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Dissipative Cavity Solitons at the Boundaries of a Topological Lattice

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Abstract: We experimentally observe the formation of dissipative cavity solitons at the boundaries of a topological lattice. Our work reveals new opportunities to study both nonlinear topological photonics and dissipative cavity solitons in coupled resonator arrays.

Over the past decade, dissipative cavity solitons (CSs) have attracted attention both for their rich nonlinear dynamics and for their potential applications to numerous technologies, including spectrometers, optical clocks, and gyroscopes. Recently, there has been growing interest in studying the dynamics of CSs in coupled resonators. Early theoretical and experimental studies of these phenomena have demonstrated that coupled resonators can enhance the pump-to-soliton conversion efficiency [1] and have revealed a slew of exciting and unexplored nonlinear dynamics [2]. However, the fabrication challenges associated with building chains or arrays of spatially coupled nonlinear resonators currently restricts the study of soliton formation and dynamics in coupled systems to only a few coupled resonators, and, to the best of the authors' knowledge, CS dynamics have only been studied in at most four coupled resonators [3]. The fabrication challenges associated with increasing this number strongly motivate searching for an alternative approach to study solitons in coupled resonators.

Time-multiplexed resonator networks are powerful architectures for studying the dynamics of coupled resonators. Although originally developed in the context of the coherent optical Ising machine [4], time-multiplexed networks have recently been used to demonstrate dissipative topological dynamics in 1D and 2D synthetic lattices and to demonstrate the first topological mode-locked laser [5, 6]. In contrast to arrays of spatially coupled resonators, time-multiplexed resonator networks are scalable to large numbers of resonators, and they enable arbitrary connectivity between the resonators in the network [5]. These architectural advantages, combined with the successful history of applying time-multiplexed networks to diverse resonator dynamics, motivates exploring time-multiplexed resonator networks as platforms for studying solitons in coupled nonlinear cavities.

In this work, we experimentally demonstrate CS formation in time-multiplexed resonator network with topologically nontrivial couplings. As shown in Fig. 1(a), this time-multiplexed resonator network consists of a main resonant cavity (the "Main cavity") and two delay lines (labeled $\pm T_\mathrm{R}$). Using a mode-locked laser (MLL), we inject 5 ps pulses separated by $T_\mathrm{R} = 8$ ns into our time-multiplexed network, and the delay lines introduce nearest-neighbor couplings between the pulses. Intensity modulators (IMs) in the delay lines control the strengths of these couplings on a pulse-to-pulse basis. Drawing inspiration from recent work on active cavity solitons [7], we partially compensate for the roundtrip losses of our time-multiplexed network (~ 12.5 dB with couplings off) by adding a section of erbium-doped fiber to the main cavity. With this additional gain, we can operate with losses as low as ~ 1.9 dB, which is sufficient for soliton generation.

We explore the coupled soliton dynamics that can emerge in our time-multiplexed resonator network by programming the IMs in the $\pm T_\mathrm{R}$ delay lines to implement the staggered couplings w and v of the Su-Schreiffer-Heeger (SSH) model [8], which is depicted schematically in Fig. 1(a). We pump $n = 50$ of the 67 time slots in our network to ensure that our SSH lattice possesses open boundary conditions. We then generate solitons in our lattice by sweeping the length of the main cavity from blue to red detuning to reveal the nonlinear cavity resonances. We use an auxiliary signal to lock the delay lines out of phase by $\varphi = -\pi/8$ with respect to the corresponding section of the main cavity.

In Fig. 1(b), we show the trace of a cavity sweep recorded in the topological phase of the SSH model ($w/v > 1$), where the SSH model is known to possess a topological edge state. The system passes through a region of modulation instability before we observe the formation of a soliton state in which the solitons only form at the edges of the SSH lattice. While, in other traces, we also sometimes observe bulk solitons, these solitons tend to annihilate

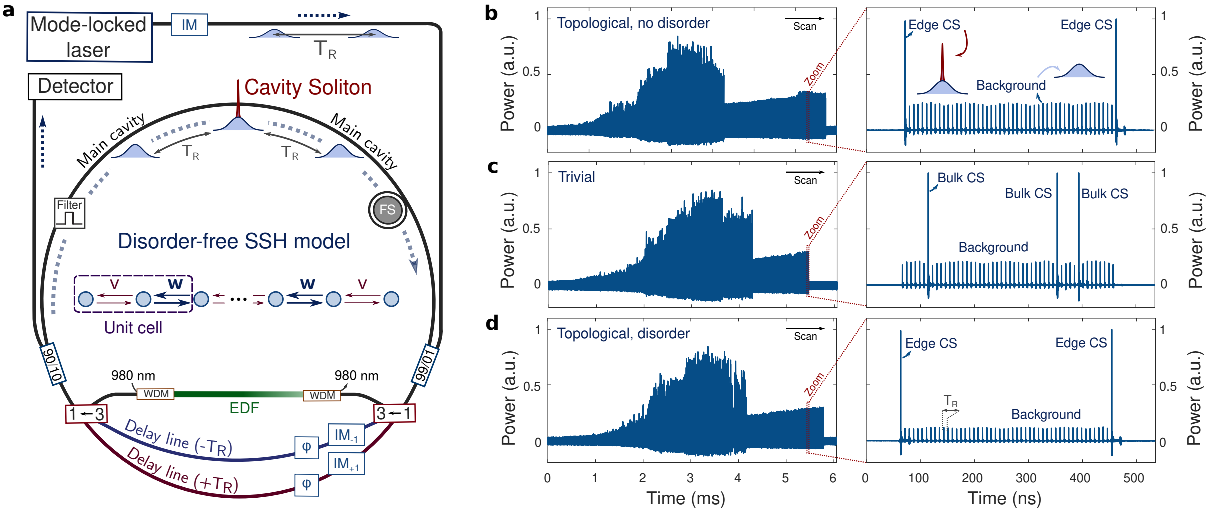

Fig. 1: **(a)** Schematic of our time-multiplexed resonator network and of the disorder-free SSH model. **(b,c,d)** Example blue-to-red detuning scans and observed soliton states for the disorder-free topological SSH lattice, the disorder-free trivial SSH lattice, and the disordered topological SSH lattice respectively.

at smaller detunings than the edge solitons, leaving soliton states that are localized at one or both of the boundaries at larger detunings .

We next switch the couplings of our network to implement the SSH model in the trivial phase ($w/v < 1$), in which the SSH model does not possess localized edge modes. In Fig. 1(c), we show the trace of a cavity sweep recorded in the trivial phase. In this phase, we observe that solitons frequently form in the bulk of the lattice, and solitons do not appear to preferentially form at the edges of the lattice.

Finally, to evaluate whether the observed edge soliton formation is robust against disorder, which we would expect if it were of a topological origin, we modify the couplings of our network to implement a topological SSH lattice with disorder distributed according to $\mathrm{Unif}(0, 0.2w)$ added independently to each delay line coupling. As is shown in Fig. 1(d), in this situation, we also predominantly observe edge soliton formation.

In conclusion, we have shown that time-multiplexed networks provide a powerful approach to study CSs in coupled resonators. By using a time-multiplexed network to implement a synthetic SSH lattice, we observed soliton formation at the boundary of a topological lattice, and we showed that these solitons continue to appear in the presence of coupling disorder. Currently, we are developing simulations to better understand the origin of these edge soliton states.

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