Quadratic Soliton Frequency Comb at 4 µm from an OP-GaP-based Optical Parametric Oscillator

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Abstract: We report generation of quadratic solitons, i.e. temporal simultons, in an OP-GaP based half-harmonic optical parametric oscillator. We achieve 4-µm pulses with sech^2 spectrum of 790nm FWHM bandwidth, 197% slope efficiency, and 38% conversion efficiency.

Introduction. Optical frequency comb generation based on quadratic nonlinearities has attracted increasing interest over the past few years, having been demonstrated in optical parametric oscillators (OPOs) working in different regimes [1,2]. Recently, the temporal simulton regime, characterized by generation of simultaneous bright-dark solitons of the signal at ω and the pump at 2ω (Fig. 1(b)), has emerged as a novel state of operation in near-synchronously pumped degenerate OPOs which features a degenerate sech^2 spectrum, high slope efficiency, high conversion efficiency and favorable laws of bandwidth scaling with power [3]. Although simulton OPOs were already demonstrated at 2.09 μm, it remained challenging to extend this regime of operation to longer wavelengths due to an incomplete understanding of its formation requirements. Here, we experimentally demonstrate simulton formation at 4.18 μm, which leads to shorter pulses and higher conversion efficiencies compared to conventional OPO operation, and use numerical simulations to show different operation regimes of the OPO. We also have studied the dependence of simulton formation on pump pulse width and show that there is an optimal pump pulse length for formation of simultons. This work paves the way toward efficient generation of broadband short-pulse frequency combs in the mid- and long-wave infrared region, which are highly desirable for molecular spectroscopic applications, and sheds new light on design rules for simulton OPOs that are in stark contrast to those of conventional OPOs.

The experimental set-up, similar to [4], is illustrated in Fig. 1(a). For the pump, we use a PPLN-based OPO at 250 MHz, which can generate pulses centered at 2.09 µm with an average power of 420 mW and FWHM bandwidth of 90 nm (corresponding to ~50-fs sech^2 transform-limited pulses). 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.

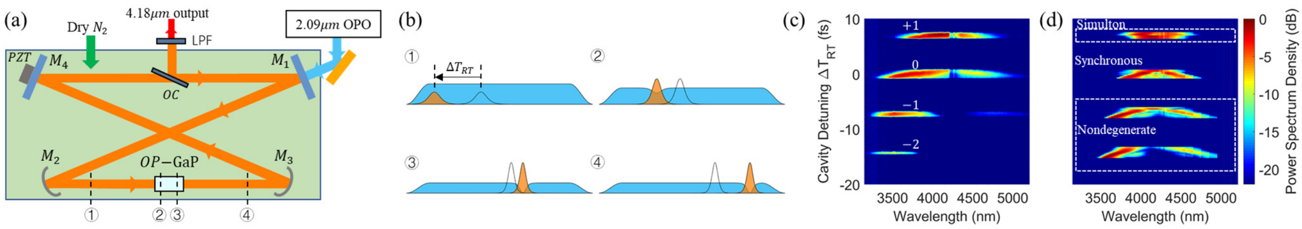

Fig. 1 (a) Schematic of the experimental setup. (b) Illustration of simulton formation: signal(orange) at ω and pump(blue) at 2ω. Solid lines (uncolored) denote a perfectly synchronous half-harmonic pulse undergoing linear propagation. ΔT_{RT} denotes the delay with respect to the incoupled pump pulse that the signal pulse acquires due to the cavity round-trip time detuning. (c) Measured signal spectrum as a function of cavity detuning for 420 mW of ~50-fs pump pulses, labeled with peak numbers. (d) Simulated signal spectrum as a function of cavity detuning, with the three identified regimes indicated. Discrepancies between simulated and experimental results arise due to differences in the spectral content of the cavity model from the experiment.

