Topological Soliton Formation in a Nanophotonic Optical Parametric Oscillator

Nicolas Englebert*†, Robert M. Gray*, Luis Ledezma, and Alireza Marandi

Department of Electrical Engineering, California Institute of Technology, Pasadena, California 91125, USA.
These authors contributed equally. †Author e-mail address: englebert@caltech.edu

Abstract: We theoretically describe and experimentally observe signatures of spontaneous topological soliton formation through the locking of domain walls in a quadratic nonlinear resonator. These dark pulses can have a temporal duration of 65 fs.

Kerr cavity solitons (CSs) have emerged as an elegant source of optical frequency combs (OFCs) [1]. This time localized nonlinear solution propagates unperturbed in passive resonators and creates an optical pulse train with high coherence properties as a portion of its energy escapes the resonator at each roundtrip. They have been used for numerous applications such as data transmission, atomic clocks, and microwave generation [2]. However, the formation of Kerr CSs requires two conditions. The first relates to the resonator's losses. As the Kerr effect is intrinsically weak, the resonator must have a high finesse, intrinsic or effective [3,4]. The second condition is that in most materials, the dispersion regime has to be anomalous for bright Kerr solitons to form. This can be difficult to achieve, particularly at visible wavelengths. However, normal dispersion is not incompatible with OFC generation since it allows the formation of dark solitons [5]. These dark pulses arise from the locking of domain walls (DWs), sometimes called wavefronts or switching waves [6]. They consist of a transition connecting the system's two different, but coexisting, stable continuous wave (CW) solutions. Although more energy-efficient than their bright counterparts, these dark pulses have proved difficult to observe experimentally, mainly due to the difficulty of exciting them spontaneously [5]. Interestingly, it was predicted over twenty years ago that degenerate optical parametric oscillators (DOPOs) can host DWs. As a result of the interplay between chromatic dispersion and parametric amplification due to $\chi^{(2)}$ nonlinearities, these DWs form stable topological temporal (dark) solitons [7]. In sharp contrast to dark solitons resulting from cubic nonlinearities, quadratic topological solitons can form spontaneously. Moreover, the large parametric gain allows their formation even in low-finesse resonators. However, although OPOs are widely used, these dark pulses have, to the best of our knowledge, yet to be observed experimentally.

In this work, we report on the first spectral signature of topological solitons induced by the locking of domain walls using a lithium niobate nanophotonic singly resonant DOPO [8-9]. The dynamic of our resonator, supposing a perfect phase-matching and a normal dispersion, is well described by the following generalized parametrically forced Ginzburg Landau equation [10-13]:

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

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 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, $I(\tau) = F^{-1}([1 - ix - e^{-ix}]/x^2)$ is the kernel with $F^{-1}(\cdot)$ the inverse Fourier transform operator, $x = i\left(\Delta\beta_1\Omega + \beta_2^p\Omega^2/2\right)L_2$ where $\Delta\beta_1$ is the group-velocity mismatch between the signal and the pump (GVM) and β_2^p is the pump GVD. The kernel convolution ($\otimes$) with A describes the pump depletion [13]. Since the focus is on DWs formation, we look first at the steady-state CW solutions [11-12]. Equation (1) has a stable trivial solution $A_h^0 = 0$ up to $B_{in} = B_{in}^{th} = \Lambda/(2\kappa L_2)$ where it undergoes a Pitchfork bifurcation. Physically, B_{in}^{th} corresponds to the DOPO oscillation threshold. In addition, Eq. (1) can admit a nontrivial CW solution ($\pm A_h$) which emerges supercritically from B_{in}^{th}. These solutions are represented in Fig. 1 for $\delta_0 = 0$. Since these solutions are linearly stable, it suggests the existence of DWs connecting $A_h \leftrightarrow -A_h$. To confirm their existence, we numerically integrate Eq. (1) with noise as an initial condition. The result, after 10,000 roundtrips, is given in Fig. 2. One can clearly see the spontaneous

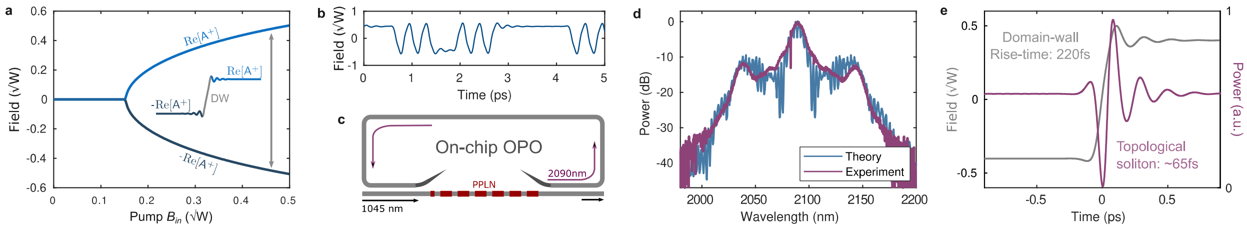

Figure 1. **a**, Bifurcation diagram as a function of the pump power. Above the threshold, two continuous-wave solutions can exist ($\pm A_h$), and a transition (gray arrow) between them can occur. b, Spontaneous formation of DWs. **c**, Schematics of the quadratic resonator. **d**, Theoretical (blue) and experimental (purple) spectrum of a topological soliton, expected to have a temporal duration of 65fs (e).

formation of multiple DWs between the two CW solutions gives rise to several dark topological solitons.

