Robust valley polarized states beyond topology

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Abstract

Valley-contrast physics\textsuperscript{1–5} has gained considerable attention, particularly for realizing photonic topological insulators (PTIs)\textsuperscript{5–11} that support reflection-free valley-polarized edge modes (VPEMs) in the absence of inter-valley scattering. It is an open question whether similar robust states can exist in the absence of topological order. We propose a new approach to VPEMs based on a line defect\textsuperscript{12} in a topologically-trivial, $C_{6v}$-symmetric photonic crystal (PhC). The VPEMs result from opposing orbital angular momenta (OAM) due to a local valley Hall effect (LVHE), where the valley polarization is locally defined as opposed to being fixed throughout the bulk of the PhC. We fabricate our device on a silicon-on-insulator (SOI) slab and characterize it at near-infrared frequencies showing robust transmission through sharp bends. Our results present a new perspective to the existence of gapless chiral edge (kink) states and outlines a new waveguiding mechanism applicable to the electromagnetic spectrum as well as other wave systems including plasmonics, mechanics and acoustics.

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Main

Until recently, routing light around sharp corners in microscopic spaces was generally believed to be impossible. This has changed with the advent of PTIs\textsuperscript{13–24}, which, like their electronic counterparts\textsuperscript{25}, enable backscattering-immune edge modes along almost arbitrarily shaped interfaces. Among the three basic topological phases –quantum Hall\textsuperscript{26}, quantum spin-Hall\textsuperscript{27,28}, and quantum valley-Hall\textsuperscript{29,30} topological insulators– the latter, which relies on the valley degree of freedom (DOF)\textsuperscript{1} in crystals is arguably the easiest to implement in bosonic systems\textsuperscript{2,5–11,31–33} and is of the most interest to the development of on-chip optical devices, motivating of this work. Generally, it is assumed that a valley-contrast response requires a transition to a topological valley phase, and so a reduction of the lattice symmetry to $C_{3v}$ symmetry. In addition, VPEMs have only been observed at the interface between valley PTIs with opposite valley Chern numbers. Here we assess the degree to which these caveats are practically important, demonstrating valley-contrast response and robust VPEMs in the absence of these criteria.

LVHE design

We consider a two-dimensional (2D) dielectric PhC slab with a triangular lattice of circular holes as shown in Fig. 1a. This PhC is widely used for waveguide applications due to its inherent bandgap of TE modes, spanning a frequency range from the K point at the first band to the M point at the higher band. The dashed line rhombus illustrates the Wigner–Seitz unit cell of the lattice with vertices located at the holes’ centers. The surface phase distribution map of the out-of-plane magnetic field ($H_z$) at the extrema of the first band –coinciding with the K point– is plotted in Fig. 1b. Opposite OAM states, as indicated by the curled arrows in the inset, are evenly distributed throughout the bulk. OAM states correspond to phase singular points, around
which the phase incrementally increases either in clockwise (cw) or counter-clockwise (ccw) direction. Fig. 1c shows the Wilson-loop\textsuperscript{34} diagram of the PhC, which plots the Berry phase, $\theta$, for the first band along the loop $k, \in [-\pi, \pi]$ for a given $k_y$. The lack of winding phase as $k_y$ goes from $-\pi$ to $\pi$ indicates that the PhC is topologically trivial. In contrast, in a valley PhC, $\theta$ varies by $\pm\pi/2$ near the K and K’ valleys, corresponding to positive and negative $k_y$ values, respectively.

Generally, one needs to break spatial inversion symmetry (SIS) to generate opposite, nonvanishing Berry curvature profiles near the K and K’ valleys leading to valley Hall effect (VHE) and topological valley phase\textsuperscript{29,30}. Here we establish, essentially, a location-dependent version of the VHE (i.e. LVHE) that does not rely on bulk Berry curvature. This is corroborated by the fact the $C_{6v}$ lattice shown in Fig. 1 has two OAM states that are evenly distributed throughout the bulk, whereas a transition to topological valley phase, achieved via reduction to $C_{3v}$ symmetry, promotes only one OAM state. Intuitively, the $C_{6v}$ symmetry doubly preserves the $C_{3v}$ rotational symmetry\textsuperscript{35} hence the PhC in Fig. 1 carries two OAM states at each valley. It is understood that the valley DOF in electronic and Bosonic systems alike is linked to OAM states\textsuperscript{4,5}. This suggests that OAM underlies valley-contrast phenomena in VHE, and that LVHE could also manifest related phenomena.

