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Dissipative synthetic topological matter: the new frontier

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Topological phases in condensed matter have become one of the most vibrant branches in contemporary physics. Reaching back more than four decades, the discovery of the quantum Hall effect (QHE) in GaAs/GaAlAs semiconductor heterostructures has been a milestone for the field of topological quantum states [1]. It embodies a paradigm change, since the topological nature does not only reveal itself through some abstract phenomenological description, but directly unfolds in a conductance measurement as a fundamental observable [2], which reflects the transport of electronic charges along the boundary of the quantum Hall sample. Independent of many microscopic parameters, at sufficiently low temperatures, the off-diagonal conductance exhibits a quantisation in multiples of e^2/h, where the multiple is given by the Chern number, an established topological invariant known from complex vector bundles since the mid-20th century [3]. Finally, Haldane's formulation of the QHE on a lattice introduced the notion of a Chern insulator [4].

The quantisation of conductance in units of e^2/h in the QHE necessitates the context of quantum physics already at the level of dimensional analysis. The topological structure of matter, such as the existence of topological edge modes, however, transcends the borders set by quantum theory, and roots in the properties of parameter rather than phase space. For topological band structures, the parameter space is given by lattice momentum, where a closed parameter loop corresponds to a sweep of the Brillouin zone by one reciprocal lattice vector. While some aspects of this had surfaced previously in several subfields of physics, it only became broadly apparent in the context of the formalism of geometric phases laid out by Berry [5].

Emanating from the work by Haldane and Raghu [6], the pursuit of topological phases, and topological band structures in particular, started to expand into photonic systems, and from there to other avenues of synthetic matter available today [7–9]. By now, these include, among others, ultra-cold atomic gases in optical lattices, exciton polaritons, mechanical, acoustic, and plasmonic systems, micro-cavities, optical waveguides, optical fibers, and others [10–16]. The advent of topological insulators and semimetals [17–19] as well as topological quantum chemistry [20] has also generated significant synergies between topological quantum materials and synthetic topological matter. Synthetic topological matter promises future technological applications that are mostly based on topological edge modes. These include uni-directional transport without backscattering, wave guidance, protected information transmission, topological lasing, or other functionalities that, due to the topological character, are tolerant to fabrication imperfections and unwanted parasitic effects.

In parallel to the rise of topology, the design of loss and gain in a system, i.e., its non-Hermitian signature, has brought about another, seemingly separate arena for exciting physics, the realization and application of which may find its most immediate materialization in synthetic matter. Phenomena such as exceptional points, non-Hermitian skin effect, exotic non-Hermitian semimetals, and more have sparked tremendous interest in the research community [21]. By experimental design, it is not obvious to identify a material or metamaterial platform that would be able to comply with both the tuning requirements of non-Hermiticity and topological signatures on similar footing. Spatially modulated loss, for instance, not to speak of spatially modulated gain, is hard if not impossible to achieve outside the realm of site-wise tunable metamaterials.

In this time of transformative change in conceiving new platforms for topological, non-Hermitian systems, topolectric circuit networks [22–30] have risen as a highly suited initialisation platform for non-Hermitian topological matter. Topological spectra and individual state configurations can be accessed by node-wise voltage

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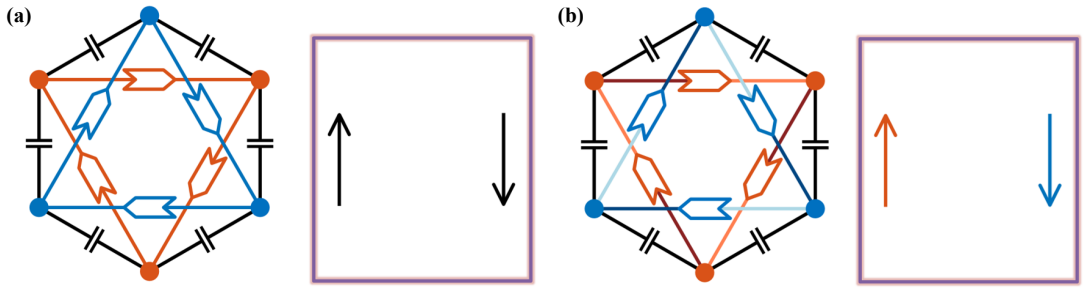

Fig. 1 Hermitian and non-Hermitian Haldane model circuits as realized in Ref. [35]. **(a)** In a Hermitian Haldane model circuit, the next-nearest-neighbor hoppings are antisymmetric (with input and output wires of INICs denoted by the same colors), resulting in non-amplifying and dissipationless chiral edge states (represented by the black arrows). **(b)** When the antisymmetry of the next-nearest-neighbor hoppings is broken (with input and output wires of INICs denoted by different colors), the circuit transposes into its non-Hermitian extension. The chiral edge states exhibit boundary-dependent lifetimes: one edge state undergoes effective amplification (indicated by the red arrow), while the edge state at the opposite boundary experiences dissipation (indicated by the blue arrow).

measurements and as such ensure a high degree of precision and signal to noise ratio [24]. Electronic components, which have benefitted from industrial refinement over the course of decades, allow to tune any desired topological band feature such as arbitrary long-range connectivity and dimensionality, non-Hermiticity by gain and loss, or non-reciprocity [24, 25, 31–33]. The flexibility of the circuit platform, and its high promise for future research, does not stop there. For instance, periodic driving can be readily implemented in all possible limits of Floquet theory. Furthermore, a plethora of passive and active non-linear elements allow to design any type of non-linear equations of motion at ease, and to tune the non-linear versus linear signal contributions at will [30, 34].

In this context, the present work by Rujiang Li *et al.* [35] reports on an exciting electric circuit network realisation of the dissipative Haldane model [4, 31]. Inspired by a previous theoretical topolectric circuit proposal to realize the Hermitian limit of the Haldane model [31], a central ingredient is the use of negative impedance converters through current inversion (INIC). In order to replicate the phase-dependent nearest-neighbor hoppings in the original Haldane proposal in a circuit, the key idea is to understand Hermiticity to be built of combined time-reversal symmetry and reciprocity, and vice versa. Setting aside subtleties related to non-linear circuit components, this implies that a circuit component can either preserve all three symmetries, just one of the three, or none. The INIC preserves Hermiticity while breaking time-reversal symmetry and reciprocity, precisely mimicking the role of the flux-dependent hopping [31]. Furthermore, the work by Rujiang Li *et al.* [35] takes a highly innovative step by extending the Haldane model circuit to its non-Hermitian cousin through tuning the resistors in the INICs which allows to break the antisymmetry, i.e., maximum non-reciprocity, of the next-nearest-neighbor hopping. In doing so, this implementation actually hits two birds with one stone. First, the authors allow their system to transpose the Hermitian Haldane phase diagram involving a Chern insulator, a trivial insulator, and a semimetallic domain into their non-Hermitian analogues. Second, in both the non-Hermitian Chern insulator and non-Hermitian semimetal phases, the chiral edge states exhibit boundary-dependent lifetimes: modulo the dissipative envelope, the chiral edge state at one boundary undergoes effective amplification, while at the opposite boundary, the edge state experiences dissipation, as schematically shown in Fig. 1.

As an outlook, this work by Rujiang Li *et al.* [35] has the potential to lay out a pillar model for studying intertwined topology and non-Hermiticity in topolectric circuits, and may prove highly influential for future topological metamaterial research.

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