

Title: Flexible Photonic Topological Insulator

Author: *Zhen Gao, Fei Gao, Youming Zhang, Yu Luo and Baile Zhang**

Dr. Z. Gao, Dr. Y. Zhang, Prof. B. Zhang

Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore.

E-mail: blzhang@ntu.edu.sg (B. Zhang)

Prof. B. Zhang

Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637371, Singapore.

Dr. F. Gao

State Key Laboratory of Modern Optical Instrumentation, and College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China.

Prof. Y. Luo

School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore.

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Abstract: A mechanically flexible photonic topological insulator that supports robust topological photonic states on a curved surface is experimentally demonstrated. Spatial topologies achieved by folding the flexible photonic topological insulator serve as a new freedom to manipulate the propagation of topological photonic states. This work bridges the gap between the emerging field of topological photonics and the technologically promising field of flexible photonics.

A topological insulator (TI) is an emerging electronic material that is insulating in the bulk of a sample, but conductive on the surfaces via a family of “topological edge states”.^[1,2] It has spurred tremendous research interests in constructing analogous topological effects in classical wave systems.^[3-9] Photonic TIs, as an analogue of TIs in photonic systems,^[10-25] have been under investigation on various platforms such as specifically designed photonic crystals^[10-17] in a volumetric parallel-plate waveguide, coupled resonators on a silicon wafer^[18-20] or a structured metal surface,^[21-23] and three-dimensional (3D) helical waveguide lattices^[24-25] fabricated in fused silica. All of these photonic TIs are inherently rigid without elastic flexibility.

On the technical level, flexibility is extremely desirable in flexible electronics^[26-28] and flexible photonics,^[29-34] which aim at achieving electronic and photonic circuits, devices, and systems on flexible, stretchable, and biocompatible curved substrates. Promising applications include personal health monitors and biomedical devices,^[26] electronic eyeball camera,^[27] paper-like display,^[28] flexible nano-membrane photonic crystal cavities,^[29-31] stretchable silicon photonic waveguides and filters,^[32] and flexible nanoantennas array.^[33] To date, however, a flexible (electronic or photonic) TI still remains unrealized.

On the scientific level, a flexible (electronic or photonic) TI that can be bent and folded allows involvement of spatial topology in manipulating topologically protected edge states. A typical nontrivial spatial topology is the Mobius strip whose upper and lower edges are indistinguishable. Although the topology of a Mobius strip has been implemented in a topological electronic circuit which does not rely on the mechanical flexibility,^[6] the photonic version of a similar nontrivial topology has not been developed.

In this paper, we report the experimental realization of a paper-like flexible photonic TI. Topologically protected photonic states can be formed on the flexible photonic TI, regardless of it being flat or curved. Owing to the extraordinary flexibility, we further fold the paper-like photonic TI and connect two edges, in order to simulate different spatial topologies. The photonic pseudospin will flip or preserve its spin direction, depending on the folding manner, and will subsequently propagate in different directions along different edges. Our work shows that the propagation of topological edge states can be manipulated by introducing spatial topologies to a flexible topological system.

To experimentally demonstrate the flexible topological system, we apply conformal surface plasmons (CSP)^[34] and standard printed circuit board (PCB) technology. CSP are surface electromagnetic waves that can propagate on ultrathin and flexible films over a long distance in a wide broadband range, covering from far-infrared to microwave frequencies.^[34] CSP hold considerable promises of controlling the propagation of surface waves on curved surfaces conformably to produce advanced plasmonic functional devices. The proposed flexible photonic TI is shown in **Figure 1a**. It consists of a square 5×5 lattice of 18- μm -thick CSP ring resonators (structured copper disk) printed on a 0.254-mm-thick paper-like dielectric film (Rogers RT5880). The ring resonators sitting on the 5×5 sites are called “lattice rings” and those that couple neighboring lattice rings are called “coupling rings”. Surface waves can circulate clockwise or anti-clockwise in the lattice rings, serving as two components of a pseudo-spin, that is, spin-down (clockwise circulation) and spin-up (anti-clockwise circulation) states.^[21-23] Previous studies have demonstrated that such a periodic system can host a topologically nontrivial “anomalous Floquet TI

phase”,^[21-23] which cannot be predicted with the conventional Chern number topological invariant.

