Defects may help scientists understand the exotic physics of topology

January 21 2021, by Karmela Padavic-Callaghan

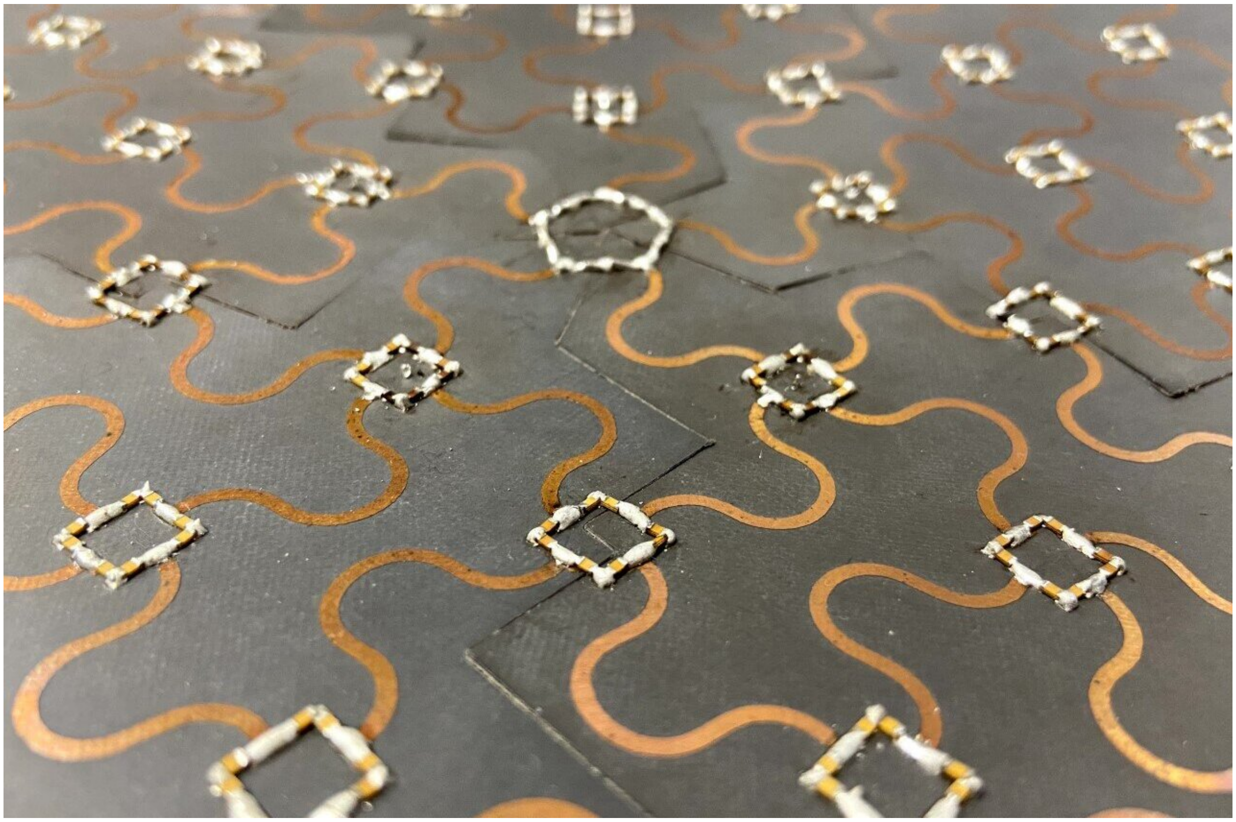


Photo of a metamaterial composed of a pattern of resonators. The defect appears as a pentagon in an otherwise regular array of circuit elements. Credit: K. Peterson

Real-world materials are usually messier than the idealized scenarios found in textbooks. Imperfections can add complications and even limit a material's usefulness. To get around this, scientists routinely strive to remove defects and dirt entirely, pushing materials closer to perfection. Now, researchers at the University of Illinois at Urbana-Champaign have turned this problem around and shown that for some materials defects could act as a probe for interesting physics, rather than a nuisance.

The team, led by professors Gaurav Bahl and Taylor Hughes, studied artificial materials, or metamaterials, which they engineered to include defects. They used these customizable circuits as a proxy for studying exotic topological crystals, which are often imperfect, difficult to synthesize, and notoriously tricky to probe directly. In a new study, published in the January 20th issue of *Nature*, the researchers showed that defects and structural deformations can provide insights into a real material's hidden topological features.

