Purely Quadratic Cavity Solitons in a Nanophotonic Parametric Oscillator

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Abstract: We experimentally observe signatures of 475-fs-long sech-squared-shaped solitons in a ps-pumped phase-mismatched parametric oscillator in the normal dispersion regime, purely due to cascaded quadratic nonlinearities. The results are in good agreement with our theoretical predictions. © 2024 The Author(s)

Optical frequency combs (OFCs) attracted considerable attention for their numerous applications in the past decade [1]. Driven nonlinear resonators have been shown to produce highly coherent OFCs by forming cavity solitons (CSs), sech-squared optical pulses that propagate indefinitely in the resonator [2]. However, the experimental realization of CS has dominantly relied on the inherently weak cubic (Kerr) nonlinearity, limiting their formation to high-Q resonators and imposing practical challenges on their use for many applications [3]. Interestingly, the Kerr nonlinearity is not a strict prerequisite for soliton formation. Indeed, studies carried out more than twenty years ago in the context of *diffractive* degenerate optical parametric oscillators (DOPOs) have shown that purely quadratic resonators can also host *spatial* solitons [4]. These pioneering works have been extended to *dispersive* DOPOs over the last few years, theorizing the existence of *temporal* quadratic CS (QCS) [5-6]. Quadratic CSs offer two main advantages over their Kerr counterparts. First, as quadratic effects can be several orders of magnitude stronger than the cubic ones, requirements for the pump power and/or resonator Q are significantly reduced. Secondly, quadratic nonlinearity allows the generation of OFCs in spectral regions otherwise hard to access. Despite these potentials, only a few experimental demonstrations have been realized to date, either on the formation of Turing rolls [7-8], simultons [9-10], or walk-off solitons [11].

In this work, we leverage recent advances in lithium niobate nanophotonic to report what we believe to be the first experimental signature of a purely sech-squared-shaped quadratic cavity soliton in an integrated, signal resonant, phase-mismatched optical parametric oscillator. The dynamics of our resonator can be described by: [5-7,12]

$$t_R\frac{\partial A}{\partial T}=\left(-\frac{\Lambda}{2}-i\delta_0-\frac{i\beta_2 L}{2}\frac{\partial^2}{\partial\tau^2}\right)A+i\kappa B_{in}L_2 e^{-i\xi}\,\mathrm{sinc}(\xi)-(\kappa L_2)^2[A^2\otimes I(\tau)]A^*, \tag{1}$$

where t_R is the cavity roundtrip time, A is the envelope of the signal electric field centered at frequency ω_0, $T=nt_R$, where n is an integer, is a slow time while τ is a time reference traveling at the signal group velocity, α is the intrinsic cavity loss, δ_0 is the phase detuning from the closest cavity resonance, β_2 is the average group velocity dispersion (GVD), L is the total cavity length, κ is the second-order nonlinear coefficient, L_2 is the second-order medium length, B_{in} is the envelope of the pump electric field centered at frequency $2\omega_0$, $\otimes$ is the convolution operator, and $I(\tau)=F^{-1}([1-ix-e^{-ix}]/x^2)$ is the response Kernel with $F^{-1}(\cdot)$ the inverse Fourier transform operator, $x=\left(\Delta\beta+i\Delta(\beta_1\Omega+\beta_2^p\,\Omega^2/2)\right)L_2$ where $\Delta\beta$ is the signal phase-mismatch, $\Delta\beta_1$ is the group-velocity mismatch between the signal and the pump (GVM) and β_2^p is the pump GVD. Finally, $\xi=\Delta\beta L_2/2$. Equation (1) is a generalized parametrically forced Ginzburg Landau equation with a delayed nonlinear response, whose origin is due to cascaded sum- and difference-frequency generation processes. For nonzero phase mismatch ($\Delta\beta\neq 0\Rightarrow \mathrm{Im}[I(\tau)]\neq 0$), Eq. (1) admits QCS solutions [5-6]. This can be intuitively understood since, in this case, the back-and-forth energy conversion between the signal and the pump confers on the former a power-dependent phase, as would be obtained with a Kerr effect [13]. The bifurcation diagram for a continuous-wave pump $|B_{in}|^2=1$ W in the normal dispersion regime ($\beta_2>0$), obtained by numerical continuations of Eq. (1) for $\Delta\beta L_2=-8$ rad, is shown in Fig. 1a. It reveals the existence of stable QCSs but also more complex localized structures (not shown). In addition, we plot the bifurcation diagram for a 2ps-long pulsed pump, as we will use in the experiment. The QCSs obtained under pulsed driving are almost identical (see inset) to those obtained with a CW pump in the detuning region where the two coexist (shading in Fig. 1a).

