Temporal Dark Solitons in an Integrated Optical Parametric Oscillator

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Abstract: We theoretically describe and experimentally demonstrate dark soliton formation in a quadratic nonlinear resonator in lithium niobate nanophotonic. The dark pulses have a temporal duration of 40 fs and form a 120-nm-wide coherent frequency comb. © 2025 The Author(s)

Optical frequency combs (OFCs) have revolutionized several fields of science, such as spectroscopy and high-precision metrology, among many others [1]. There is a growing demand to reduce the footprint of frequency comb sources to enable their large-scale deployment. On the chip scale, the formation of Kerr cavity solitons (CSs), a localized nonlinear solution that propagates unperturbed in passive resonators, has emerged as a potential alternative to mode-locked lasers (MLL) and currently dominates the landscape of microcomb formation [2]. However, the formation of Kerr CSs requires two conditions: low loss and anomalous dispersion. On the other hand, second-order nonlinear resonators can also support soliton formation [3-4]. Such quadratic CSs offer three main advantages over their Kerr counterparts: (i) reduced requirements on pump power and/or resonator Q, (ii) no constraint on the dispersion regime, and (iii) the generation of OFCs in spectral regions that are otherwise hard to access. Despite these potentials, experimental demonstrations have been limited to the formation of purely quadratic CSs have been limited to Turing rolls [3], simultons [6], or walk-off solitons [7].

In this work, we report the formation of temporal quadratic dark solitons in an integrated degenerate optical parametric oscillator (DOPO) for the first time. These dark pulses arise from the locking of domain walls (DWs, Fig. 1b) between two different but coexisting, stable continuous wave (CW) solutions [3-4]. Therefore, to find the region of parameters where these dark solitons exist, one must first look at the existence and stability of the system's CW solutions. Our DOPO dynamics, supposing a perfect phase-matching, is described by the following generalized non-local Ginzburg Landau equation [3-5]:

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

where t_R is the cavity roundtrip time, A is the signal electric field envelope, $T = nt_R$, where n is an integer, is a slow time while τ is a time reference traveling at the signal group velocity, Λ are the roundtrip losses in intensity, δ_0 is the phase detuning from the closest cavity resonance, β_2 is the average group velocity dispersion (GVD), L is the resonator's total length, κ is the second-order nonlinear coefficient, L_2 is the second-order medium length, B_{in} is the pump electric field envelope and $I(\tau)$ is the kernel [3-5] whose convolution ($\otimes$) with the signal describes the pump depletion. Equation (1) admits a trivial solution ($A_h^0 = 0$) up to $B_{in} = B_{in}^{th} = \Lambda/(2\kappa L_2)$ which corresponds to the DOPO oscillation threshold. Above $B_{in} = B_{in}^{th}$, at $\delta_0 = 0$, the trivial solution supercritically bifurcates into two nontrivial CW solutions of the same amplitude but different signs ($\pm A_h$). Since these solutions are linearly stable and co-exist, it suggests the existence of a DW connecting $A_h \leftrightarrow -A_h$. In power, each DW lead to the formation of a single dark pulse (Fig. 1b). To confirm it, we ran a simulation of Eq. (1) with noise as an initial condition. The simulation result shows the spontaneous formation of dark pulses that maintain their shape during their propagation (Fig. 1c). For this reason, but also the seminal work done in spatial DOPOs [8] and owing to the π phase difference between the two CW waves, we call these dark pulses *temporal topological solitons.* To confirm their existence, we use a DOPO lithium niobate nanophotonic [9], schematically depicted in Fig. 1a. We use wavelength-selective couplers that allow the signal to resonate in the DOPO with of length L = 14.5 mm while letting the pump go only through a periodically poled section (L_2=5 mm). The poled section, phase-matched for degenerate optical parametric amplification of the signal with a λ_p=1045nm pump at room temperature, has a second-order nonlinear effective coefficient of κ = 300 $m^{-1}W^{-0.5}$ and is dispersion-engineered to achieve both low walk-off between the signal and the

