7. Background of Research

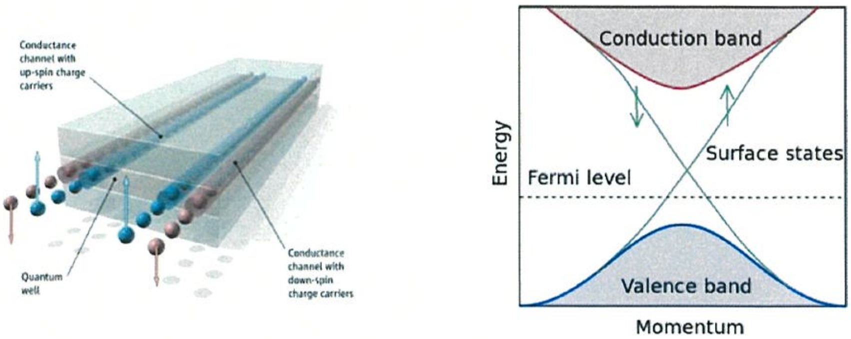

Fig. 1 Schematic of topological insulators, where helical spin-polarized current flows thorough the edges of the sample while the bulk remains insulating as displayed by the energy band

Development of novel materials is always one essential driving force for productivity revolution. Starting from Stone Age, people have experienced Bronze Age, Iron Age, and currently are enjoying the so-called Information Age. The foundation of Information Age is built on the mastery of controlling electrons. For controlling electrons people need solid-state materials such as semiconductors, a type of materials that electrons can pass through only under strong voltage. Recently, a novel type of solid-state materials dubbed as "topological insulators" has been theoretically proposed and experimentally discovered. In topological insulators, electrons cannot go through inside of the materials but can travel freely on their surfaces. These unique surface conducting channels are protected by nontrivial topology of the material, and thus are insensitive to local material defects. In other words, these surface conducting channels may provide us dissipation-less current, which is a key part for realizing faster and smaller central processors. Thus, understanding the effects of material topology to electrons' behavior is not only important from fundamental science view but is also essential for discovery of novel materials for future electronic devices.

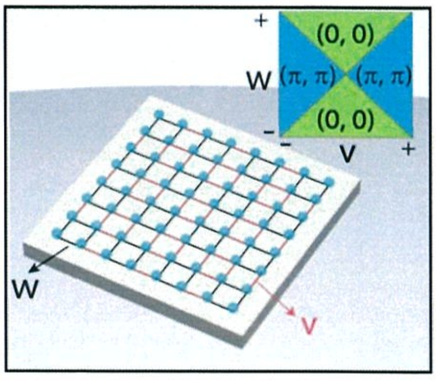

Fig. 2 Schematic of 2D SSH model, which shows nontrivial topological phase in the absence of Berry curvature when |W|<|V|.

Usually, topological materials are associated with non-vanishing Berry curvatures, as Berry curvature is a geometric analogue of magnetic field in the momentum space. However, inspired by the situation of Aharonov–Bohm effect, where electrons are affected by the vector potential in spite of zero magnetic field, we have discovered a novel nontrivial topological phase in 2D systems in the absence of Berry curvature. 2 This novel topological phase is characterized by the Berry connection, which is the geometric counterpart of vector potential in the momentum space, and its integration over BZ yields the 2D Zak phase accompanying fractional wave polarization in each direction. These fractional wave polarization manifests themselves as doubly degenerate edge states with opposite parities. This novel topological phase resides in a 2D square lattice model with Peierl's distortions on the basis of Su-Schrieffer-Heeger model, where the hoppings are classified as intracellular and intercellular ones, receptively (Fig. 1). When the intracellular hopping is smaller than the intercellular one, the system enters topological nontrivial phase characterized by Zak phase (π, π) [as displayed by the inset of Fig.1]. The discovery of this novel topological phase offers a new view point for designing topological materials.

8. Research methodology

Our main research methodology includes both analytical derivations and also numerical calculations. Combining these two methods, we are aiming to discover novel topological phases of matters. For analytical derivations, we use various methods, such as Fourier transformation, group theory, calculus and so on. For numerical calculations, we use tight-binding model, finite-element method and also first principle calculations.

9. Results/impacts

Result II: **Helical topological edge states in a quadrupole phase**

A topological electric quadrupole is a recently proposed concept that extends the theory of electric polarization of crystals to higher orders. Such a quadrupole phase supports topological states localized on both edges and corners. In this work, we show that in a quadrupole phase of a honeycomb lattice, topological helical edge states and pseudospin-polarized corner states appear by making use of a pseudospin degree of freedom related to point group symmetry. Furthermore, we argue that a general condition for the emergence of helical edge states in a (pseudo)spinful quadrupole phase is the existence of either mirror or time-reversal symmetry. Our results offer a way of generating topological helical edge states without spin-orbital couplings.

