Valley-Hall Photonic Topological Insulators with Dual-Band Kink States

Qiaolu Chen, Li Zhang, Mengjia He, Zuojia Wang, Xiao Lin, Fei Gao, Yihao Yang,* Baile Zhang,* and Hongsheng Chen*

Extensive researches have revealed that valley, a binary degree of freedom (DOF), can be an excellent candidate of information carrier. Recently, valley DOF is introduced into photonic systems, and several valley-Hall photonic topological insulators (PTIs) are experimentally demonstrated. However, in the previous valley-Hall PTIs, topological kink states only work at a single frequency band, which limits potential applications in multiband waveguides, filters, communications, and so on. To overcome this challenge, here we present a valley-Hall PTI, where the topological kink states exist at two separated frequency bands, is experimentally demonstrated in a microwave substrate-integrated circuitry. Both the simulated and experimental results demonstrate the dual-band valley-Hall topological kink states are robust against the sharp bends of the internal domain wall with negligible inter-valley scattering. This work may pave the way for multichannel substrate-integrated photonic devices with high efficiency and high capacity for information communications and processing.

Over the past few years, “valleytronics”[1–5] has emerged as an area where valley, a binary degree of freedom, has a potential to be an excellent candidate of information carrier. The concept of valley has also been introduced into different kinds of physical systems, such as photonics,[6–13] acoustics,[14–17] and elastics.[18–20] In the photonic community, researchers have found that domain walls between two types of inversion-breaking photonic crystals, that is, valley-Hall photonic topological insulators (PTIs),[9,11] could support topologically nontrivial valley-polarized kink states. Such valley-Hall PTIs have been experimentally demonstrated at different frequencies and found potential applications in topologically protected refraction,[8] high-efficiency waveguides,[6,11,12] topological waveguide splitters,[12] and so forth.

To overcome the above challenge, in this work, we propose and experimentally realize a valley-Hall PTI with dual-band kink states. The valley-Hall PTI is designed with an inversion-breaking graphene-like structure in a substrate-integrated microwave circuitry. At a domain wall between two valley-Hall PTIs with opposite effective masses, the topological kink states exist at two separated frequency bands. Such dual-band topological kink states are robust against sharp corners, as demonstrated in both simulations and experiments. Our work may lead to a number of potential multiband photonic devices and applications with high capacity for information storage and processing.

The designed valley-Hall PTI is in a hexagonal lattice with lattice constant of $a = 16.45$ mm, as illustrated in Figure 1a. Each unit cell (insets in Figure 1a) includes two cylindrical metallic scatterers with radius of $r = 1.9$ mm and thickness of $h = 3.2$ mm, and a metallic mesh pattern on their top. For a unit cell, the top metallic mesh pattern includes two disks with different radii, $r_A$ and $r_B$, respectively, connected by a metal wire with width of $w = 1.65$ mm. In our work, the symmetry and topological phase transition of photonic crystals are controlled by varying the radii of metallic disks. The whole structure is arranged between two parallel metallic plates, loaded with a dielectric material with
relative permittivity of $\varepsilon = 3.2$. The cylindrical metallic scatters touch the bottom metallic plate, and there is a gap with distance of $g_0 = 0.8$ mm between metallic mesh patterns and top metallic plate. In our implementation, the experimental sample is composed of two printed circuit boards (PCBs) as shown in Figure 1b. The metallic mesh patterns and via holes are printed on the bottom PCB. The top copper PCB provides a gap and is attached on the bottom PCB. It is clear that our structure has advantages of easy access, excellent electromagnetic shielding, and compatibility with conventional substrate-integrated microwave circuitry.

When $r_A = r_B$, the photonic crystal possesses inversion symmetry and time-reversal symmetry.\textsuperscript{[13,14]} As shown in Figure 2a, there are two pairs of Dirac-like degenerate points in the first Brillouin zone at the frequency of 5.34 and 14.11 GHz, respectively. The numerical dispersions are obtained by employing the eigenvalue module of the commercial software COMSOL Multiphysics.

When slightly breaking the inversion symmetry by changing the radii $r_A$ and $r_B$ to make them nonequivalent, while keeping $r_A + r_B$ constant, the symmetry of hexagonal lattice is reduced from $C_{6v}$ to $C_3$. This perturbation renders the Dirac points at K (or K') valley lifted and hence two bandgaps open at the previous Dirac frequencies. For example, when $\Delta r = r_A - r_B = 1.2$ mm, two bandgaps appear, whose operational frequency ranges vary from 4.94 to 5.74 GHz for the first bandgap, and from 13.35 to 14.12 GHz for the second bandgap, respectively, as shown in Figure 2b. Note that though the gap between metallic mesh patterns and top metallic plate breaks the z-inversion symmetry, the designed PTI differs from bianisotropy-induced spin-Hall PTIs that involve both transverse-electric (TE) and transverse-magnetic (TM) waves.\textsuperscript{[21–26]} Because the height of parallel wave circuitry.