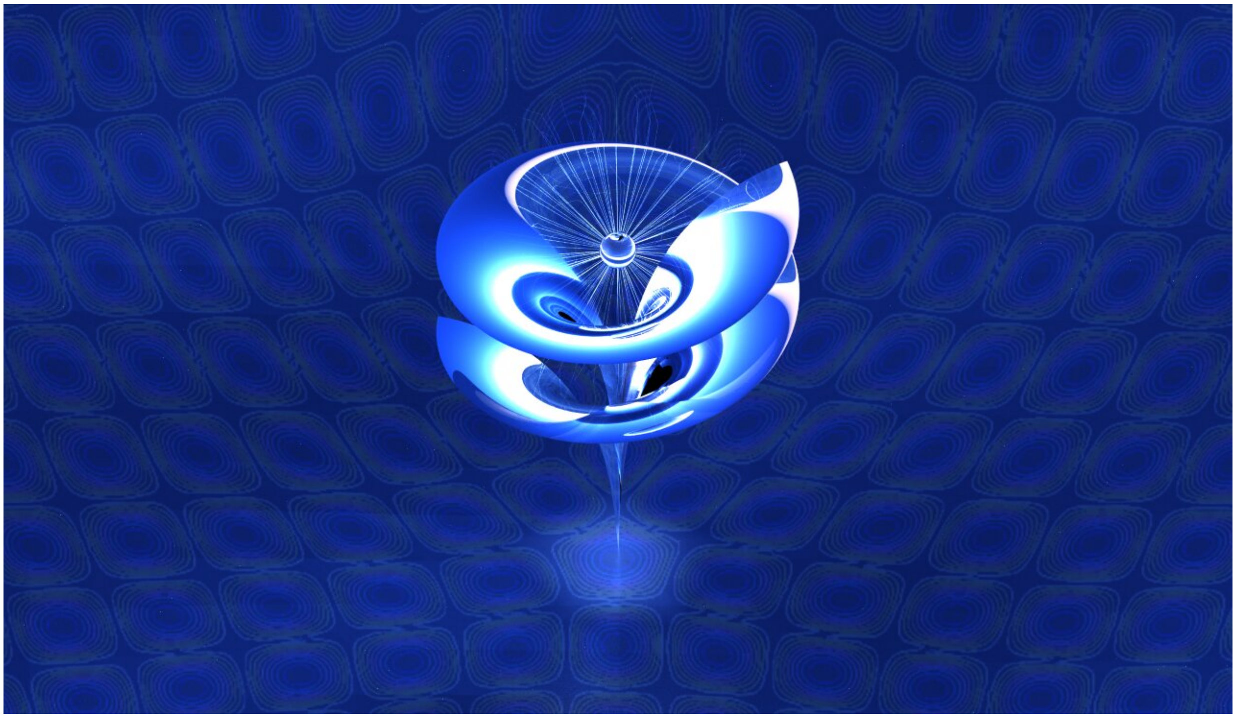
"Most studies in this field have focused on materials with perfect internal structure. Our team wanted to see what happens when we account for imperfections. We were surprised to discover that we could actually use defects to our advantage," said Bahl, an associate professor in the Department of Mechanical Science and Engineering. With that unexpected assist, the team has created a practical and systematic approach for exploring the topology of unconventional materials.

Topology is a way of mathematically classifying objects according to their overall shape, rather than every small detail of their structure. One common illustration of this is a coffee mug and a bagel, which have the same topology because both objects have only one hole that you can wrap your fingers through.

Materials can also have topological features related to the classification of their atomic structure and energy levels. These features lead to unusual, yet possibly useful, electron behaviors. But verifying and harnessing topological effects can be tricky, especially if a material is new or unknown. In recent years, scientists have used metamaterials to study topology with a level of control that is nearly impossible to achieve with real materials.

"Our group developed a toolkit for being able to probe and confirm topology without having any preconceived notions about a material." says Hughes, who is a professor in the Department of Physics. "This has given us a new window into understanding the topology of materials, and how we should measure it and confirm it experimentally."

In an earlier study published in *Science*, the team established a novel technique for identifying insulators with topological features. Their findings were based on translating experimental measurements made on metamaterials into the language of electronic charge. In this new work, the team went a step further—they used an imperfection in the material's structure to trap a feature that is equivalent to fractional charges in real materials.



Artistic depiction of a fractional charge trapped at a lattice defect, which, according to the authors, signals the presence of certain kinds of topology. Credit: E. Edwards

A single electron by itself cannot carry half a charge or some other fractional amount. But, fragmented charges can show up within crystals, where many electrons dance together in a ballroom of atoms. This choreography of interactions induces odd electronic behaviors that are otherwise disallowed. Fractional charges have not been measured in either naturally occurring or custom-grown crystals, but this team showed that analogous quantities can be measured in a metamaterial.

The team assembled arrays of centimeter-scale microwave resonators onto a chip. "Each of these resonators plays the role of an atom in a crystal and, similar to an atom's energy levels, has a specific frequency where it easily absorbs energy—in this case the frequency is similar that of a conventional microwave oven." said lead author Kitt Peterson, a former graduate student in Bahl's group.

The resonators are arranged into squares, repeating across the metamaterial. The team included defects by disrupting this square pattern—either by removing one resonator to make a triangle or adding one to create a pentagon. Since all the resonators are connected together, these singular disclination defects ripple out, warping the overall shape of the material and its topology.

The team injected microwaves into each resonator of the array and recorded the amount of absorption. Then, they mathematically translated their measurements to predict how electrons act in an equivalent material. From this, they concluded that fractional charges would be trapped on disclination defects in such a crystal. With further analysis, the team also demonstrated that trapped fractional charge signals the presence of certain kinds of topology.

"In these crystals, fractional charge turns out to be the most fundamental observable signature of interesting underlying topological features" said Tianhe Li, a theoretical physics graduate student in Hughes' research group and a co-author on the study.

Observing fractional charges directly remains a challenge, but metamaterials offer an alternative way to test theories and learn about manipulating topological forms of matter. According to the researchers, reliable probes for topology are also critical for developing future applications for topological quantum materials.

The connection between the topology of a material and its imperfect geometry is also broadly interesting for theoretical physics. "Engineering a perfect material does not necessarily reveal much about real materials," says Hughes. "Thus, studying the connection between defects, like the ones in this study, and topological matter may increase our understanding of realistic materials, with all of their inherent complexities."

More information: Christopher W. Peterson et al. Trapped fractional charges at bulk defects in topological insulators, *Nature* (2021). DOI: 10.1038/s41586-020-03117-3

Provided by University of Illinois at Urbana-Champaign

Citation: Defects may help scientists understand the exotic physics of topology (2021, January

21) retrieved 4 May 2024 from https://phys.org/news/2021-01-defects-scientists-exotic-physics-topology.html