To reveal the existence of these topological solitons, we built a singly resonant DOPO in lithium niobate nanophotonic, schematically depicted in Fig. 1c [8-9]. We use wavelength-selective couplers that allow the signal to resonate in the DOPO with a free spectral range of $\sim$ 10GHz ($L = 14.5$ 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 $\lambda_p = 1045$nm pump at room temperature, has a second-order nonlinear effective coefficient of $\kappa = 300\ \mathrm{m}^{-1}\mathrm{W}^{-0.5}$, and is dispersion-engineered to achieve both low GVM between the signal and the pump ($\Delta\beta_1 = 30\ \mathrm{fs/mm}$) and low signal ($\beta_2^s = 50\ \mathrm{fs}^2/\mathrm{mm}$) and pump GVD ($\beta_2^p = 230\ \mathrm{fs}^2/\mathrm{mm}$). Finally, the total roundtrip losses are estimated as $\Lambda = 50\%$. We synchronously pumped the DOPO to keep the average power below the damage threshold. The pump is an electro-optic comb, producing 2-ps-long pulses centered at $\lambda_p = 1045$ nm, coupled to the DOPO by a lensed fiber. The light coming out of the resonator is collected with another lensed fiber and sent to an optical spectrum analyzer (OSA). Simulation of Eq. (1) shows that a slight desynchronization is necessary to reach a stationary state where topological solitons exist, as they have a group velocity that slightly differs from the one of the degenerate signal. If perfectly synchronized, the solitons disappear after a few hundred roundtrips. We stress that this disappearance under perfect synchronization is due to the pulsed pump; topological solitons would endlessly persist with a CW pump, as shown in Fig. 1b. The experiment is as follow. We pump the DOPO about four times above its oscillation threshold and slightly tune the pump repetition rate mismatch up to the observation of a significant spectral broadening at the signal wavelength ($\Lambda_s = 2090$nm). The experimental spectrum is plotted in Fig. 1d alongside the numerical integration of Eq. (1). Since the topological solitons positions are random and lead to spectral interferences, we averaged the results of five independent simulations. The agreement between with the experiment is excellent. The corresponding temporal profile is given in Fig. 1e and reveals DWs with a rising time of 220 fs, leading to topological solitons as short as 65 fs.

In conclusion, we observed the spectral signature of topological solitons [7] arising from the locking between domain walls in a singly resonant degenerate optical parametric oscillator [7,11-12]. Our on-chip DOPO operates in the normal dispersion regime with an intrinsically low finesse. The experimental results are in good agreement with the simulations, showing the formation of 65-fs-long dark pulses. We are currently working on precise temporal characterization [5] to confirm the pulse shape. Since the topological solitons can be individually addressed, for instance using an intracavity phase modulator, our findings represent the first step towards the formation of highly coherent and broadband OFCs in low-finesse high-gain OPOs.

References

[1] F. Leo, *et al.*, Nat. Photon. **4**, 471 (2010).
[2] T. J. Kippenberg, *et al.*, Science **361**, eaan8083(2018).
[3] S. Coen, *et al.*, Optics Letters **38**, 1790 (2013).
[4] N. Englebert, *et al.*, Nat. Photon. **15**, 536 (2021).
[5] X. Xue, *et al.*, Nat. Photon **9**, 594 (2015).
[6] P. Parra-Rivas, *et al.*, Phys. Rev. A **93**, 063839 (2016).
[7] S. Trillo, *et al.*, Opt. Lett. **22**, 970 (1997).
[8] L. Ledezma, *et al.*, Sci. Adv.**9**, eadf9711 (2023).
[9] A. Roy *et al.*, Nat Commun **14**, 6549 (2023).
[10] S. Mosca, *et al.,* Phys. Rev. Lett. **121**, 093903 (2018).
[11] P. Parra-Rivas, *et al.*, Opt. Lett. **44**, 2004 (2019).
[12] P. Parra-Rivas, *et al.*, Phys. Rev. Research **4**, 013044 5(2022).
[13] C. Mas Arabí, *et al.*, Opt. Lett. **48**, 1950 (2023).