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PHOTONICS

Topology puts solitons in the corner

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Nonlinearity and topology are both linked to symmetries, but what happens when the two are combined is not a trivial question. In a nonlinear photonic higher-order topological insulator, solitons localize on the corners together with the topological modes.

Many physical phenomena are described as linear effects, even though nonlinearities are important in a range of systems across the natural sciences. From fluids to atomic condensates and optics, one hallmark of nonlinear systems is the soliton — a robust and highly localized wave that doesn't change size or shape. Solitons are self-sustained by a perfect balance between linear and nonlinear effects. But what happens to this delicate balance when other localization effects are introduced? For example, one can wonder if solitons can coexist with the localized edge states of a topological insulator. Writing in *Nature Physics*, Marco Kirsch and colleagues have tackled this issue by investigating the fate of topological boundary modes in the nonlinear regime of a photonic system [1].

Topology is the study of the properties that are immutable under continuous deformations. In condensed-matter physics, it was first applied to explain the quantum Hall effect and topological insulators — bulk insulating materials that carry a perfectly quantized transverse Hall current [2]. We now understand this quantum Hall current as the transport of electrons through topological one-way states along a single-atom layer on the edge of the system, and the existence of such edge states depends only on intrinsic properties of the bulk. These states are characterized by a topological invariant — a property that is constant under continuous deformations. If this invariant is zero, the state has no specifically topological properties and is called 'trivial'. If it is nonzero, the state is topological.

Topological concepts are no longer limited to condensed–matter systems, but appear in every aspect of physics — from quantum mechanics to classical-waves like light. Topological photonics, in particular, uses artificial structures specifically designed to exhibit topological properties. Like the electronic states in a topological insulator, the light propagation in such a non-trivial topological structure depends only on the intrinsic design and not on external perturbations. This ability to control robust optical transport is one of the main motivations for topological photonics. With the demonstration of unidirectionally propagating edge states of light and topological lasers, the field promises to deliver a range of applications.

If boundary modes of a standard topological insulator are localized at the edge, those of higher-order topological insulators are located at the edge of the edge — corners of a 2D system or hinges of a 3D system [3]. Higher-order topological systems require the existence of crystalline symmetries of the lattice — such as inversion or mirror symmetries — that affect how the electron density is centred within the unit cell, which in turn determines the polarization of the crystal. In higher-order topological insulators, the polarization is quantized, and a fractional charge accumulates on the corners of the system.

So far, topological phases have mostly been studied in the linear regime, but work on the effects of optical nonlinearities in photonic topological insulators has just begun [4, 5]. Kirsch and colleagues contributed to this recent effort by studying the role of nonlinearities in higher-order topological systems. They used a system of coupled waveguide arrays, arranged in a breathing kagome lattice (Fig. 1), which is known to be a higher-order topological insulator model in the linear regime. By changing the distance between the lattice sites, they realized two possible configurations: a topological and a trivial one. Laser light entered the waveguides at the corner of the lattice, propagated through the array by evanescently coupling to neighbouring sites, and was collected at the end, where the intensity distribution on the detector provided information about the lattice mode. Kirsch and colleagues introduced nonlinearities by using a waveguide medium with a Kerr-type nonlinearity, such that the refractive index depended on the light intensity.

For sufficiently high input power, solitons formed and the output light was confined around the input waveguide. In the trivial case, the soliton was localized over the entire unit cell of the lattice, whereas, for the topological case, the soliton was more strongly localized on the corner site (Fig. 1). Kirsch and colleagues then calculated the topological invariant, which for higher-order topological insulators is given by the bulk polarization, to back up the different nature of these two types of corner modes. Interestingly, the onset of nonlinearity proved not to be detrimental to the polarization value, which remains non-zero in the topological case, and strictly zero in the trivial configuration. Added nonlinearity therefore did not change the topological nature of the modes. This analysis distinguishes between the emergence of nonlinear topological corner states and the formation of trivial solitons in such structures.

The added nonlinearities had another effect: the bulk polarization was no longer quantized, meaning that the symmetries protecting the topological corner modes were broken. A very interesting scenario would be if nonlinearities could leave these symmetries unbroken. Or even more strikingly if they could induce a non-trivial topological phase starting from a trivial one. Preliminary steps in this direction have been taken [6], but the study of nonlinear topological phases is still in its infancy. The regime of strong nonlinearities is particularly interesting because it requires a quantum optical description and genuine interaction-induced topological effects can appear [7, 8], which could result in the realization of strongly correlated topological phases of photons.

<u>Figure 1:</u>

Topological soliton formation. An array of waveguides arranged on a breathing kagome lattice is an optical model for a linear higher-order topological insulator. Such a model has topological corner modes originating from a nonzero bulk invariant. When the system enters a nonlinear regime, the light becomes more localized and topological solitons form on the corners of the system. This shows that the topological order is robust against the onset of nonlinearity, leaving the bulk invariant nonzero.

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