this interplay lies at the forefront of ongoing studies of non-Hermitian physics.

Another enticing possibility is observing the non-Hermitian skin effect in cold atoms in the presence of spin–orbit coupling. The non-Hermitian skin effect is a property shared by a broad class of non-Hermitian systems wherein the eigenstates exponentially accumulate at boundaries[8]. It influences a variety of bulk properties such as band topology, parity–time symmetry, dynamics and beyond. Moreover, recent theoretical studies have revealed the presence of the non-Hermitian skin effect under the very same set-up[9,10]. In the foreseeable future, phenomena associated with the non-Hermitian skin effect may well be accessible in cold atoms, where sophisticated quantum control techniques and intrinsic many-body effects offer fresh opportunities. ❐

Wei Yi [1,2] ✉

[1]*CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei, China.* [2]*CAS Center For Excellence in Quantum Information and Quantum Physics, Hefei, China.*
✉*e-mail: wyiz@ustc.edu.cn*

Published online: 12 April 2022
https://doi.org/10.1038/s41567-022-01580-5

References

1. Ashida, Y., Gong, Z. & Ueda, M. *Adv. Phys.* **69**, 249–435 (2020).
2. Miri, M.-A. & Alù, A. *Science* **363**, eaar7709 (2019).
3. Özdemir, S. K., Rotter, S., Nori, F. & Yang, L. *Nat. Mater.* **18**, 783–798 (2019).
4. Ren, Z. et al. *Nat. Phys.* https://doi.org/10.1038/s41567-021-01491-x (2022).
5. Milburn, T. J. et al. *Phys. Rev. A* **92**, 052124 (2015).
6. Galitski, V. & Spielman, I. B. *Nature* **494**, 49–54 (2013).
7. Wu, Z. et al. *Science* **354**, 83–88 (2016).
8. Yao, S. & Wang, Z. *Phys. Rev. Lett.* **121**, 086803 (2018).
9. Zhou, L., Li, H., Yi, W. & Cui, X. Preprint at https://arxiv.org/abs/2111.04196 (2021).
10. Guo, S., Dong, C., Zhang, F., Hu, J. & Yang, Z. Preprint at https://arxiv.org/abs/2111.04220 (2021).

Competing interests

The author declares no competing interests.

Check for updates

PHOTONIC NETWORKS

Loss leads the way to utopia

The interactions between coupled photonic resonators influence the properties of the whole network. Dissipative coupling extends the ability to engineer photonic networks and brings fully controllable, ‘utopian’ networks within reach.

Hrvoje Buljan, Dario Jukić and Zhigang Chen

Many systems can be classified as coupled networks, for example, networks of airports, neural networks or atomic lattices. All these different systems have in common that their behaviour is governed by the characteristics of the individual elements and by the interactions between them. Reconfigurable networks with tunable coupling between their constituting elements have great potential for developing new technologies and exploring exotic phenomena[1–3]. However, these explorations have mostly been confined to conservatively coupled systems, where no energy is lost in the coupling. Writing in *Nature Physics*, Christian Leefmans and colleagues report that they have now built a reconfigurable photonic resonator network with purely dissipative coupling to display non-trivial topology in the system’s dissipation rates[4].

A crystal lattice can be thought of as a network of coupled atomic orbitals for the motion of electrons. The crystal structure determines the connections that define the network, and the overlap of the atomic orbitals determines the strength of the coupling. All these properties affect the band structure of the lattice, which in turn governs the electronic properties. In an analogous way, an optical lattice of ultracold atoms can also be considered as a network with a reconfigurable lattice structure. It offers the possibility to engineer the coupling, which has led to experimental demonstrations of famous topological models, such as the Haldane model or the Harper–Hofstadter model[3], and their characteristic phases.

Photonic systems are another popular platform to realize networks because they have demonstrated tremendous ability to design and control the coupling and other features of the network[2]. For example, by engineering the complex phase of the coupling amplitudes between optical resonators, one can mimic electrons moving through a crystal lattice in a magnetic field[2].