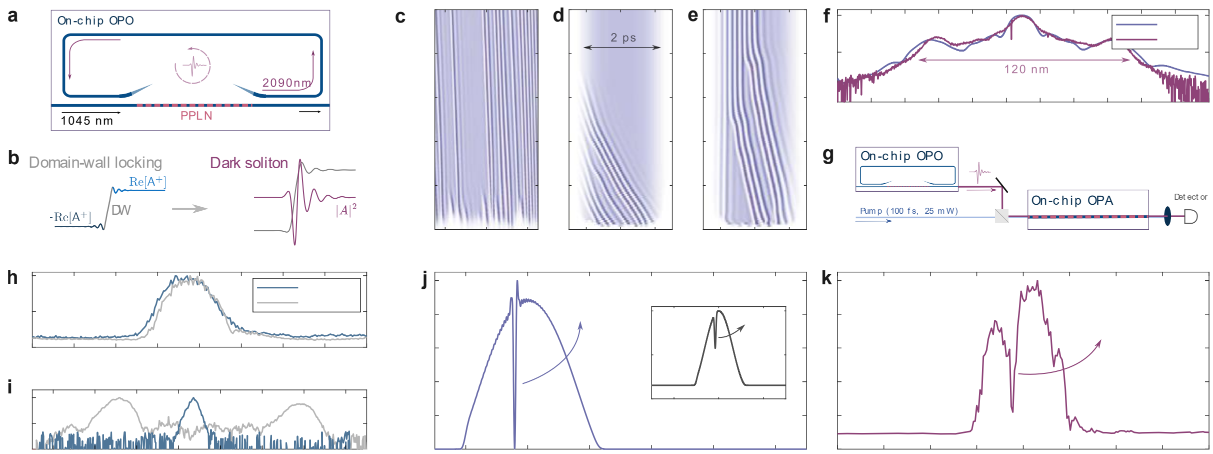

Figure 1. ***a***, Schematics of the quadratic resonator. ***b***, *The locking of two continuous wave (CW) stable solution ($\pm A^{+}$) give rise to a dark pulse. Simulation of Eq. (1) under CW driving (**c**), synchronized (**d**) and desynchronized (**e**) pulsed driving.* ***f***, *Theoretical (blue) and experimental (purple) spectrum.* ***g***, *On-chip temporal characterization setup.* ***h***, *The degenerate (blue) and non-degenerate (gray) temporal (top) and spectral (bottom) measurements.* ***i***, *Dark soliton theoretical profile and cross-correlation (inset).* ***j***, *Experimental temporal measurement of the dark soliton state.*

pump ($\Delta\beta_1$=30 fs⁄mm) and low signal (β_2^s=50fs²⁄mm) and pump chromatic dispersion ($\beta_2^p = 230$ fs²⁄mm). Finally, the total roundtrip losses (Λ) are estimated as 37%. We synchronously pump the DOPO with 3-ps-long pulses centered at λ_p= 1045 nm, to keep the average power below the damage threshold. In the perfectly synchronized regime, we don't observe a broadband comb. Indeed, simulation of Eq. (1) shows that the dark pulses disappear after a few roundtrips (Fig. 1d). However, by slightly but precisely desynchronizing the pump repetition rate, the topological solitons can lock at one side of the pulse (see Fig. 1e). Under these conditions, we experimentally observe a 120-nm wide spectrum (Fig. 1f), in excellent agreement with the simulation of Eq. (1), predicting 40-fs-short topological solitons (see also Fig. 1j). We also measure similar spectra in the anomalous dispersion regime (not show).

To unambiguously confirm the topological existence and the coherence of our quadratic microcomb, we proceed to a complete temporal characterization of our pulse train. For that purpose, we fabricate a dispersion-engineered TFLN poled waveguide. It acts as an optical parametric amplifier (OPA) in a cross-correlation measurement [10]. The setup is shown in Fig. 1g. The DOPO output is sent directly to the OPA chip, together with the output of a fs-MLL (100 fs, 25 mW average power) at 1045nm. As expected, under perfect synchronization, but also in the (uncoherent) non-degenerate regime, the signal is a homogeneous pulse of about 2 ps (Fig. 1h). Finally, we pump the DOPO approximatively 10% above the oscillation threshold, where simulations of Eq. (1) shows that the single topological soliton state can be reached (Fig. 1j). The result, plotted in Fig 1k, clearly highlights the presence of a 90-fs-long dark pulse. This is in good agreement with the generation of a 40-fs-long topological soliton, whose cross-correlation is 80-fs long (see Fig. 1j, inset).

To conclude, we theoretically study and experimentally characterize the formation of temporal topological solitons in a pump non-resonant DOPO in both normal and anomalous dispersion regimes. Our spectral and temporal results agree well with the theory. Specifically, we confirmed the formation of 40-fs-long dark pulses through on-chip cross-correlation measurements. Our results represent the first step towards forming highly coherent and broadband frequency combs in quadratic nanophotonic resonators.

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