, corresponding to a free spectral range (FSR) of ~ 249 MHz and 57 signal pulses circulating in the cavity at 14.2 GHz repetition rate. The cavity consists of two curved mirrors (from Layertec Inc.), M_1 and M_2 ($r=100$ mm), anti-reflection (AR) coated around $1.03 \mu\text{m}$ ($R<2\%$) and high reflection (HR) coated for $1.4\text{--}2.1 \mu\text{m}$ ($R>99.8\%$), as well as a plane mirror M_3 with the same HR coating and an output coupler (OC) with $\sim 2\%$ transmission across $1.5\text{--}1.7 \mu\text{m}$, ensuring singly resonant operation for the signal wave. The two curved mirrors made of fused silica are not coated for the mid-IR idler. Thus, the OPO characterization is mainly based on the near-IR signal. Finally, for synchronization between the comb and signal pulses, the OC is placed on a high-precision linear translation stage and followed by a long-pass filter with a cut-on wavelength of 1200 nm to block visible parasitic light.

We first characterized the EO comb before pumping the OPO. Figure 1(b) shows the AC trace of the comb pulses after compression at 14.2 GHz. Considering a deconvolution factor of 1.4 (inherent to EO comb generated pulses), the pulse duration is 1.16 ps at 5 W. The spatial profile of the EO comb at 5 W is also captured using a CCD camera, indicating a single-mode distribution, as shown in the inset of Fig. 1(b). The spectrum of the EO comb seed at 14.2 GHz is measured and plotted in Fig. 1(c). The modulated spectrum has a 10 dB bandwidth of ~ 2.5 nm and a signal-to-noise ratio (SNR) of 36 dB measured with a resolution of 0.02 nm. After amplification, the final spectrum has no significant change except that the profile becomes slightly tilted due to the limited gain bandwidth of the used YDFAs, which is centered at a longer wavelength.

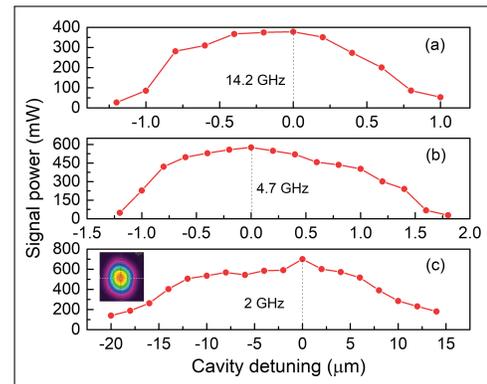


Fig. 2. Output signal powers as functions of cavity detunings at (a) 14.2 GHz, (b) 4.7 GHz and (c) 2 GHz with 5 W pump power. Inset: Beam profile of the signal at 2 GHz and 700 mW.

Using this 5 W EO comb as pump, we further implemented the OPO. Initially, we kept the MgO:PPLN crystal at 50°C and used the grating period of $29.98 \mu\text{m}$, corresponding to a signal wavelength of $1.52 \mu\text{m}$. At the fundamental repetition rate of 14.2 GHz, the OPO threshold was observed for ~ 3 W of pump power. Then, we recorded the output signal power at different cavity detuning values. The OPO allows a synchronization range of $2.2 \mu\text{m}$ and delivers a maximum signal power of 378 mW, corresponding to a signal extraction efficiency of 7.6%, as

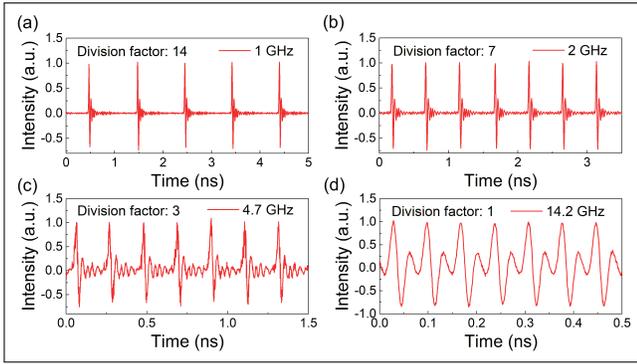


Fig. 3. Measured pulse trains of the OPO signal at different repetition rates: (a) 1 GHz, (b) 2 GHz, (c) 4.7 GHz and (d) 14.2 GHz.

shown in Fig. 2(a). For comparison, fig. 2(b) and (c) show the same measurement at divided repetition rates of 4.7 GHz and 2 GHz, corresponding to division factors of 3 and 7, respectively. With three times higher pump pulse energy, the OPO allows a larger synchronization range of $3 \mu\text{m}$ at 4.7 GHz and delivers a higher signal power of 576 mW at zero detuning. At 2 GHz with seven times higher pump pulse energy, the obtained synchronization range reaches $34 \mu\text{m}$, much larger than the previous two cases, but the output signal power only increases to 700 mW, implying the OPO enters a saturation regime where back-conversion and signal pulse breakdown [19] have occurred due to high pulse energy circulating in the cavity. Besides, we also captured a single-mode profile of the signal beam at 700 mW using a pyroelectric camera, as shown in the inset of Fig. 2(c).