**Valley selective coupling**

Fig. 1d indicates the locations in the bulk of the PhC (denoted by points A and B), at which the OAM states (depicted in Fig. 1b) are centered. According to the LVHE, at points A and B, the K valley should exhibit the opposite characteristic (OAM state) than the K’ valley. Fig. 1e shows the surface field map over the PhC when an external OAM source carrying cw polarity (ccw polarity) at point A (B) is excited at the peak frequency of the first band. We observe wave
propagation towards only three corners of the PhC region (see Fig 1a for illustration). These directions correspond to the K point in momentum space, which means that the cw (ccw) OAM polarity locally defines the K valley-polarized state at point A (B). In contrast, Fig. 1f shows, when exciting ccw (cw) OAM source at point A (B), waves propagate to the opposite directions, indicating that ccw (cw) OAM polarity is locked to the K’ valley at point A (B). Meanwhile, the opposite response is observed for band 2 at the K and K’ valleys (not shown), i.e. ccw/cw (cw/ccw) OAM states locally define the K/K’ valley polarization at point A (B), respectively. This proves that our PhC supports valley-contrast response that is analogous to conventional VHE and valley PTIs. Note that K and K’ valleys are related by time-reversal symmetry; hence the fields at the K’ valley could be deduced by applying a time-reversal symmetry operation to the fields at the K valley, which reverses the direction of the energy flux and the phase rotation, and hence the polarity of the OAM and CP states.

**Valley-polarized edge modes**

While the bulk-boundary correspondence principle prohibits topological edge states between a valley-projected topological phase and a topologically trivial phase, the domain wall between crystals with half-integer valley-Chern numbers of opposite signs allow for edge states (also referred to as kink states for distinction). Accordingly, we infer that the conservation of the binary valley DOF is responsible for VPEMs and that VPEMs must appear at the interface between opposite OAMs. Where only a local region is concerned, as is the case for a waveguide scenario, the LVHE upholds valley DOF. Therefore, despite the bandgap in our PhC not being the result of a broken SIS like in a valley PTI, we should expect VPEMs to appear if we could enforce opposite OAM polarities across some defect line.
Fig. 2a plot the band diagram of the PhC with a defect line (see Fig. 2e), showing guided edge modes that span the bulk bandgap of the PhC (i.e. between first and second TE bulk bands). The line-defect waveguide (LDWG) is simply a one row of holes that is more densely packed than to the rest of the PhC (see inset of Fig. 2e). Far from the defect region, the PhC on the two sides appear identical unlike valley PTIs where two different valley PhCs are interfaced to form a domain wall. Like the valley PTI, however, the translation symmetry of the lattice is preserved along the direction parallel to LDWG (denoted by \(k_{//}\) in Fig. 2d). That is, the line defect is aligned with the \(\Gamma K\) and \(\Gamma K'\) directions of the PhC. Fig. 2b and c, which plot the \(H_z\) phase and the Poynting vectors, respectively, across the LDWG, show a forward propagating wave concentrated along the defect interface with phase singular points appearing to the right and left sides that carry cw and ccw OAMs, respectively. This corresponds to the mode denoted by a dark purple color in Fig. 2a at a frequency in the middle of the bandgap. The linkage between the propagation direction (\(\Gamma K\) or \(\Gamma K'\) direction) and the specific OAM states across the line defect gives rise to direction-locked propagation, meaning the edge modes are valley polarized (i.e. VPEMs). Since the band diagram is symmetric with respect to the wavevector, there exists a pair of counter-propagating edge states with opposite valley-polarizations; the mode denoted by light magenta color in Fig. 2a is associated with a backward propagating wave, which has the reversed orientation of OAM states.