This analogy between photons and electrons has paved the way for the exploration of many fundamental phenomena with photons, including quantum Hall effect physics, unidirectional topologically protected edge states and photonic topological insulators[1,2]. The ability to engineer the connectivity of photonic network modes has led to new explorations of physics in synthetic dimensions[2], enabling experiments in higher-dimensional spaces.

As interesting as these studies are, they often neglect an inherent feature of optical systems — losses. Rather than treating it as an obstacle to the functionality of a topological network, Leefmans and colleagues have now shown that dissipation can be an asset by judiciously designing a photonic network with purely dissipative coupling (Fig. 1a). In dissipative coupling, two elements of the network are coupled via an intermediate reservoir (external bath);[5] information is irreversibly lost in this process, and the energy is not conserved. However, it provides a new knob to engineer the coupling between different network elements[5].

Leefmans and colleagues designed their networks to exhibit the non-trivial topology of the one-dimensional Su–Schrieffer–Heeger lattice and the two-dimensional Harper–Hofstadter lattice[1,2] (Fig. 1b, c). In the presence of purely dissipative coupling, the band structure is not shown in energies, as in standard conservatively coupled systems, but rather in dissipation rates. Consequently, the topological edge states of these systems exist in dissipation rate gaps. In this way, the losses of the edge states — that is, the quality factor[4] — were topologically protected.

Time-multiplexed networks use synthetic dimensions, which extend the dimension of a system’s phase space without adding physical dimensions. Extra

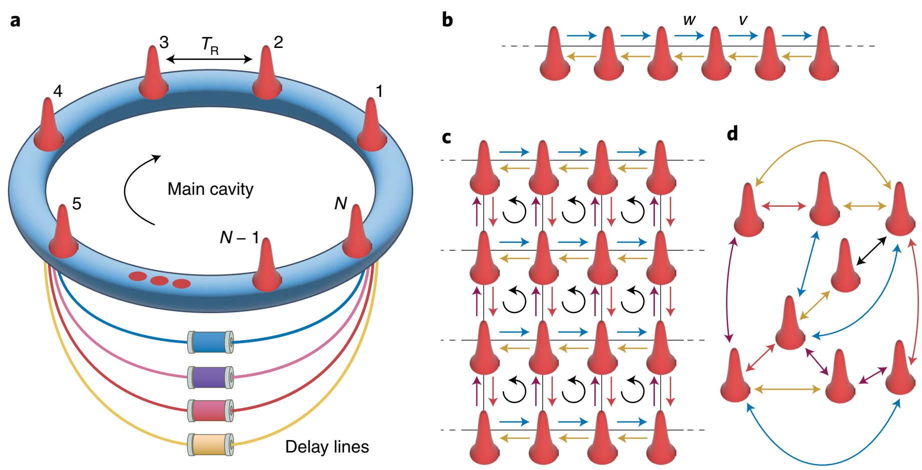

Fig. 1 | Reconfigurable time-multiplexed photonic resonator network and topological lattices with dissipative coupling. a, The main cavity of the time-multiplexed network and delay lines that enable coupling between N travelling pulses separated by a repetition time T_R. **b**,**c**, Pulses represent network elements that are, depending on the active delay lines, coupled in one-dimensional (**b**) or two-dimensional (**c**) configurations. The dissipative coupling is engineered to obtain one-dimensional Su–Schrieffer–Heeger and two-dimensional Harper–Hofstadter topology in dissipation rates. Different couplings are obtained with different delay lines as indicated by their corresponding colours. The ratio between the coupling rates w and v determines the topology of the Su–Schrieffer–Heeger lattice. The synthetic flux through plaquettes, indicated with black curved arrows, determines the state of the Harper–Hofstadter lattice. **d**, Illustration of a utopian resonator network where any element can be coupled to any other element, and coupling may take various forms (conservative, with tunable amplitude and phase, dissipative and so on).

dimensions are synthesized by using the coupling between short pulses propagating in a resonator. Leefmans and colleagues realized the time-multiplexing with a long fibre loop, called the main cavity, which supported 64 travelling pulses (Fig. 1a). These pulses were coupled through four optical delay lines. With a sufficient number of delay lines, such a setup offers substantial control over the pairs of pulses that will be coupled.