Adv. Optical Mater. 2019, 7, 1900036

1900036 (2 of 5) © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
To verify the above statement, we perform simulations for two “kink”-type domain walls consisting of two valley-Hall PTIs with opposite valley-Chern numbers (or opposite $\Delta r$), as shown in Figure 3a,b. The kink states at two domain walls exhibit different spatial symmetries: even-symmetry (Figure 3a) or odd-symmetry (Figure 3b). The dispersions of dual-band topological kink states are shown in Figure 3c,d, where the gray regions and lines represent the projections of bulk bands and the dispersions of kink states, respectively. Considering a certain bandgap, there is only a single kink state for each valley. Moreover, the propagation directions of kink states at different valleys are precisely opposite, exhibiting “valley-locked” chirality. Such a phenomenon exists at two separated frequency bands, resulting in dual-band topological kink states. As the dual-band topological kink states are locked to K/K’ valley, the intervalley scattering is strongly suppressed in the presence of disorders, for example, sharp corners. Such a property makes the designed valley-Hall PTI to be an excellent candidate for wave-guiding.

To verify the robustness of the proposed topological kink states at two separated frequency bands, we design and compare two types of domain walls: straight (Figure 4a) and z-shape domain walls (Figure 4d). As shown in Figure 4b,c, the $E_z$ field distributions depict that energy is strongly confined at the straight domain wall when the operational frequency is within the first or second bandgap. We also simulate the $E_z$ field distributions around the z-shape domain wall featuring two sharp corners (Figure 4e,f). One can see that the topological kink states smoothly go through both of sharply twisted corners ($120^\circ$ turn) with negligible reflections at two separated frequency bands. Besides, our simulations show that when increasing the bandgap size, the valley-dependent transports are still valid and the kink states can pass through the sharp corners with negligible reflections for both bandgaps (see Note S1, Supporting Information).

In order to further experimentally prove the high-transmission property of the designed photonic topological waveguides, we measure the transmissions of kink states around two topological bandgaps for three cases (Figure 4g,h):
Figure 3. Dispersion relations of two “kink”-type domain walls consisting of opposite symmetry-breaking geometries. a,b) Two “kink”-type domain walls formed by two valley-Hall PTIs with opposite symmetry-breaking geometries, $\Delta r = 1.2$ mm on the left (right) and $\Delta r = -1.2$ mm on the right (left). The field patterns represent the $E_z$ field distributions of mode A and A’ (even-symmetry), mode B and B’ (odd-symmetry) labeled in (c) and (d), respectively. c,d) Band structures of domain walls at two separated frequency bands. Green lines: valley-Hall topological kink states of the domain wall in (a). Red lines: valley-Hall topological kink states of the domain wall in (b). Gray areas: projected bulk states.

Figure 4. Experimental demonstration of robust valley-Hall topological kink states at two separated frequency bands. a,d) Schemes of straight and z-shape domain walls. The excitations are on the left. The orange (blue) hexagonal lattice represents the structures with positive (negative) $\Delta r$. b,e) Simulated electric field intensity distributions at 5.4 GHz corresponding to (a) and (d), respectively. c,f) Simulated electric field intensity distributions at 13.6 GHz corresponding to (a) and (d), respectively. The color depicts the amplitudes of $E_z$. g,h) Normalized measured transmissions of kink states around two topological bandgaps for three cases: without domain wall (black), with straight domain wall (blue), and with z-shape domain wall (red). Gray areas: bandgaps. The experimental results are normalized by the maximum values of the corresponding bulk transmissions.
without domain wall (black lines), with straight domain wall (blue lines), and with z-shape domain wall (red lines). As expected, for the case without domain wall, there are two obvious drops from 5.0 to 6.1 GHz, and from 12.9 to 14.5 GHz, revealing the presence of dual bandgaps. Besides, the transmissions of experimental sample with straight domain wall are ≈30 dB higher than those without domain wall at both bandgaps, which indicates the existence of dual-band topological kink states. Meanwhile, the transmissions along the z-shape domain wall are almost identical to those along the straight domain wall, manifesting the dual-band topological kink states are robust against sharp corners. It is clear that experimental observations are consistent with the simulated results, confirming our theoretical prediction that the dual-band valley-Hall topological kink states are robust against the sharp bends, and proving the topological protection of the kink states.

In summary, we experimentally demonstrate a valley-Hall PTI with topological kink states at two separate frequency bands in a microwave substrate-integrated circuitry. Both the simulated and experimental results verify that the dual-band topological kink states are robust against the sharp bends with negligible intervalley scattering. Our valley-Hall PTI with dual-band kink states has advantages of self-consistent electrical shielding, easy access, and comparability with conventional substrate-integrated waveguide circuitry, which may find applications in multichannel wave-guiding and communications. Moreover, though the design principle of valley-Hall PTIs with dual-band kink states is verified at microwave frequency, its universality could be applied in terahertz and even optical regimes.

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

Acknowledgements
Q.C. and Y.Y. contributed equally to this work. This work was sponsored by the National Natural Science Foundation of China under Grant Nos. 61625502, 61574127, and 61801426, the Top-Notch Young Talents Program of China, the Fundamental Research Funds for the Central Universities, and the Innovation Joint Research Center for Cyber-Physical-Society System. Work at Nanyang Technological University was sponsored by Singapore Ministry of Education under Grant Nos. MOE2018-T2-1-022 (S), MOE2015-T2-1-070, MOE2016-T3-1-006, and Tier 1 RG174/16 (S).