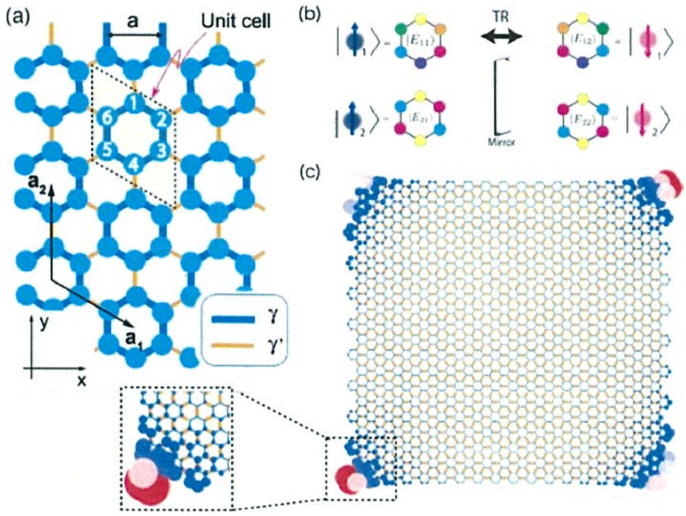

Fig. 3 (a) schematic of Kekule-like hopping texture on a honeycomb lattice. (b) Pattern of degenerate eigenmodes that can be regarded as pseudo-spins. (c) Topological corner states appear in the band gaps of Kekule-like honeycomb model.

For details, we have studied a Kekule-like hopping textures on honeycomb lattice, as displayed in Fig. 3(a). Because of C_{6v} point group symmetry, there are a pair of degenerate egien modes, which can be regarded as pseudo-spins [see Fig. 3(b)]. Unlike conventional spins which transforms to each under a SU(2) chiral symmetry, these two pseudospins only transform to each by either time reversal symmetry or mirror symmetry. Thus, it is possible that band inversion between these two degenerate energy band can induce helical topological edge states. Furthermore, because of C_{6v} symmetry, these edge states can further induce topological corner states, as displayed in Fig. 3(c).

The interesting part of this result is the coexistence of helical topological edge states and corner states, which may be considered similar to “1” and “0” status in a transistor.

This study is published on **Physical Review Letters**, currently has accumulated citation around 20 times (from google scholar datum). This result has been reported by medium such as 日本の研究.com (2019.02.17).

Result III: **Novel topological photonic crystal without Berry curvature**

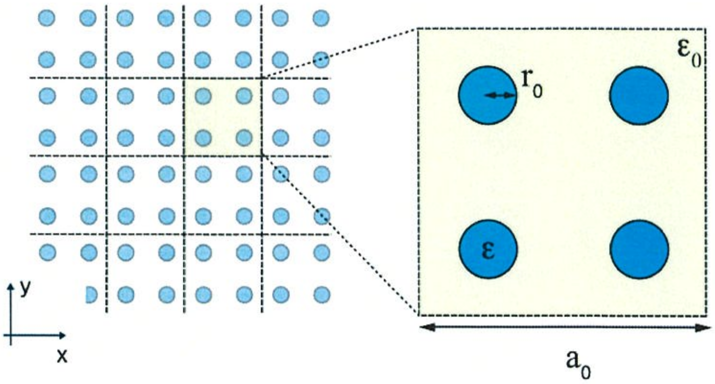

Fig. 4 Schematic of designated structure called Shinome dielectric photonic crystal mimicking the 2D SSH model.

We design topological photonic crystals based on the concept of Zak's phase rather than the topological invariants such as the Chern number and spin Chern number, which rely on the existence of a nonvanishing Berry curvature. Our photonic crystals (PCs) are made of pure dielectrics and sit on a square lattice obeying the C4v point-group symmetry. Two varieties of PCs are considered: one closely resembles the electronic two-dimensional Su-Schrieffer-Heeger model, and the other continues as an extension of this analogy. In both cases, the topological transitions are induced by adjusting the lattice constants. Topological edge modes (TEMs) are shown to exist within the nontrivial photonic band gaps on the termination of those PCs. The high efficiency of these TEMs transferring electromagnetic energy against several types of disorders has been demonstrated using the finite-element method as displayed in Fig. 4.