Fig. 2e shows an LDWG with multiple sharp turns excited by an OAM source (marked by yellow star) at a frequency within the PhC bandgap. The simulated surface field map shows that the edge mode is transmitted unidirectionally to the right of the sample and propagates through every bent segment without reflection. As is the case of a valley PTI, a zigzag-shaped pathway along the \(\Gamma K\) inclination, which conserves the valley DOF, can evidently support robust VPEMs.
in our PhC. We further prove the nature of these edge modes and the reason for their robustness by testing the wave routing through a magic-T junction, as shown in Fig. 2f. The surface field map shows that when a wave is injected from port 2, it is routed into ports 1 and 3 but, counterintuitively, not port 4. This can be explained by the edge mode being valley polarized. As marked in Fig. 3d, the guided mode in the input port 1 belongs to the K valley, which is of the same valley polarization as that of the output ports 1 and 3. On the other hand, the valley polarization of the output port 4 belongs to the K' valley, so light cannot be coupled into this port. As such, the edge states in our PhC indeed share the same origin as the VHE and inherit similar features to topological edge states in valley PTIs.

**Optical Measurements**

We fabricated LVHE-based LDWG devices on a standard SOI wafer with straight, zigzag, and double zigzag pathways (see Methods) as shown by the scanning-electron-microscope (SEM) images in Fig. 3a. We chose a lattice constant of 380 nm, air hole diameter of 160 nm and slab thickness of 220 nm. The separation distance between adjacent holes at the line defect was 60 nm and the devices were covered with 3μm buried oxide layer. This gives a TE bandgap spanning the wavelength range of 1514nm to 1595nm. The PhC bandgap is in the guide part of the band diagram (i.e. below the light line), hence the VPEMs will be confined in the plane of the PhC slab.

Fig. 3b shows the measured transmission spectra of the proposed waveguides in the wavelength range of 1530–1565nm, which is limited by the grating coupler performance used for testing (see Methods). The measurement results show high transmittance that is comparable for the three interfaces, as expected of VPEMs. We attribute the reported insertion losses to scattering into
plane waves in the high-dielectric SiO$_2$ substrate and buried cladding layer (see methods). For reference, similar waveguide devices using a conventional valley PTI$^8$ were fabricated and tested, as shown in Fig. 3c (see Methods). The measured transmission spectra are comparable to the results from the LVHE-based LDWGs. In addition, we fabricated and tested typical LDWGs$^{12}$ with similar sharp bends, as shown in Fig. 2d (see Methods). As expected, light transmission is greatly deteriorated due to the sharp bends in contrast to the previous two devices.

**Conclusion**

We have presented a new paradigm for realizing VPEMs and experimentally confirmed their robust light transmission through sharp bends using an SOI slab at telecommunication wavelengths. These modes share similar characteristics to topological modes in VHE-based PTIs albeit happening in a bandgap PhC with no topological order. Instead, the VPEMs here can be understood as the product of a line defect in a lattice with LVHE (a general feature of $C_{6v}$ point symmetry), where the defect causes a phase discontinuity in spatially-varying OAM states. Our results reveal the role of interface effects in forming gapless chiral edge (kink) states and expand how we can exploit valley DOF and engineer valleytronic devices. This includes new opportunities to develop low-loss compact delay lines$^{11}$, on-chip isolation, slow-light optical buffers, and lasers$^{10,33}$. Lastly, the waveguiding phenomenon demonstrated here is applicable not only to the electromagnetic spectrum and various optical systems, but also to other wave systems such as plasmonics, mechanics and acoustics.
Methods

Fabrication:

The PhCs were fabricated on an SOI wafer, with a 220-nm-thick silicon (Si) device layer over silica (SiO$_2$). The device patterns were defined by high-resolution e-beam lithography and then transferred to the silicon device layer by plasma dry etching. Subsequently, a 3-μm-thick buried SiO$_2$ cladding layer was deposited on top of the Si layer for protection using PECVD process. We fabricated the reference valley PTI on the same SOI wafer using the same process. The associated PhC has a honeycomb lattice of circular air holes with diameters of 160 nm and 80 nm for A and B sites, respectively, and a periodicity of 380 nm. The layout of the waveguide interface was chosen to be the same as reported in Ref. 8. In addition, we fabricated a conventional LDWG for comparison on the same SOI wafer using the same parameters as our LVHE PhC. This LDWG’s width was 658 nm, which is defined as the distance between the centers of the air holes nearest the waveguide.