A photo of the fabricated flexible photonic TI is shown in the inset of **Figure 1a**. Each ring resonator is formed by 48 gratings. The periodicity, width and height of the gratings are $d = 4.0$ mm, $a = 2.0$ mm and $h = 4.0$ mm, respectively. The radius of each ring resonator is $R = 30.57$ mm. The inter-ring distance is $g = 2.0$ mm. By taking the phase delay (ϕ) of surface waves along a quarter of a lattice ring resonator as the quasi-energy, it can be shown that a topological phase transition will occur when the inter-ring coupling strength increases beyond a critical value ($\theta = 0.25\pi$ in Ref. 21). The detailed calculations can be found in Supporting Information. Owing to its ultra-thin thickness, the fabricated photonic TI can be bent, folded, or even twisted to mold the flow of the topological edge states on curved surfaces, as schematically shown in **Figure 1b**.

Figure 2a shows the simulated band structure for a semi-infinite strip of the photonic TI, which has five lattice rings in the y direction, and is infinite in the x direction. Here we only consider a single spin (spin-down) and assume no spin mixing. The band diagram reveals a gap between 10.4 and 12.4 GHz, spanned by unidirectional states localized to opposite edges of the flexible TI. Note that within such a narrow bandwidth, the inter-ring coupling strength is mainly determined by the inter-ring spacing g . We estimate that for the current setting with $g = 2.0$ mm, the inter-ring coupling strength is about $\theta = 0.42\pi$ within the bandgap of interest.^[21] According to calculation from the network model in Figure S1 (Supporting Information), this bandgap is topologically nontrivial. In the measurement, the spin-down (up) state can be excited via the input port 1 (2) of a U-shape waveguide, as illustrated in **Figure 1a**. **Figure 2b** shows the measured transmission spectra of

topological edge states on a planar (blue line) and folded (red line) flexible photonic TI from the input port 1 to another U-shaped waveguide at the right side of the photonic TI (as shown in **Figure 1a** and **Figure 1b**). It can be seen that both of the measured transmission matches well with the calculated band structure in **Figure 2a**. Within the frequency range of edge states [shaded by a blue transparent rectangle], the transmission spectra of the edge state on a planar TI (blue line) is preserved even when the flexible photonic TI is folded (red line).

We then adopt a microwave near-field imaging system^[36-38] to map the near-field distributions on this topological structure. The near-field imaging system consists of a vector network analyzer (R&S ZVL-13) and two homemade monopole antennas as the source and probe. The probe, placed 1 mm above the sample, can move freely to map the electric near-field distributions. First, we excite a central site in the bulk of the planar topological structure, as schematically shown in **Figure 3a**. The operating frequency is fixed at 11.6 GHz. The insulating nature of the bulk is revealed by the localized resonant mode emerged at the vicinity of the source, as shown in **Figure 3b**. Then we wrap the flexible photonic TI on a foam cylinder with radius of 12.5 cm and excite the same central site. Similar field pattern can still be observed on the curved cylindrical surface, as shown in **Figure 3c**.

Next, we excite the flexible topological system via input port 1 indicated by a red arrow, as schematically shown in **Figure 3d**. The frequency is at 11.6 GHz. **Figure 3e** shows that in the planar photonic TI, surface waves remain confined to the edges, propagating around the corner. Then we wrap the flexible topological structure on a foam cylinder and map the field pattern of the edge state again, as shown in **Figure 3f**. It can be seen that the topological edge state on a curved surface does not change significantly.

To probe the robustness of the topological edge states, we fabricate a new sample with a defect, which is formed by removing a lattice ring and its three coupling rings on one edge, as shown in **Figure 3g**. The frequency remains at 11.6 GHz. As shown in **Figure 3h**, in the planar photonic TI, because of the topological protection, the edge states detour around the defect and continue to propagate along the original edge. Then we wrap the structure on the cylindrical foam to test the robustness of the topological protection on a curved surface. The measured results (**Figure 3i**) show that the topological protection survives even on a curved surface.