By fully exploiting the frequency division function, we could divide the 14.2 GHz repetition rate by any integer number up to 14, making the EO comb highly flexible for repetition rate selection with almost constant output power and pulse duration after compression, with the assistance of the fiber CPA system which avoids excess nonlinear effects. When pumping the OPO at different divided repetition rates, there are always subharmonic cavity FSRs near 249 MHz. Thus, by just adjusting the cavity length, we could obtain the corresponding FSRs and operate the OPO across 1-14.2 GHz. Using a fast InGaAs photodiode (Optilab, PD-40x) with a bandwidth of 40 GHz and a sampling oscilloscope (Keysight, DCA-X 86100D) with a bandwidth of 45 GHz, we measured the signal pulse trains at various repetition rates. Figures 3(a)-(d) display four recorded traces at 1.01 GHz, 2.03 GHz, 4.73 GHz and 14.2 GHz. They correspond to division factors of 14, 7, 3 and 1, respectively. As can be seen, when increasing the OPO repetition rate, the pulse structures are getting close to the bandwidth limit of the measuring equipment. Besides, the negative values of the detected pulses followed by decaying oscillations are electronic response of the photodiode to ultrashort pulses, which are not present in the AC traces.

At the fundamental repetition rate of 14.2 GHz, we further measured the AC traces of the signal pulses at different cavity detunings, as shown in Fig. 4(a). With a positive cavity detuning of +500 nm, the FWHM duration of the AC trace is 830 fs. With cavity detunings of zero and -800 nm, the AC durations increased to 980 fs and 1 ps, respectively. Compared to the pump, the generated signal pulses have shorter durations and cleaner profiles due to the filtering effect of this nonlinear process. Figure 4(b) depicts the corresponding measured spectra. For +500 nm detuning, the signal spectrum is centered at 1524

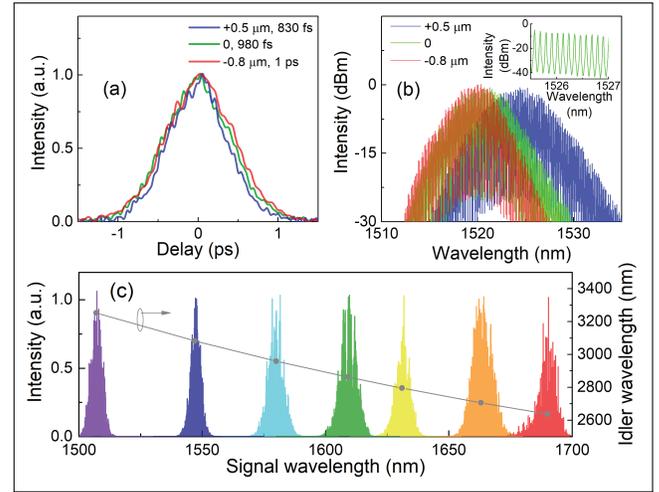


Fig. 4. (a) Autocorrelations and (b) spectra of the signal pulses at 14.2 GHz with different cavity detunings. (c) Measured signal spectra tunable across 1.5-1.7 μm and the corresponding calculated idler wavelengths.

nm and has a 10 dB bandwidth of 10.7 nm. For zero and -800 nm detunings, the signal spectrum is blue-shifted to 1520.5 nm and 1520 nm, and has a 10 dB bandwidth of 9.1 nm and 7.8 nm, respectively. Fourier transform of these spectra indicates that the measured AC traces are only 1.08, 1.1 and 1.03 times their transform limits for +500 nm, 0 and -800 nm detunings, respectively. The above signal evolution can be explained as follows. With positive cavity detunings, the signal pulses arrive behind the pump pulses at the entrance of the MgO:PPLN crystal and catch up during propagation in the crystal with a GVM of $\sim 0.1 \text{ ps/mm}$. The latter leads to relatively uniform amplification for the whole temporal and spectral profiles of the signal pulses. At contrast, with negative cavity detunings, the pump pulses are mainly overlapped with the trailing wings of the signal pulses and these trailing wings are dragged and prolonged by the pump pulses due to GVM in the crystal. Besides, considering that the crystal provides positive dispersion for the signal, the signal trailing wings containing higher optical frequencies experience more parametric gain than the leading part. This leads to narrower and blue-shifted signal spectra, as well as near transform-limited pulses.