Measurement:

To measure the transmission spectra of the fabricated devices, light from a tunable semiconductor laser was coupled via a single-mode fiber to the SOI waveguides through an integrated grating coupler, which had a bandwidth of ～35 nm. The TE-polarized continuous waves at the telecommunication wavelength were coupled to a 1.55μm-width input rectangular waveguide and then launched into the PhC sample. We used a linear taper to connect the waveguide of 500 nm width at the grating coupler to the waveguide of 1550 nm width at the PhCs’ facets. After passing through the PhC, the propagating wave was coupled to the output
rectangular waveguide and then collected by another grating coupler. The transmission spectra of
the devices were obtained by sweeping the laser wavelength and simultaneously measuring the
transmitted signal using a high-sensitivity optical power meter. Note that the dimensions of the
strip waveguides that couple into and out of the PhC devices was chosen the same as given in
Ref. 8 without further optimization, which explains the enhanced coupling efficiency (higher
transmittance) of the corresponding devices compared to the proposed LVHE-based LDWGs.

Numerical simulation:

All the numerical simulation results, including band diagrams, eigen-field patterns and optical
transmission data in this work were retrieved from full-wave electromagnetic simulation using
the commercial finite element method solver software HFSS. To generate an OAM excitation
source, we used a circular arrangement of a group of $H_z$ dipole-point sources with same
magnitudes and incrementally increasing phases as illustrated in Fig. 1d. To plot the Wilson-
loop, we calculate the Berry phase for the $n^{th}$ band along the loop $k_x \in [-\pi, \pi]$ for a fixed $k_y$ as

$$\phi_{n,k_y} = \int_{-\pi}^{\pi} dk_x A_{n,k}^{(x)}$$

which is obtained by the integration over the Berry connection, $A_{n,k}^{(x)} = \int d^2r \ H_{n,k}^*(r) \cdot \nabla_{k_x} H_{n,k}(r) / \int d^2r \ H_{n,k}(r) \cdot \mu(r) \cdot H_{n,k}(r)$, where $H_{n,k}(r)$ is the periodic part of the
magnetic field. The Chern number can be obtained by counting the winding phase of $\phi_{n,k_y}$ when $k_y$
goes from $-\pi$ to $\pi$. Note that although $\phi_{n,k_y}$ depends on the choice of the origin of the spatial
coordinates, the winding phase of $\phi_{n,k_y}$ does not.
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Conflict of Interest

The authors declare no conflict of interest.

Contributions

D.J.B conceived the idea, performed the numerical simulations and experiments, and analyzed the data. D.F.S supervised the project and interpreted the results. D.J.B prepared the manuscript and D.F.S provided feedback.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.
References