It is important to note that the pulses in these configurations represent synthetic network sites. The configuration of their connectivity, among other things, determines the dimensionality of the system (Fig. 1b, c). The team inserted intensity and phase modulators into the delay lines, with which they controlled the strength and the phase of each coupling, respectively. Together with tailored boundary conditions, this precise control over conservative and dissipative couplings equips the system with great flexibility in the network design. For example, it allows the introduction of synthetic magnetic (gauge) fields and synthetic higher dimensions.

The equation representing this purely dissipatively coupled system looks similar to its conservative counterpart with one important difference: time is replaced with an imaginary time. This implies that the topological dissipative dynamics observed by Leefmans and colleagues correspond to the imaginary time dynamics in a suitable conservative Hamiltonian system. In fact, it was proposed over a decade ago that dissipation can be utilized to drive a quantum system into a desired strongly correlated steady state[6,7].

The ultimate goal — a utopian resonator network, so to speak — would be one that can be scaled to huge numbers of elements, where any pair of resonators can be easily coupled in a controlled fashion (Fig. 1d). This could be achieved by conservative coupling with controllable strength and phase, dissipative coupling, by a combination of both, or in some other way. Such a utopian resonator network could be used not only to explore existing exotic physical phases in a controlled fashion but also to discover new phenomena. It could, for example, mimic new materials, to develop novel computation schemes or to advance existing ones[8,9].

However, scalability and reconfigurability of networks and long-distance coupling are challenging tasks. The time-multiplexed photonic resonator network designed by Leefmans and colleagues to explore topological protection of losses makes a strong case that further developments could lead to utopian resonator networks with desired features. Controlled long-distance coupling via feedback loops and controlled boundary conditions now seem within reach. The current network has 64 resonators in a roughly 100-metre-long fibre loop, but future experiments will have to show how scalable this approach is without losing its interesting features.

The time-multiplexed network Leefmans and colleagues used is classical, but it could be extended to the quantum regime, where it offers promising possibilities, for example, in integrated quantum photonics. One can envision many other directions where this research could lead, such as developments in non-Hermitian topological photonics and artificial-intelligence-empowered photonics in the coming decade[10]. ❐

Hrvoje Buljan[1,2] ✉, Dario Jukić[3] ✉ and Zhigang Chen[2,4] ✉

[1]*Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia.* [2]*The MOE Key Laboratory of Weak-Light Nonlinear Photonics, TEDA Applied Physics Institute and School of Physics, Nankai University, Tianjin, China.* [3]*Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia.* [4]*Department of Physics and Astronomy, San Francisco State University, San Francisco, CA, USA.*
✉*e-mail: hbuljan@phy.hr; djukic@phy.hr; zgchen@nankai.edu.cn*

Published online: 14 February 2022
https://doi.org/10.1038/s41567-022-01518-x

References

1. Lu, L., Joannopoulos, J. & Soljačić, M. *Nat. Photon.* **8**, 821–829 (2014).
2. Ozawa, T. et al. *Rev. Mod. Phys.* **91**, 015006 (2019).
3. Cooper, N. R., Dalibard, J. & Spielman, I. B. *Rev. Mod. Phys.* **91**, 015005 (2019).
4. Leefmans, C. et al. *Nat. Phys.* https://doi.org/10.1038/s41567-021-01492-w (2022).
5. Metelmann, A. & Clerk, A. *Phys. Rev. X* **5**, 021025 (2015).
6. Verstraete, F., Wolf, M. M. & Cirac, J. I. *Nat. Phys.* **5**, 633–636 (2009).
7. Diehl, S. et al. *Nat. Phys.* **4**, 878–883 (2008).
8. Marandi, A., Wang, Z., Takata, K., Byer, R. L. & Yamamoto, Y. *Nat. Photon.* **8**, 937–942 (2014).
9. Inagaki, T. et al. *Science* **354**, 603–606 (2016).
10. Chen, Z. & Segev, M. *eLight* **1**, 2 (2021).

Competing interests

The authors declare no competing interests.