TOPOLOGICAL PHOTONICS

Matryoshka frequency combs

Light propagating in the topological edge channel of an array of ring resonators is predicted to generate nested frequency combs: like a Matryoshka doll containing a set of smaller dolls, each 'tooth' of the comb comprises another frequency comb.

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Frequency combs are light sources that get their name from the shape of their spectrum, which consists of sharp, equidistant lines — like the teeth of a comb. They allow for fast and precise spectral measurements and have become an essential tool for metrology, spectroscopy and precision clocks. In ring resonators, frequency combs are generated by dissipative soliton waves. But ring resonators not only create frequency combs; they are also an important component for topological photonics devices comprising hundreds of evanescently coupled resonators[1], whose characteristic topological edge channels mimic the behaviour of the individual resonators. Now, writing in *Nature Physics*, Sunil Mittal and collaborators report that this self-similarity of the normal modes of a topological resonator array gives rise to self-similarity in its nonlinear dynamics in the form of nested dissipative solitons, creating nested frequency combs[2].

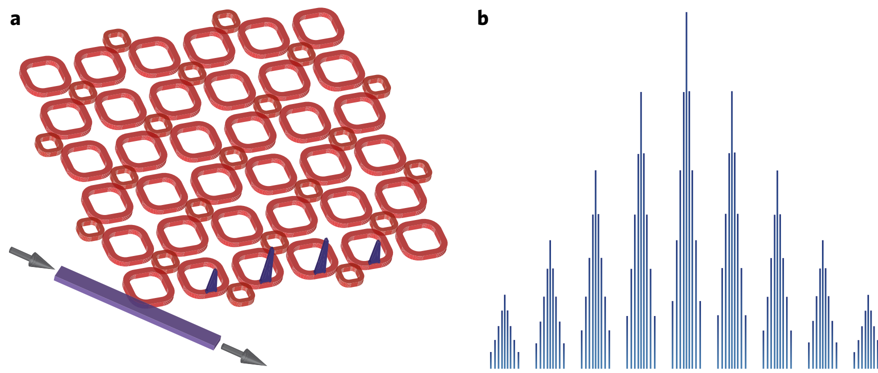

Fig. 1 | Nested frequency comb generation. a, Dissipative solitons (blue) are generated in the individual ring resonators by continuous driving via a waveguide (purple). The soliton amplitude is different at each site and forms a super-soliton propagating on the outer perimeter of the array, where the microrings support a topological edge channel. **b**, A schematic representation of the nested frequency comb generated by the topological array. Each 'tooth' of the frequency comb is itself a comb. Figure adapted with permission from ref. [2], Springer Nature Ltd.

Topological photonics emerged more than a decade ago following the realization that the concepts underlying the robust transport of topological electrons apply also to classical waves, and in particular to electromagnetic radiation[3]. This formal mapping between photons and electrons is only possible within a single-particle (or normal modes) description, and the focus of topological photonics has therefore remained restricted to the linear regime. It is only recently that the interest for practical applications and the quest to uncover new topological physics without a counterpart in electronic systems[4] has motivated a shift towards nonlinear topological devices.

This has raised a conceptual difficulty: nonlinear interactions tend to strongly mix different normal modes without necessarily distinguishing between trivial and topological ones, making predictions about the resulting topological properties difficult. However, the response of a photonic system can be controlled by engineering its structure and excitation. This has allowed the design of devices in which the topological normal modes are exclusively (or at least predominantly) excited. This in turn results in useful devices characterized by robust nonlinear dynamics, such as quantum-limited amplifiers[5], efficient quantum-state generators[6] and lasers[7,8] — at least within a narrow bandwidth.

In their calculations, Mittal and collaborators considered an array of evanescently coupled microring resonators (Fig. 1a). In these structures, light circulates in only one direction within a single ring resonator but can also hop from resonator to resonator while conserving the direction. In the presence of an appropriately engineered coupling between resonators, photons hopping from ring to ring on a closed loop acquire a Berry phase similar to the Aharonov–Bohm phase for electrons in a magnetic field. Indeed, in the linear regime, the photon motion can be mapped onto the motion of these electronic counterparts.

Like electrons in a magnetic field, these topological photons can propagate unidirectionally along edge channels, the properties of which are largely insensitive to local disorder and depend only on global topological properties. In this setting, the perimeter of the array can be viewed as a super-ring resonator because the topological edge modes connect the individual resonators. In other words, the collective excitations of all the rings along the perimeter of the array mimic the internal dynamics of the single building-block resonator. This self-similarity is a peculiarity of topological photonics devices based on arrays of microring resonators that does not occur in other platforms.

In the nonlinear regime studied by Mittal and collaborators, a dissipative soliton circulated in each ring on the array perimeter. The phases of these intraring solitons were locked throughout the whole perimeter of the array, but the amplitude was position dependent and propagated as a soliton wave along the super-ring resonator — a super-soliton (Fig. 1a).

In the setup investigated by Mittal and colleagues, one of the rings was evanescently coupled to a waveguide to provide continuous pumping (Fig. 1a). The waveguide also helped to extract the radiation circulating in the array as a regularly repeating burst of pulses.

Subsequent bursts were separated by the round-trip time of the super-soliton around the perimeter of the array, whereas subsequent pulses were separated by the (much shorter) roundtrip time of the intraring soliton. The result was a nested frequency comb (Fig. 1b): like a Matryoshka doll containing a similar but smaller doll, each tooth of the comb, generated by individual pulses, split into another frequency comb, generated by the repeating bursts.

Compared with other nonlinear topological devices, the dynamics investigated by Mittal and collaborators stands out for its complexity: it involves not only tens of ring resonators along the perimeter of their device but also tens of internal modes of the ring resonators. As a result, it spans a much larger bandwidth than other topological nonlinear systems. As expected for such a strongly driven multimode system, the dynamics is actually chaotic in most of the available parameter space. However, even a partial numerical exploration of this space was enough to uncover several parameter islands characterized by robust, ordered collective motion of the ring resonators. In these non-equilibrium topological phases, the ring resonators on the perimeter of the array can be excited by multiple nested solitons or host identical phase-locked soliton crystals, that is, a regular arrangement of phase-locked solitons[9].

The topological frequency combs conceived by Mittal and collaborators, with their complex but highly ordered and robust motion, illustrate how nonlinear photonic devices can expand the realm of topological physics and its applications. ❐

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Competing interests

The author declares no competing interests.