Results. Depending on the deviation of the cavity round-trip time from the repetition period of the pump pulses (ΔT_{RT}), the three regimes of OPO operation can be defined as: simulton ($\Delta T_{RT} > 0$), synchronous ($\Delta T_{RT} = 0$) and nondegenerate ($\Delta T_{RT} <$

0) [3]. In addition to the synchronous peak (labeled "0" in Fig. 1(c)), one more degenerate resonance, the simulton (labeled "+1"), is found when the cavity is positively detuned. Exhibiting an irregularly spaced threshold and sech^2 spectrum, the simulton is measured to have 197% slope efficiency and 38% conversion efficiency (Fig. 2(a)), which are much higher than those of synchronous and nondegenerate peaks. Note that the pump OPO can also generate 2.09-μm pulses with an average power of 500 mW and FWHM bandwidth of 180 nm (corresponding to 25-fs sech^2 transform-limited pulses), but there is no simulton found for such pump [4]. The conversion efficiencies of the synchronous peaks at both pump conditions for this OPO are close (~30%) and lower than that of the simulton.

We compare the signal bandwidth scaling with pump power for the simulton and synchronous regimes of OPO operation. As the output power increases, the bandwidth of the signal spectrum monotonically increases when the OPO is working in the simulton regime (Fig. 2(b)) and decreases when in the synchronous regime (Fig. 2(c)), in accordance with the simulton theory [3] and conventional box-pulse scaling [5], respectively.

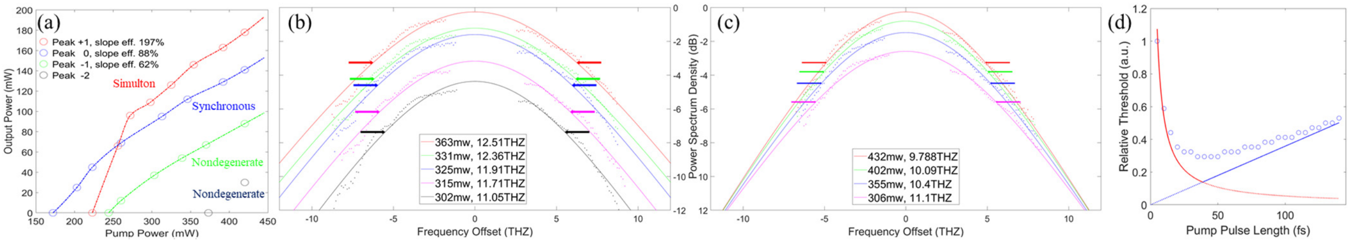

Fig. 2 (a) Measured output power for each peak (circles). Dashed curves are to guide the eye. (b), (c) Spectra recorded as a function of pump power for the 4.18-μm OPO working in simulton and synchronous regime, respectively. The corresponding pump power and FWHM bandwidth for each curve is denoted in the legend. The FWHM bandwidths are also denoted by colored arrows on the curves. (d) Simulated threshold dependence on pump pulse width for the simulton OPO at 4.18 μm (circles). Two asymptotes are plotted to show the tendencies based on a reduced OPO theory (solid curves).

Discussion. Shorter pump pulses with higher average power are usually thought to be preferential for high conversion efficiencies in short-pulse OPOs. However, we show that in this OPO, the highest conversion efficiency is achieved in the simulton regime, which is not accessible with the shortest available pump pulse. Further numerical study shows a non-trivial dependence of simulton threshold on the pump pulse length (T_p) (circles in Fig. 2(d)). To give an intuitive interpretation on the threshold scaling, two asymptotes (solid lines in Fig. 2(d)) are plotted based on a reduced OPO theory [5]. On the long pulse side, a linear dependence is denoted by the right asymptote, where the peak power of the pump pulse limits the threshold; on the short pulse side, the limiting factor becomes the temporal walk-off, i.e., the length of the crystal where the signal and pump can effectively interact with one another, which leads to the $1/T_p$ dependence denoted by the left asymptote.

Conclusion. We demonstrate the formation of simultons in a 4-μm OPO which features favorable performance compared to its conventional operation in terms of conversion efficiency, FWHM bandwidth and bandwidth scaling. This opens the door to a powerful new source of broadband frequency combs in the mid-infrared region which has numerous applications. Our results enable us to further improve the conversion efficiency of the simulton OPO by optimizing the pump pulses, dispersion, loss, length of the nonlinear crystal and output coupling. The study on pump pulse width dependence of simulton formation suggests new design rules for cascaded simulton OPOs which can lead to phase-locked femtosecond pulses at even longer wavelengths.

Reference

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