# Multi-dimensional band structure spectroscopy in the photonic synthetic frequency dimension

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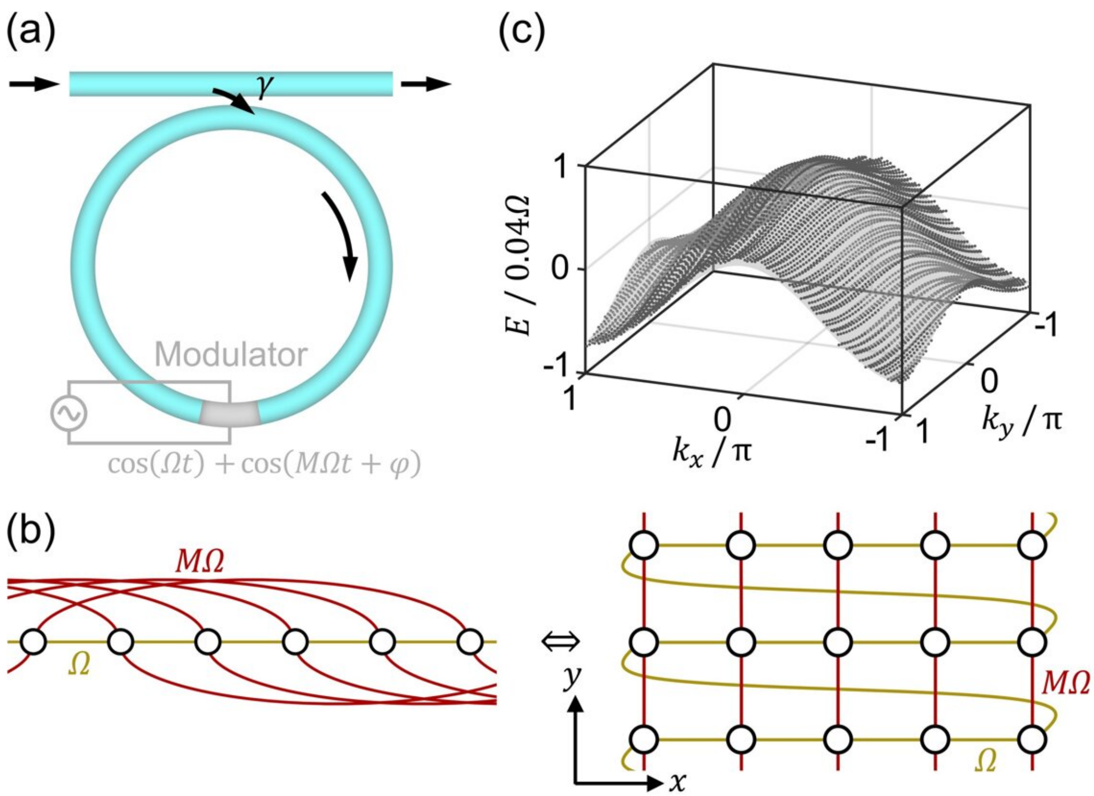


Credit: Shanhui Fan

In the photonic synthetic dimension, the coupling of internal degrees of freedom of photons, such as frequency, spatial mode, and orbital angular momentum, generates extra dimensions in addition to real space. This approach is a powerful tool to investigate novel physical phenomena that are exclusive to high-dimensional systems, using low-dimensional platforms that offer advantages in terms of engineering and control.

Many nontrivial aspects of high-dimensional physics can be revealed by band structure measurements. In the photonic synthetic frequency dimension, existing band structure measurements are limited to one-dimensional Brillouin zones or one-dimensional subsets of two- or three-dimensional Brillouin zones.

Consequently, there is a need for a technique that enables band structure measurements across the entire multi-dimensional Brillouin zone. Benefiting from such a technique, researchers can have a more comprehensive understanding of the underlying physics and gain insights into the unique behaviors that emerge in the high-dimensional regimes.

In a recent publication in *Light: Science & Applications*, a team led by Professor Shanhui Fan from Stanford University have reported such multi-dimensional band structure spectroscopy in the photonic synthetic frequency dimension. The researchers used a photonic resonator under dynamical modulation as the experimental platform. Using multiple modulation frequencies, a multi-dimensional lattice in the synthetic frequency dimension was created with this single resonator.

To measure the band structure of this lattice, the resonator was excited by a laser with tunable frequency, and the time-dependent transmission signal was collected by a photodetector. As the input laser frequency was swept, the band energies were extracted from the resonance features in the transmission spectrum. Significantly, by tuning the relative phases between different modulation frequencies, the researchers could resolve the lattice band structure over the entire multi-dimensional Brillouin zone.

Using this multi-dimensional band structure spectroscopy, the researchers measured the two-dimensional band structure of a non-Hermitian system, and unveiled some properties related to the nontrivial eigenvalue topology. These properties are particularly intriguing as they are associated with the non-Hermitian skin effect, an exotic phenomenon where all the eigenstates of a finite non-Hermitian system sexponentially located on the boundaries.

The demonstration of these properties brings us one step closer to harnessing the potential of non-Hermitian systems.

The researchers' findings underscore the importance of multi-dimensional band structure spectroscopy as a tool for exploring the mysteries of high-dimensional systems, ultimately driving advancements in the field of physics and engineering.

The researchers commented, "The essence of the synthetic dimension lies in the potential to expand our toolbox in high-dimensional physics. Considering the wealth of physical information embedded in the band structures, we believe that the multi-dimensional band structure spectroscopy represents a crucial milestone in this direction. It will facilitate our comprehension and manipulation of high-dimensional systems, and potentially provide inspirations for optical devices with innovative functionalities."

The researchers also emphasized the generalizability of their spectroscopic approach in systems of more complexity.

**More information:** Dali Cheng et al, Multi-dimensional band structure spectroscopy in the synthetic frequency dimension, *Light: Science & Applications* (2023). DOI: 10.1038/s41377-023-01196-1

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