Conflict of Interest
The authors declare no conflict of interest.

Keywords
dual-band, kink states, photonic topological insulators, valley-Hall

Received: January 7, 2019
Revised: April 19, 2019
Published online: May 8, 2019

[1] L. Ju, Z. Shi, N. Nair, Y. Lv, C. Jin, J. Velasco Jr., C. Ojeda-Aristizabal, H. A. Bechtel, M. C. Martin, A. Zettl, J. Analytis, F. Wang, Nature 2015, 520, 650.
[2] H. Zeng, J. Dai, W. Yao, D. Xiao, X. Cui, Nat. Nanotechnol. 2012, 7, 490.
[3] A. Rycerz, J. Tworzydlo, C. W. J. Beenakker, Nat. Phys. 2007, 3, 172.
[4] D. Xiao, W. Yao, Q. Niu, Phys. Rev. Lett. 2007, 99, 236809.
[5] J. R. Schaibley, H. Yu, G. Clark, P. Rivera, J. S. Ross, K. L. Seyler, W. Yao, X. Xu, Nat. Rev. Mater. 2016, 1, 16055.
[6] X. Wu, Y. Meng, J. Tian, Y. Huang, H. Xiang, D. Han, W. Wen, Nat. Commun. 2017, 8, 1304.
[7] J. W. Dong, X. D. Chen, H. Zhu, Y. Wang, X. Zhang, Nat. Mater. 2016, 17, 298.
[8] F. Gao, H. Xue, Z. Yang, K. Lai, Y. Yu, X. Lin, Y. Chong, G. Shvets, B. Zhang, Nat. Phys. 2018, 14, 140.
[9] T. Ma, G. Shvets, New J. Phys. 2016, 18, 025012.
[10] J. Noh, S. Huang, K. P. Chen, M. C. Rechtsman, Phys. Rev. Lett. 2018, 120, 063902.
[11] M. I. Shalaev, W. Walasik, A. Tsukernik, Y. Xu, N. M. Litchinitser, Nat. Nanotechnol. 2019, 14, 31.
[12] L. Zhang, Y. Yang, M. He, H.-X. Wang, Z. Yang, E. Li, F. Gao, B. Zhang, R. Singh, J.-H. Jiang, H. Chen, Appl. Phys. 2018, preprint arXiv:1805.03954.
[13] Z. Gao, Z. Yang, F. Gao, H. Xue, Y. Yang, J. Dong, B. Zhang, Phys. Rev. B 2017, 96, 201402.
[14] J. Lu, C. Qiu, L. Ye, X. Fan, M. Ke, F. Zhang, Z. Liu, Nat. Phys. 2017, 13, 369.
[15] J. Lu, C. Qiu, M. Ke, Z. Liu, Phys. Rev. Lett. 2016, 116, 093901.
[16] J. Lu, C. Qiu, W. Deng, X. Huang, F. Li, F. Zhang, S. Chen, Z. Liu, Phys. Rev. Lett. 2018, 120, 116802.
[17] C. He, S.-Y. Yu, H. Ge, H. Wang, Y. Tian, H. Zhang, X.-C. Sun, Y. B. Chen, J. Zhou, M.-H. Lu, Y.-F. Chen, Nat. Commun. 2018, 9, 4555.
[18] M. Yan, J. Lu, F. Li, W. Deng, X. Huang, J. Ma, Z. Liu, Nat. Mater. 2018, 17, 993.
[19] R. K. Pal, M. Ruzzene, New J. Phys. 2017, 19, 025001.
[20] J. Vila, R. K. Pal, M. Ruzzene, Phys. Rev. B 2017, 96, 134307.
[21] F. Laghezza, F. Scotti, P. Ghelfi, A. Bogoni, J. Lightwave Technol. 2014, 32, 2896.
[22] G. Shambat, M. S. Mirotnick, G. W. Euliss, V. Smolski, E. G. Johnson, R. A. Athale, J. Nanophotonics 2009, 3, 031506.
[23] O. Turkmen, E. Ekmecki, G. Turhan-Sayan, IET Microw. Antennas Propag. 2012, 6, 1102.
[24] X. Cheng, C. Jouvaud, X. Ni, S. H. Mousavi, A. Z. Genack, A. B. Khanikaev, Nat. Mater. 2016, 15, 542.
[25] A. B. Khanikaev, S. H. Mousavi, W.-K. Tse, M. Kargarian, A. H. MacDonald, G. Shvets, Nat. Mater. 2013, 12, 233.
[26] T. Ma, A. B. Khanikaev, S. H. Mousavi, G. Shvets, Phys. Rev. Lett. 2015, 114, 127401.
[27] X. T. He, E. T. Liang, J. J. Yuan, H. Y. Qiu, X. D. Chen, F. L. Zhao, J. W. Dong, Nat. Commun. 2019, 10, 872.