Imaging and Manipulation of Layer Pseudospins in Photonic Valley-Hall Phases

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Abstract
Valley-Hall phases, first proposed in two-dimensional (2D) materials, originate from nontrivial topologies around valleys which denote local extrema in momentum space. Since they are extended into classical bosonic systems, their designs draw inspirations from existing quantum counterparts, and their transports show similar topological protections. In contrast, it is recently established in acoustics that layer pseudospins in valley-Hall phases can give rise to special valley-Hall edge states with fundamentally different transport behaviors at the interfaces compared with various 2D materials. Their realization in other bosonic systems, such as photonics, would allow us to design classical topological systems beyond inspiration from quantum systems. In this work, we show that layer pseudospins exist in photonic valley-Hall phases, using vertically coupled designer surface plasmon crystals, a non-radiative system in open environment supporting tightly-confined propagating modes. The negligible thermal and radiative losses in our structure pave the way for our direct observations of the layer pseudospins and associated topological phenomena stemmed from them in both real and reciprocal spaces. Photonic devices that manipulate signals based on layer pseudospins of the topological phase, such as layer convertors and layer-selected delay lines, are experimentally demonstrated, confirming the potential applications of layer pseudospins as a new degree of freedom carrying information.

**Introduction**

In the last decade, extensive pursuits of valley-dependent transports in
two-dimensional (2D) materials — valleys denoting local extrema in momentum space [1,2] — have led to a new type of electronics termed ‘valleytronics’ [3,4]. It focuses on bulk-gapped valley-Hall phases whose nontrivial topology around well-separated valleys is the key to generate valley-polarized currents [5-7]. Recently, valley-Hall phases, like previous Chern [8-12], Floquet [13-17] and spin-Hall phases [18-23], has been extended to classical bosonic systems. Classical valley-polarized edge states as the analogy of valley-polarized currents, including their topologically protected transports, have been successfully observed [24-29]. Devices based on classical valley-Hall phases are also demonstrated [30-32]. Remarkably, layer pseudospins in acoustic valley-Hall phases can give rise to topological transport behaviors currently unfound in 2D materials [33], and they may become a new degree of freedom (DOF) carrying information for their easy detections by external probes.

Do layer pseudospins and their extraordinary transport exist in other bosonic systems? If so, we could start designing classical topological systems beyond inspiration from quantum systems.

In this Letter, we report a scheme to realize layer pseudospins in photonic valley-Hall phases using vertically coupled designer surface plasmon (DSP) crystals, where tightly-confined modes propagate on periodically patterned metallic surfaces [25,34-40]. Valley-Hall phases and layer pseudospins are generated from twisting of anisotropic slots. Through near-field mappings, both layer-mixed and layer-polarized valley-Hall edge states characterized by a pair of half-integer quantized valley Chern
numbers (VCNs) are directly observed and resolved. Unique devices which can manipulate photonic valley-Hall edge states based on layer pseudospins are demonstrated.

Results

Our system is a triangular-lattice crystal shown in Fig. 1(a), and the inset shows its first Brillouin zone (FBZ). A unit cell outlined by the red hexagon is shown in details in Fig. 1(b). This composite DSP crystal comprises three metallic layers and two dielectric spacers. A series of top-view schematics depicting the metallic layers are shown in Fig. 1(c). Identical but twisted “ceiling fan”-shaped slots are arranged in a triangular lattice on upper and lower metallic layers. Circular slots are arranged in a honeycomb lattice on the middle metallic layer, introducing interlayer couplings between the lower and upper DSP crystals. The orientations of “ceiling fan”-shaped slots can be parameterized by the common rotation angle $\beta$ and relative rotation angle $\alpha$. As a specific example, we consider following geometric parameters: lattice constant $a = 12$ mm, metallic layer thickness $t_{\text{metal}} = 35 \, \mu\text{m}$, spacer thickness $t_{\text{sub}} = 1.5$ mm, and for “ceiling fan”-shaped slots, radii $R_0 = 1$ mm, $R_1 = 5.6$ mm (three longer fans), $R_2 = 4.6$ mm (three shorter fans), and for circular slots, radius $R_c = 2.5$ mm.

We numerically calculate its band structures using COMSOL Multiphysics. To reduce loss, we use F4B laminates as dielectric spacers (see Note 5 for simulation setup [41]) [25,42,43]. The band structure when $(\alpha, \beta) = (0, 0)$ is shown in Fig. 1(d),
where dashed lines mark the light cone, and only bound states under it are shown. Two Dirac cones form around K point with a frequency split due to the interlayer hoppings mediated by the circular slots on the middle metallic layer. They intersect each other at an equal-frequency circle in reciprocal space, leading to a nodal-ring degeneracy (see Figs. S1 and S2 for details).