1. Schaibley, J. R. et al. Valleytronics in 2D materials. *Nature Reviews Materials* **1**, 1–15 (2016).
2. Dong, J.-W., Chen, X.-D., Zhu, H., Wang, Y. & Zhang, X. Valley photonic crystals for control of spin and topology. *Nature Materials* **16**, 298–302 (2017).
3. Ni, X. et al. Spin- and valley-polarized one-way Klein tunneling in photonic topological insulators. *Science Advances* **4**, eaap8802 (2018).
4. Xiao, D., Yao, W. & Niu, Q. Valley-Contrasting Physics in Graphene: Magnetic Moment and Topological Transport. *Phys. Rev. Lett.* **99**, 236809 (2007).
5. Chen, X.-D., Zhao, F.-L., Chen, M. & Dong, J.-W. Valley-contrasting physics in all-dielectric photonic crystals: Orbital angular momentum and topological propagation. *Phys. Rev. B* **96**, 020202 (2017).
6. Ma, T. & Shvets, G. All-Si valley-Hall photonic topological insulator. *New J. Phys.* **18**, 025012 (2016).
7. Xu, Z. et al. Topological valley transport under long-range deformations. *Phys. Rev. Research* **2**, 013209 (2020).
8. He, X.-T. et al. A silicon-on-insulator slab for topological valley transport. *Nature Communications* **10**, 872 (2019).
9. Noh, J., Huang, S., Chen, K. P. & Rechtsman, M. C. Observation of Photonic Topological Valley Hall Edge States. *Phys. Rev. Lett.* **120**, 063902 (2018).
10. Noh, W. et al. Experimental demonstration of single-mode topological valley-Hall lasing at telecommunication wavelength controlled by the degree of asymmetry. *Opt. Lett., OL* **45**, 4108–4111 (2020).
11. Yang, Y. et al. Terahertz topological photonics for on-chip communication. *Nature Photonics* **14**, 446–451 (2020).
12. Vlasov, Y. A., O’Boyle, M., Hamann, H. F. & McNab, S. J. Active control of slow light on a chip with photonic crystal waveguides. *Nature* **438**, 65–69 (2005).
13. Khanikaev, A. B. et al. Photonic topological insulators. *Nature Materials* **12**, 233–239 (2013).

14. Ozawa, T. et al. Topological photonics. *Rev. Mod. Phys.* **91**, 015006 (2019).

15. Kim, M., Jacob, Z. & Rho, J. Recent advances in 2D, 3D and higher-order topological photonics. *Light: Science & Applications* **9**, 130 (2020).

16. Bisharat, D. J. & Sievenpiper, D. F. Electromagnetic-Dual Metasurfaces for Topological States along a 1D Interface. *Laser & Photonics Reviews* **13**, 1900126 (2019).

17. Bahari, B. et al. Nonreciprocal lasing in topological cavities of arbitrary geometries. *Science* **358**, 636–640 (2017).

18. Rechtsman, M. C. et al. Photonic Floquet topological insulators. *Nature* **496**, 196–200 (2013).

19. Zangeneh-Nejad, F. & Fleury, R. Nonlinear Second-Order Topological Insulators. *Phys. Rev. Lett.* **123**, 053902 (2019).

20. Wu, L.-H. & Hu, X. Scheme for Achieving a Topological Photonic Crystal by Using Dielectric Material. *Phys. Rev. Lett.* **114**, 223901 (2015).

21. Barik, S. et al. A topological quantum optics interface. *Science* **359**, 666–668 (2018).

22. Blanco-Redondo, A. Topological Nanophotonics: Toward Robust Quantum Circuits. *Proceedings of the IEEE* **108**, 837–849 (2020).

23. Jiang, T. et al. Experimental demonstration of angular momentum-dependent topological transport using a transmission line network. *Nature Communications* **10**, 434 (2019).

24. Silveirinha, M. G. Bulk-edge correspondence for topological photonic continua. *Phys. Rev. B* **94**, 205105 (2016).

25. Hasan, M. Z. & Kane, C. L. Colloquium: Topological insulators. *Rev. Mod. Phys.* **82**, 3045–3067 (2010).

26. Stone, M. *Quantum Hall Effect*. (World Scientific, 1992).
27. Kane, C. L. & Mele, E. J. $\mathbb{Z}_2$ Topological Order and the Quantum Spin Hall Effect. *Phys. Rev. Lett.* **95**, 146802 (2005).

28. Bernevig, B. A. & Zhang, S.-C. Quantum Spin Hall Effect. *Phys. Rev. Lett.* **96**, 106802 (2006).

29. Mak, K. F., McGill, K. L., Park, J. & McEuen, P. L. The valley Hall effect in MoS2 transistors. *Science* **344**, 1489–1492 (2014).

30. Ju, L. *et al.* Topological valley transport at bilayer graphene domain walls. *Nature* **520**, 650–655 (2015).

31. Gao, F. *et al.* Topologically protected refraction of robust kink states in valley photonic crystals. *Nature Physics* **14**, 140–144 (2018).