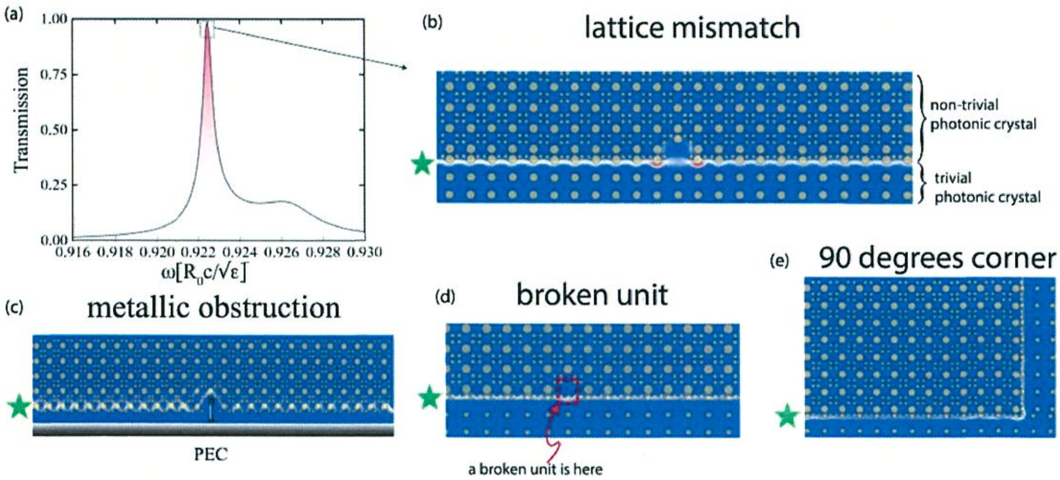

Fig. 5 Demonstration of the robustness of the electromagnetic waves against various types of disorders: (a) lattice mismatch, (b) metallic obstruction, (c) broken unit, (d) 90-degree corner. A harmonic electromagnetic wave is generated by a source, marked by a green start, and partially transmitted through the interface. Transmission probability and energy flow (indicated in white) are computed using the commercial software COMSOL. The transmission for the lattice mismatch is displayed in (a), where we see that the peak transmission reaches around 100%. Comparably high transmission has been observed for the obstructions shown in (b), (c) and (d).

Inspired by these designs we have collaborated with an experimental group from Tokyo University. We successfully observer the topological edge and corner states, which may be useful for laser technology. Besides laser technology, the proposed photonic crystal can also be useful for electromagnetic wave transmission. As these topological edge states forms waveguides those are not sensitive to local defects. According to our numerical calculations, defects such lattice mismatch, missing unit cell, sharp turning corner and metallic defect do not cause serious back-scattering in the proposed topological wave guides. The simulated datum is present in Fig. 5.

These results are published on **Physical Review B** and **Optica**, currently has accumulated citation around 40 times (from google scholar datum).

10. Research Presentations during the period of the fellowship (Name of the conference, title, place, date)

1) APS marching meeting, Novel topological phase with a zero Berry curvature, Los Angeles Convention Center, Los Angles, United States, Mar. 5~11, 2018

2) JPS annual meeting (spring) 2018, Light-induced topological nontrivial phases in quantum wires, Tokyo University of Science, Tokyo, Mar. 22-25,2018

3) JPS annual meeting (autumn) 2018, Topological photonic crystal under zero Berry curvature, Doshiha Univeristy, Kyoto, Sep. 9~12, 2018

4) 31st International Microprocesses and Nanotechnology, Topological dipoles and quadrupoles, Hokkaido, Japan, Nov. 13~16, 2018

5) JPS annual meeting (spring) 2019, Helical topological edge states in a quadrupole phase, Kyushu University, Hakata, Mar. 14~17, 2019

6) The Conference of Condensed Matter Physics 2019, Topological dipoles and quadrupoles, Tianmu Lake Hotel, Liyang, China, Jun. 27~30, 2019 (**Invited talk**)

7) 1D&2DM conference, Topological dipoles and quadrupoles, Tokyo Japan, Nov.13 -16, 2019

11. A list of paper published during or after the period of the fellowship, and the names of the journals in which they appeared (Please fill in the format below). Attach a copy of each article if available.

Author(s)	Title	Name of	Volume	Page	Date	Note
F. Liu, M. Yamamoto and K. Wakabayashi	Topological edge states of honeycomb lattices with zeroBerry curvature	Journal of Physical Society of Japan	86	123707	2017	
F. Liu, H.-Y. Deng and K. Wakabayashi	Topological photonic crystals with zero Berry curvature	Physical Review B	97	035442	2018	
T. Kameda, F. Liu, S. Dutta and K. Wakabayashi	Topological edge states induced by the Zak phase in A3B monolayers	Physical Review B	99	075426	2019	
F. Liu, H.-Y. Deng and K. Wakabayashi	Helical topological edge states in a quadrupole phase	Physical Review Letters	122	086804	2019	
F. Liu and K. Wakabayashi	A photonic Weyl semimetal in two-dimensional dielectric arrays	Japanese Journal of Applied Physics	58	SDDD01	2019	
Y. Ota, F. Liu, R. Katsumi, K. Watanabe, K. Wakabayashi, Y. Arakawa and S. Iwamoto	Photonic crystal nanocavity based on a topological corner state	Optica	6	786	2019	
D. Obana, F. Liu, and K. Wakabayashi	Topological edge states in the Su-Schrieffer-Heeger model	Physical Review B	100	075437	2019	