Similarly, at 4.7 GHz, with 5 W of pump power, we observed identical temporal and spectral behaviours of the signal. However, at 2 GHz with seven times higher pump energy, strong pedestals appear on the signal AC trace around zero cavity detuning. This indicates that the signal pulse breakdown into a few satellite pulses, which could increase the overlap range between the pump and signal pulses and thus explain the much larger synchronization range in Fig. 2(c). Similar to [19], by reducing the pump power, we managed to eliminate the pulse breakdown effect. Another mitigation method could be using another OC with a higher signal transmission.

At 14.2 GHz, we also performed coarse tuning measurement for the signal wavelength. Using the grating periods of 29.98 μm and 30.49 μm in the crystal together with the temperature varying from room temperature up to 150°C, we achieved a signal output tunable across 1.5-1.7 μm , as shown in Fig. 4(c). Despite the lack of proper optics for extracting the mid-IR idler, we calculated the generated idler wavelength, which was tun-

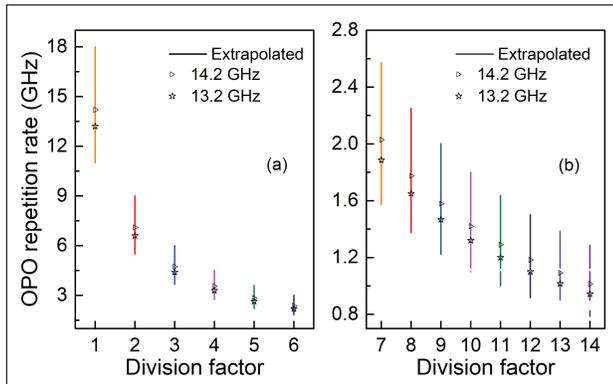


Fig. 5. Demonstrated OPO repetition rates and extrapolated ranges assuming using a diffraction grating based compressor at division factors of (a) 1-6 and (b) 7-14.

able across 2.64-3.25 μm , based on photon energy conservation, as also shown in Fig. 4(c).

Last, to highlight the potential of our system for generating extremely flexible repetition rates, we calculated the OPO repetition rates which could be achieved by tuning the fundamental frequency of the EO comb and adjusting the cavity FSR. In the calculation, we considered the tuning range of the fundamental frequency of the EO comb to be 11-18 GHz which has been demonstrated previously [2] and a $\pm 10\%$ FSR variation around 250 MHz, within which the cavity remains stable. The corresponding extrapolated OPO repetition rates at each division factor are displayed in Fig. 5(a) and (b). As can be seen, this concept allows the OPO to cover a wide quasi-continuous repetition rate range of 0.8-18 GHz however interrupted between 9 and 11 GHz and with small gaps for division factors greater than 9. In the experiment, since we are using a compressor providing a fixed dispersion, we have limited the fundamental frequency tuning to 1 GHz (14.2 to 13.2 GHz), where the pulse duration of the EO comb after compression remains shorter than 1.35 ps. The corresponding divided repetition rates were also achieved and plotted in Fig. 5. Note here that using a diffraction grating based compressor would allow to maintain short pulses across 11-18 GHz [2], and thus allowing the OPO to operate on the much wider repetition rate range.

In conclusion, we have demonstrated an ultrafast OPO with flexible repetition rate across 1-14.2 GHz pumped by an EO comb at 1.03 μm . At 14.2 GHz, up to 378 mW of signal power at 1.52 μm is obtained with 5 W pump power. A wavelength tunability over 1.5 to 1.7 μm is further achieved by changing the temperature of the MgO:PPLN crystal. Combining the frequency division technique and cavity length scanning of the high subharmonic OPO, we could operate the OPO at flexible repetition rates from 1 to 14.2 GHz. Furthermore, by including the concept of adjusting the fundamental frequency of the EO comb as well as the cavity FSR, we show that the OPO repetition rate could be potentially highly tunable. The demonstration of our OPO system paves the way for further development of GHz-repetition-rate sources tunable in the near- and mid-IR regions. Besides, it also provides a new solution for mid-IR multi-GHz frequency comb generation with additional cavity locking systems.

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