

0.5-W Few-Cycle Frequency Comb at 4 μm from an Efficient Simulton-based Optical Parametric Oscillator

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Abstract: We report generation of three-cycle pulses at 4.18 μm with 565-mW average power, 900-nm instantaneous FWHM bandwidth, 350% slope efficiency, and 44% conversion efficiency, based on a half-harmonic optical parametric oscillator operating in simulton regime. © 2021 The Author(s)

Optical frequency comb generation in the mid-infrared (MIR) spectral region has been intensively explored over the past decades [1]. Among various techniques, the synchronously pumped degenerate optical parametric oscillator (SPDOPO) has been particularly promising because of its high power, high conversion efficiency, broad instantaneous bandwidth, and more importantly, the intrinsic phase and frequency locking of the output to the pump [2–4], which are highly desirable for a plethora of applications from fundamental science to molecular sensing. Recently, the temporal simulton, a special form of quadratic solitons, has emerged as a novel state of operation in SPDOPO in the uncommon high-gain low-finesse regime. It features higher conversion efficiency and favorable laws of power-dependent bandwidth scaling without losing any advantages of conventional SPDOPOs [5]. Although simulton OPOs have been recently demonstrated at 2.09 μm [5] and at 4.18 μm [6], several questions regarding their performance in the mid-IR and proper design parameters remain unanswered. Here we demonstrate a SPDOPO, working in the simulton regime, which generates a frequency comb centered at 4.18 μm , with a record instantaneous FWHM bandwidth from 3.6 to 4.5 μm , pulses of 45-fs duration, an average power of 565 mW, and a record conversion efficiency of 44%, making it an outstanding mid-IR frequency comb source. A direct experimental comparison between the simulton and conventional regimes under the exact same pump condition attributes many of these outstanding characteristics to simulton formation. Moreover, we perform numerical simulations to capture the behavior exhibited by different regimes of the OPO, which agree well with our experimental results. This work presents a powerful scheme for MIR frequency comb generation and demonstrates its potential to be extended to longer wavelengths.

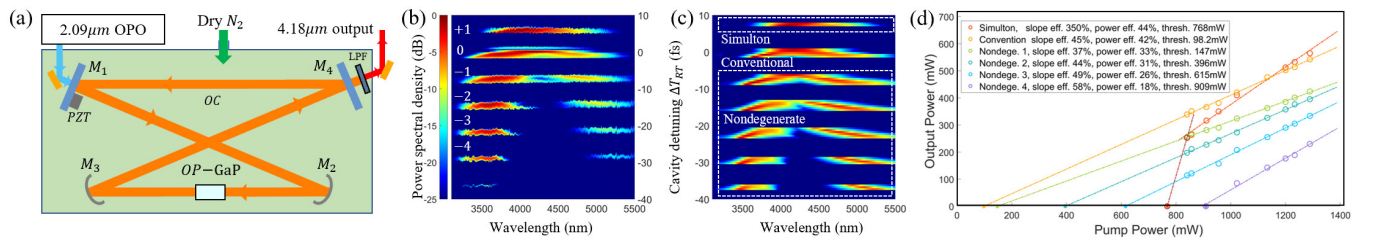


Fig. 1 (a) Schematic of the experimental setup. (b) Measured signal spectrum as a function of cavity detuning at the highest pump power of 1290mW, labeled with peak numbers. (c) Simulated signal spectrum as a function of cavity detuning corresponding to (b), with the three identified regimes indicated. (d) Measured output power for each peak (circles). Dashed curves are linear fitting for estimation of slope efficiencies.

The experimental set-up, similar to [7], is illustrated in Fig. 1(a). We use a PPLN-based OPO at 250 MHz as the pump, which can generate pulses centered at 2.09 μm with an average power up to ~ 1290 mW and a FWHM bandwidth of ~ 155 nm. The nonlinear gain is provided by a 0.5-mm-long OP-GaP with a poling period of 92.7 μm for type 0 phase matching. The output coupler is a dielectric mirror (M_4) coated for broadband transmission ($T=25\%$) from 3.5 μm to 5.5 μm .