Due to the flexibility of the fabricated photonic TI, spatial topologies can be constructed via folding and connecting. Here we implemented two spatial topologies by overlapping the last ring resonator at the top edge to the first ring resonator at the bottom edge [red disks in **Figure 4a** and **4d**] with different folding manners. The first topology is realized by twisting the paper-like photonic TI before connecting the corresponding ring resonators, as shown in **Figure 4b**. This kind of Mobius-like topology can flip the spin. To facilitate experiment, we only probe one point along each ring resonator and plot the electric field distribution at 11.6 GHz, as shown in **Figure 4c**. It can be seen that the original spin-down state on the upper edge is now converted to the spin-up state on the lower edge, both propagating in the same direction. Then we implement another spatial topology, as shown in **Figure 4e**, which is realized by overlapping the corresponding ring resonators without twisting the photonic TI. The measured field pattern in **Figure 4f** shows that the spin-down state on the upper edge still remains its spin state when being coupled to the overlapped ring resonators. This spin-down state keeps propagating upwards on the left edge of the photonic TI.

In summary, we have realized experimentally a mechanically flexible photonic TI that supports robust topological edge states on a curved surface. Two spatial topologies are implemented with different folding manners to manipulate the propagation of topological edge states which are inaccessible in conventional bulky and rigid topological systems. Such a flexible platform provides a versatile approach towards controlling and manipulating topological edge states on curved surfaces.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest

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Figures

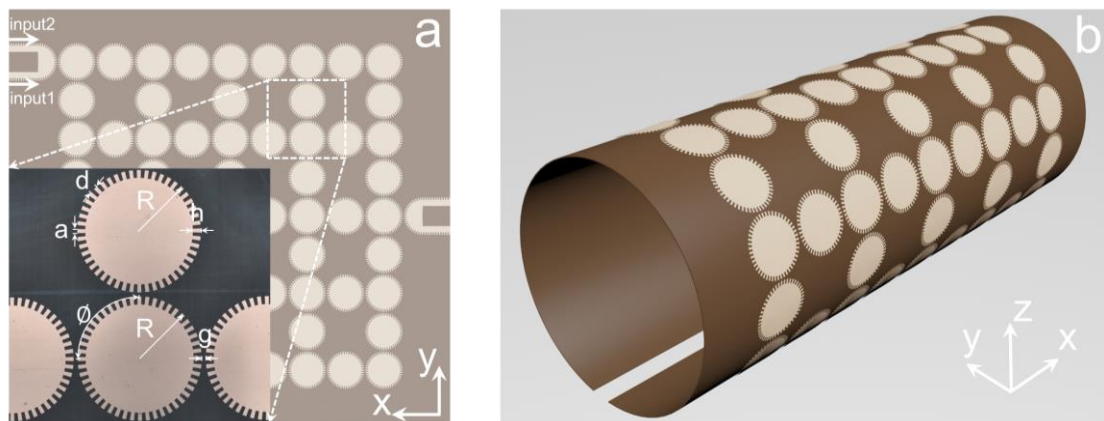


Figure 1. a) Schematic of the flexible photonic topological insulator. Inset is a photo of the CSP ring resonators printed on a flexible paper-like dielectric film. b) Schematic of the folded flexible photonic topological insulator.

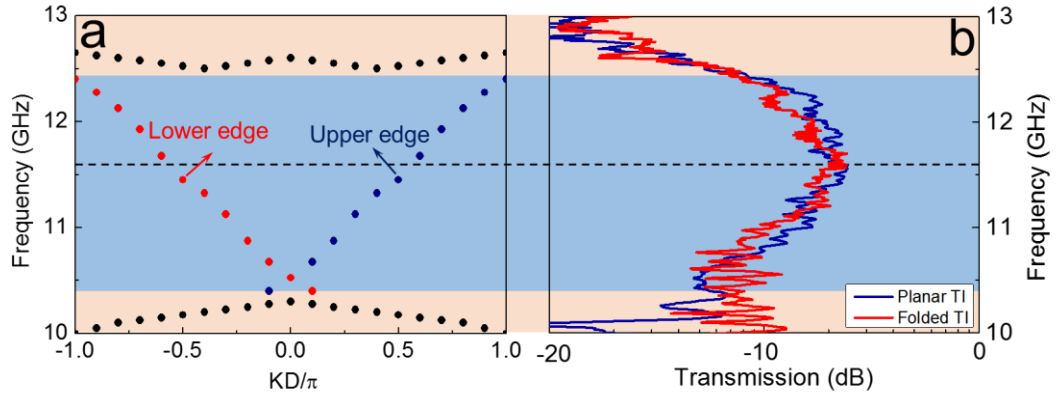


Figure 2. a) Simulated band diagram of the flexible photonic topological insulator realized with CSP ring resonators. b) Measured transmission spectra of the topological edge states on a planar (blue line) and folded (red line) photonic TI.

