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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.

For more details, please refer to the full text of the article.
we employ a chirped volume Bragg grating (CVBG) based compressor only provides a fixed dispersion, we adjust the driving voltage to de-chirp the comb pulses. In the compressor, a half-wave plate; λ/2, 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 μm 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 μm), providing 50-102 mW output power correspondingly. The second and final stages are cladding-pumped YDFAs (10/125 μm and 30/250 μm), 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 ~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 ~49 μm for achieving phase matching and cavity mode matching. The MgO:PPLN crystal housed in an oven contains five different grating periods with 29.98 μm and 30.49 μm 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.), M1 and M2 (r=100 mm), anti-reflection (AR) coated around 1.03 μm (R<2%) and high reflection (HR) coated for 1.4-2.1 μm (R>99.8%), as well as a plane mirror M3 with the same HR coating and an output coupler (OC) with ~2% transmission across 1.5-1.7 μm, 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.

![Figure 1](image1.png)

**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; λ/2, half-wave plate; λ/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 signal at 2 GHz and 700 mW. (c) Measured spectrum of the EO comb seed at 14.2 GHz.

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 μm, corresponding to a signal wavelength of 1.52 μm. 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 μm and delivers a maximum signal power of 378 mW, corresponding to a signal extraction efficiency of 7.6%, as

![Figure 2](image2.png)

**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.
With three times higher pump pulse energy, the OPO allows a larger synchronization range of 3 µm 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 µm, 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 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 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 ~0.1 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-
The corresponding divided repetition rates were also achieved (AST_AT_2018-043); H2020 LEIT Information and Communication Technologies (H2020-ICT-2018); Conseil Régional Nouvelle Aquitaine (2019-1RSM04).

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Disclosures. The authors declare no conflicts of interest.

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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.
FULL REFERENCES