To demonstrate the existence of QCS experimentally, we built an on-chip OPO using nanophotonic lithium

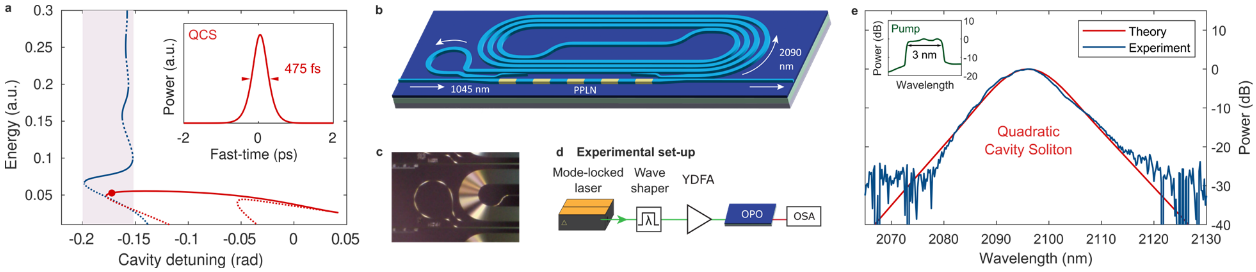

Figure 1 a, Bifurcation diagram showing the stable (plain) and unstable (dashed) solitons as a function of the cavity detuning for a homogeneous (blue) and a pulsed (red) pump. Inset: temporal profile at the red dot ($\delta_0 = -0.16$). **b**, Schematic of the on-chip OPO and **c**, the actual device. **d**, Simplified experimental set-up. **e**, Experimental spectra of the QCS together with the theory [cf. red dot in (a)]. Inset: pump spectrum.

niobate waveguides. The OPO, schematically depicted in Fig. 1b and shown in Fig. 1c, has a free spectral range of 250 MHz ($L = 53$cm). It includes a poled section of $L_2 = 10.8$ mm that acts as an optical parametric amplifier, located between two adiabatic couplers and phase-matched for degenerate optical parametric amplification of the signal with a 1045 nm pump at room temperature. Taking advantage of recent advances in dispersion engineering [14], we minimized the GVM between the signal and the pump ($\Delta\beta_1 = 15$ fs/mm). Operating with low GVM is crucial since QCSs do not exist otherwise. Besides, we also minimized the signal ($\beta_2 = 40\ \mathrm{fs^2/mm}$) and pump GVD ($\beta_2^p = 220\ \mathrm{fs^2/mm}$) to ensure broadband but also high parametric gain ($\kappa = 300\ \mathrm{m^{-1}W^{-1/2}}$), required to compensate for the high roundtrip losses ($\Lambda = 0.5$). We neglect the pump losses. Figure 1d shows the experimental setup for QCS formation. The OPO is synchronously pumped with 2ps-long pulses at 1049 nm, obtained by filtering the output of a mode-locked laser (repetition rate of 250 MHz) with a wave-shaper (Fig. 1e, inset). After filtering, the pulses are amplified and coupled to the OPO via the input bus waveguide using a lensed fiber. The on-chip pump peak power is about $|B_{in}|^2 = 1$ W. The light at the OPO output bus waveguide is collected with a fiber collimator and sent to an optical spectrum analyzer (OSA). The on-chip OPO temperature is stabilized at 29°C to ensure a sufficiently large phase mismatch. We scanned the detuning from positive to negative values to access the soliton state. At first, when the oscillation threshold is crossed, the OPO spectrum corresponds to a non-degenerate emission. Above the transition to degeneracy, for slightly positive detunings, we observe the appearance of a sech-squared spectrum (see Fig. 1e). We repeated the same experiment for different pulse durations to confirm the formation of a localized structure independent of the pump temporal profile. In each case, we observed a similar spectrum. These observations cannot be explained by the intrinsic focusing Kerr effect of lithium niobate, since it cannot lead to bright pulse formation in the normal dispersion regime. It is worth mentioning that bright QCSs only exist for negative phase mismatches since they lead to a strong effective defocusing Kerr effect. In fact, we could not find similar experimental results for $\Delta\beta > 0$. The QCS experimental spectrum (Fig. 1e) is in excellent agreement with the theoretical predictions obtained with Eq. (1) for $\delta_0 = -0.16$, indicating the formation of a 475fs-long sech-squared shaped QCS (Fig. 1a, inset).

In conclusion, we experimentally observed the evidence of a purely quadratic cavity soliton in a $\chi^{(2)}$ nanophotonic resonator. We used a singly resonant, phase-mismatched on-chip optical parametric oscillator in lithium niobate. We measured a sech-squared-shaped spectrum at the signal wavelength thanks to precise dispersion engineering and a pulsed pump. The experimental results agree with the theoretical predictions and indicate the formation of a 480-fs-long QCS. These results pave the way for broadband OFC formation in low-Q high-gain resonators, and at wavelength that direct lasers are less accessible. We are currently working on comprehensive temporal characterization of the OPO output and extending the cavity design to achieve even shorter pulses.

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