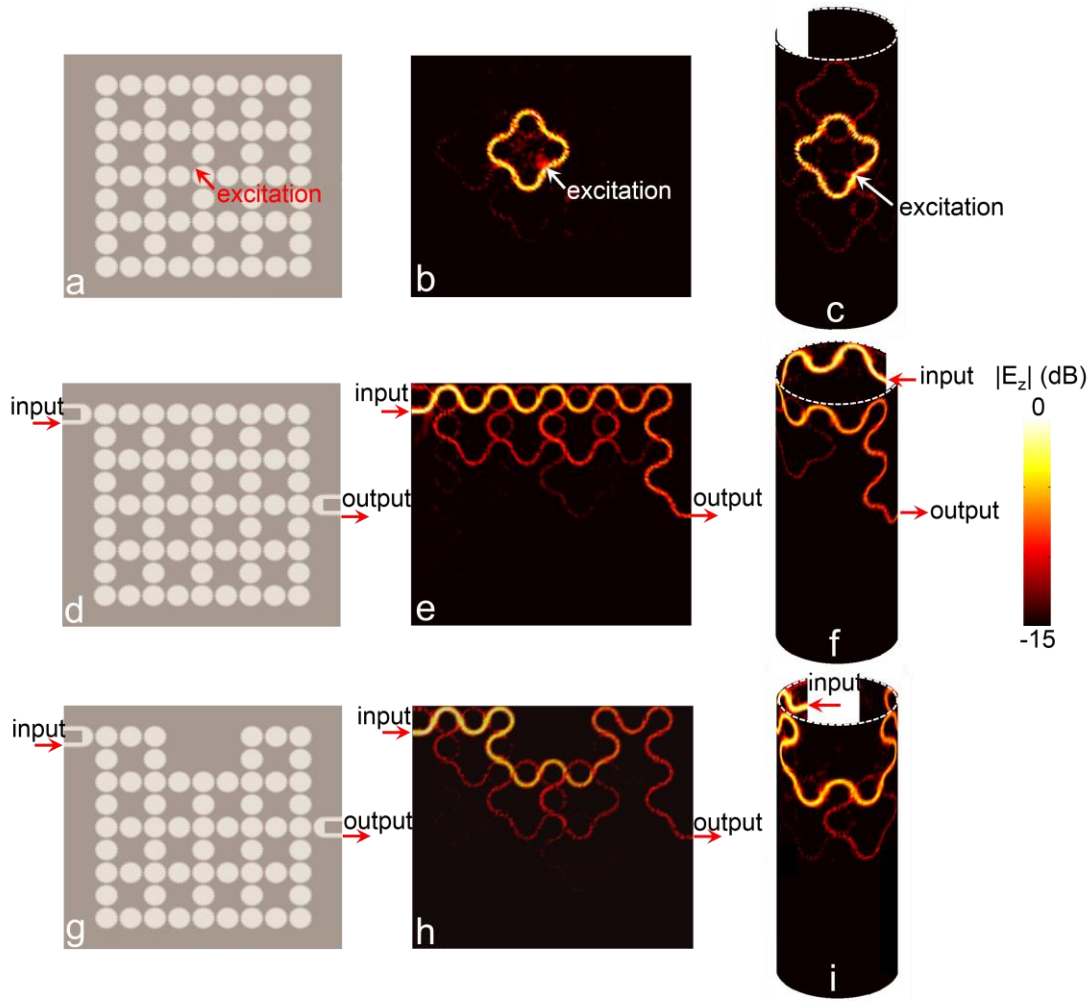


Figure 3. a) Schematic of the flexible photonic TI with the excitation at a central lattice site. b) Observed field pattern when the excitation is inside the bulk on a planar surface. c) Observed field pattern when the excitation is inside the bulk on a curved cylindrical surface. d) Schematic of the flexible photonic TI with the excitation at the edge. e) Observed topological edge state on a planar surface. f) Observed topological edge state on a curved cylindrical surface. g) Schematic of the flexible photonic TI with an introduced defect (one lattice ring and three surrounding coupling rings removed) on the edge. h) Observed topological protection on a planar surface. i) Observed topological protection on a curved cylindrical surface.