The operation of synchronously pumped OPO can be classified into three regimes according to the deviation of the cavity round-trip time from the repetition period of the pump pulses (ΔT_{RT}), named simulton ($\Delta T_{RT} > 0$), conventional ($\Delta T_{RT} = 0$) and nondegenerate ($\Delta T_{RT} < 0$) [5]. On top of the conventional peak (labeled “0” in Fig. 1(b)), one more degenerate resonance, the simulton (labeled “+1”), is found when the cavity is positively detuned. Exhibiting an irregularly spaced threshold, the simulton is measured to have a $\sim 350\%$ slope efficiency and a 44% conversion efficiency, which are much higher than those of synchronous and nondegenerate peaks (Fig. 1(d)).

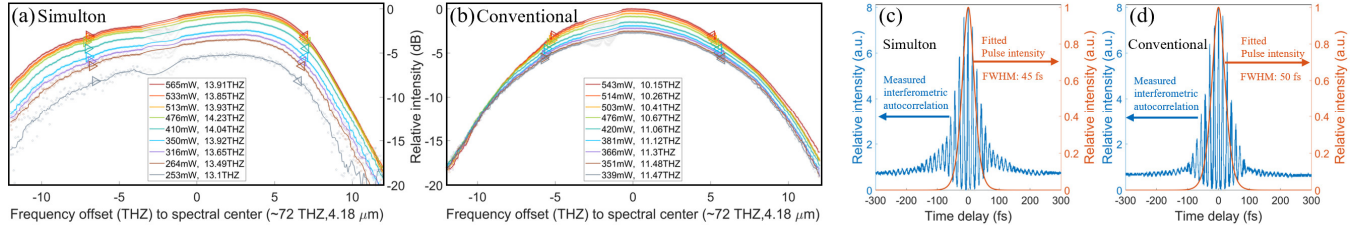


Fig. 2 (a) (b) Spectra recorded as a function of signal power for the 4.18- μm OPO working in simulton and conventional regime, respectively. The corresponding signal power and FWHM bandwidth for each curve is denoted in the legend. The FWHM bandwidths are also denoted by colored arrows on the curves. (c) (d) two-photon interferometric autocorrelation (blue) and fitted intensity (red) of the signal pulses for the simulton and conventional regimes.

Corresponding to points in Fig. 1(d), spectra of signal at each output power for both the simulton and conventional regimes are measured, and results are shown in Fig. 2 (a) and (b), respectively. As the power increases, the bandwidth of the signal spectrum increases when the OPO is working in the simulton regime if the pump power is not too high (Fig. 2(a)) and monotonically decreases when in the conventional regime (Fig. 2(b)). Those tendencies are in accordance with the simulton theory [5] and conventional box-pulse scaling [8]. Note that at the highest two pump powers, the signal band of the simulton regime stops broadening further, which also agrees with our theoretical prediction that the simulton theory would fail if the signal is well above the threshold [8]. This power-dependent signal spectral characterization shows that the simulton regime outperforms the conventional regime not only in power and efficiency, but also in spectral bandwidth.

The interferometric autocorrelation of the 4.18- μm signal pulses at the pump power of 1290 mW, in both the simulton and conventional regimes, are measured by a two-photon extended-InGaAs detector, and the corresponding results are presented in Fig 2 (c) and (d), together with the fitted pulse intensity. The measurements suggest a FWHM pulse width of ~ 45 fs for the simulton regime and of ~ 50 fs for the conventional regime. The slight chirp for both pulses is due to the dispersion from the substrates of the output coupler of the OPO cavity and the long-pass filters in the path of the autocorrelator.

In summary, we present the generation of a high-power and efficient MIR frequency comb centered at 4.18 μm based on a simulton OPO, achieving a 14-THz instantaneous FWHM bandwidth, sub-three-cycle pulses, a 565-mW output power and a record high 44% conversion efficiency. By direct comparisons with the conventional regime, the favorable performance of the simulton regime is demonstrated in terms of output power, conversion efficiency, pulse duration, instantaneous bandwidth and bandwidth scaling. This work paves the way to a compelling new source of broadband frequency combs in the mid-infrared region which can benefit numerous applications. We expect to further improve the performance of the simulton OPO by tuning the pump conditions and optimizing dispersion and loss within the cavity. Besides, given the high power of this 4.18- μm OPO as the second stage of our cascaded half-harmonic OPOs, we anticipate the realization of one more stage pumped by it, i.e., half-harmonic generation of a signal comb at 8.16- μm .

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