32. Shalaev, M. I., Walasik, W., Tsukernik, A., Xu, Y. & Litchinitser, N. M. Robust topologically protected transport in photonic crystals at telecommunication wavelengths. *Nature Nanotechnology* **14**, 31–34 (2019).

33. Zeng, Y. *et al.* Electrically pumped topological laser with valley edge modes. *Nature* **578**, 246–250 (2020).

34. Wang, H.-X., Guo, G.-Y. & Jiang, J.-H. Band topology in classical waves: Wilson-loop approach to topological numbers and fragile topology. *New J. Phys.* **21**, 093029 (2019).

35. Yu, S.-P., Muniz, J. A., Hung, C.-L. & Kimble, H. J. Two-dimensional photonic crystals for engineering atom–light interactions. *PNAS* **116**, 12743–12751 (2019).

36. Wu, S. *et al.* Electrical tuning of valley magnetic moment through symmetry control in bilayer MoS2. *Nature Physics* **9**, 149–153 (2013).
Fig. 1: Spatial distribution of OAM states and valley-contrast response based on LVHE in a triangular lattice PhC. 

**Fig. 1 (a)** Two-dimensional triangular lattice of circular air holes in a dielectric. Due to the C$_{6}$$_{0}$ symmetry, the lattice does not qualify as a valley PhC. **Fig. 1 (b)** Simulated surface phase map of $H_{z}$ field at the K valley of the fundamental TE band of the PhC. The map shows phase vortices, which correspond to OAM states of opposite polarities (as shown in the inset) that appear equally through the bulk. **Fig. 1 (c)** Wilson loop diagram of the PhC showing no signature of any topological order. **Fig. 1 (d)** Points A and B specify the locations, at which a source carrying an OAM state would excite a wave with maximum directionality. **Fig. 1 (e)** Surface map of $H$-field intensity over the PhC region illustrated in **Fig. 1 (a)**, showing wave propagation towards K valley direction when excited by cw OAM state at point A or ccw OAM state at point B. **Fig. 1 (f)** same map as in **Fig. 1 (e)** but showing wave propagation towards K’ valley direction when excited by ccw OAM state at point A or cw OAM state at point B.
Fig. 2: Schematics and characteristics of a line defect in a triangular PhC supporting VPEMs based on LVHE. a, Band diagram of TE modes of the 2D air holes triangular PhC containing a line defect (illustrated in b and e), showing the dispersion of guided edge modes within the bulk bandgap. b, Surface phase map of $H_z$ filed across the line defect, which is formed by closer packing of holes along one row of holes compared to the rest of the PhC. The map shows opposite OAM states (denoted by curled arrows) across the defect that are associated with upward traveling wave, i.e. a VPEM. c, Plot of the Poynting ($S$) vectors corresponding to the results in b, showing energy flow along the line defect and flux vortices on the two sides in accordance with the OAM states in b. d, Illustration of the Brillouin zone of the PhC indicating the orientation $k//_{\parallel}$ parallel to the line defect, showing that the translation symmetry of the PhC in $\Gamma K$ and $\Gamma K'$ directions is preserved at along the defect. e, Surface map of $H$-field intensity over the PhC showing unidirectional excitation of the VPEM when using a proper polarized source (denoted by yellow star), and reflection-free transmission along a meandering interface pathway (marked by dashed line). f, Planar magic-T junction showing VPEMs, routing each polarization state towards its corresponding valley direction analogous to spin-momentum locking.
Fig. 3: Experimental observation of robust VPEMs in an SOI triangular PhC slab. a, Perspective views of scanning-electron-microscope (SEM) images of the fabricated PhC waveguide device (LVHE-based LDWG) with the zigzag pathway on SOI slab. The PhC is coupled directly by a standard rectangular strip silicon waveguide. b, Measurements of transmission spectra of the proposed LDWG in case of straight, zigzag (two 120° bends) and double zigzag (four 120° bends) waveguide pathways. c, d Same as b but for VHE-based PTI and common LDWG. Only in case of the LVHE and VHE devices, the spectra in the bandgap maintain high transmittance for a sharp-bending geometry.