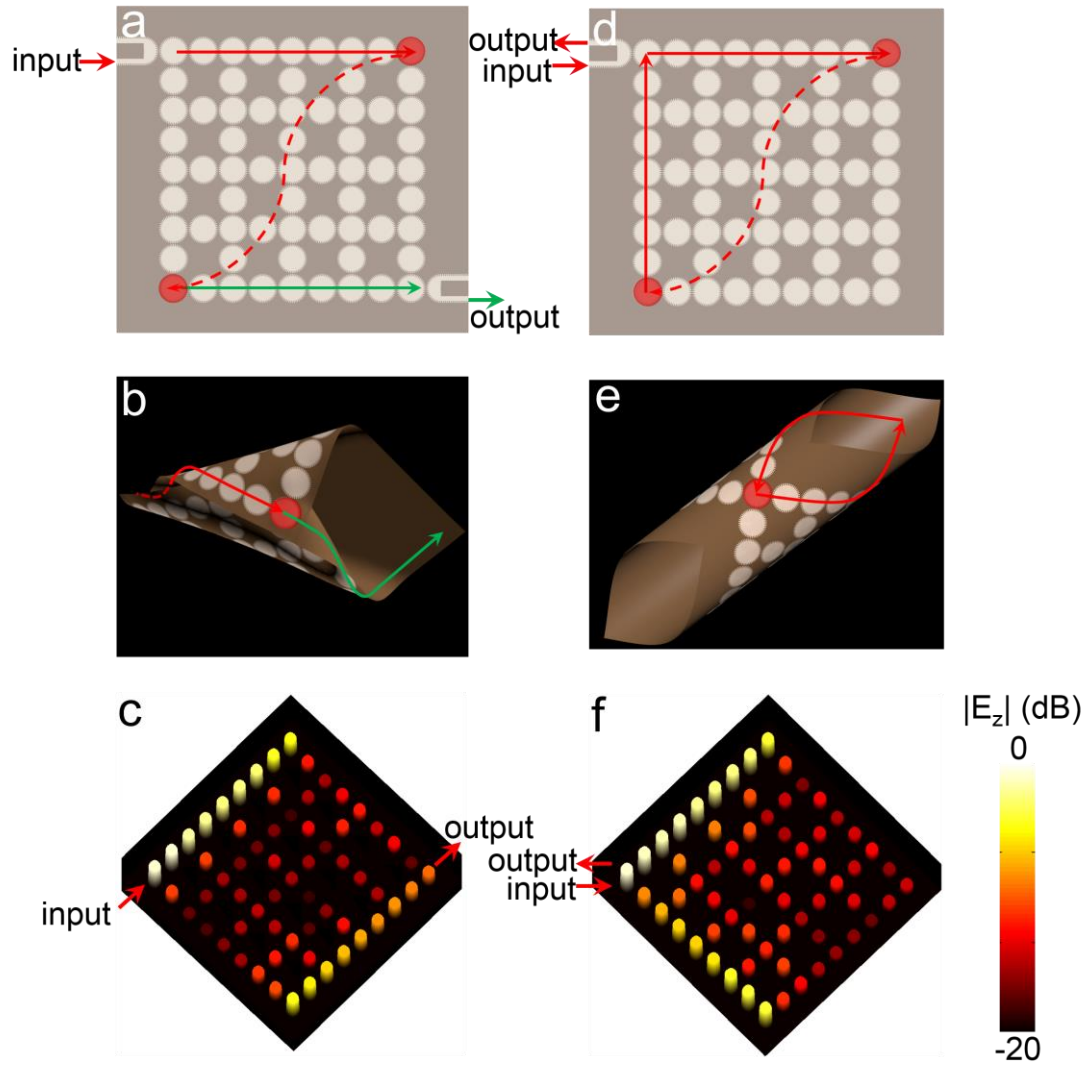


Figure 4. a-b) Schematic of folding the flexible photonic TI with twisting. The red (green) line indicates the path of spin-down (spin-up) states. c) Observed field pattern of topological edge state for the folding in (b). d-e) Schematic of folding the flexible photonic TI without twisting. The red line indicates the path of spin-down state. f) Observed field pattern of topological edge state for the folding in (e).