Since nodal rings are usually associated with mirror symmetries [44], we tune $\alpha$ and $\beta$ to twist the “ceiling fan”-shaped slots, reducing mirror symmetries to open a full bandgap between the 2nd and 3rd bands (Fig. 1(e)). We first only increase $\alpha$, which breaks the mirror symmetry with respect to the middle layer. It is seen that the nodal ring is fully gapped once $\alpha$ becomes non-zero but the degeneracy at K point persists, protected by the two-fold rotational symmetry along $\Gamma K$ direction. This point degeneracy is lifted if we further tune $\beta$ to a non-zero value (not shown in Fig. 1(e)). Alternatively, we solely increase $\beta$, which only breaks the mirror symmetry with respect to $\Gamma K$ direction. Initially, both Dirac cones are gapped but the nodal ring still persists. Next, after $\beta$ exceeds a threshold value, the 2nd and 3rd bands detach each other, opening a full bandgap.
Figure 1. (a) Isometric schematic of the triangular-lattice crystal and the red hexagon.
denotes a unit cell. The inset shows its first Brillouin zone (FBZ). (b) Details of a unit cell. (c) Top view of the three metallic layers. “Ceiling fan”-shaped slots on upper and lower layers are rotated through the angles $\beta+\alpha$ and $\beta-\alpha$, respectively. (d) When $(\alpha, \beta) = (0, 0)$, a pair of Dirac cones emerges at K valley. (e) Band structures when $(\alpha, \beta)$ deviates from (0, 0). (f) Berry curvatures along the line $k_y = 2\pi / (\sqrt{3}a)$. Red or blue scatters (sold lines) are calculated from COMSOL Multiphysics (the perturbation Hamiltonian). (g) Phase diagram of the crystal classified by VCNs $C^0_K$ and $C^1_K$. Yellow circles represent the phase boundaries obtained numerically, where the full bandgap closes.

We have obtained full bandgaps by tuning $\alpha$ or $\beta$ or both. However, do they belong to the same topological phase? Numerically, we calculate Berry curvatures [25,45] of the bands below the full bandgap for two typical cases: $(\alpha, \beta) = (10^\circ, 5^\circ)$ and $(0, 10^\circ)$. The results along the line $k_y = 2\pi / (\sqrt{3}a)$ are shown as scatters in Fig. 1(f) (see Fig. S8 for 2D maps of Berry curvatures [41]). It can be seen that the Berry curvatures of the 1st bands are localized and largely identical, but those of the 2nd bands have opposite signs, which implies the two cases are possibly different topological phases. Since topological phase transitions usually happen after the close and reopen of full bandgaps [24,25], we sweep the $(\alpha, \beta)$ parametric space numerically and record the values when the 2nd and 3rd bands touch each other, which delineate the parametric space into four different regions, as shown in Fig. 1(g).
Now, we use $k \cdot p$ method to develop a perturbation Hamiltonian around K valley to explain our numerical findings. The perturbation Hamiltonian is spanned by the four degenerate states in the absence of twisting and interlayer coupling. To the first-order, it is written as [33] (see Notes 1 and 2 for details [41])

$$\delta H_K = v_D s_i \otimes (\delta k_x \sigma_x + \delta k_y \sigma_y) + \eta (\alpha s_z + \beta s_\theta) \otimes \sigma_z - \Delta_c s_z \otimes \sigma_0,$$

(1)
in which $s_i$ and $\sigma_i$ are Pauli matrices ($i = 0, x, y, z$) acting on layer pseudospin and orbital DOFs, respectively. The Hamiltonian includes three parameters, $v_D$ group velocity, $\eta$ and $\Delta_c$ characterizing the couplings between the orbitals and layer pseudospins. They depend on the geometry and material of the unit cell and can be extracted from numerically calculated band structures. Solving the perturbation Hamiltonian, we obtain the Berry curvatures of the 1st and 2nd bands around K valley, plotted as solid lines in Fig. 1(f). It is observed that the first-order perturbation Hamiltonian nicely capture the essence of exact distributions of the Berry curvature, reassure us to use the Hamiltonian to classify the band topology. Inspired by the topological invariants characterizing quantum spin Hall effect [46], we introduce a pair of VCNs [33]: besides the conventional VCN $C^K_V$, a layer VCN $C^K_L$ is also introduced, which is the difference of integrals of layer-projected Berry curvatures in one half of the FBZ (see Note 3 for formal definitions [41]). From the Hamiltonian, the half-integer quantized $C^K_V$ and $C^K_L$ are obtained and summarized in Fig. 1(g). For reasons discussed below, the phases with non-zero $C^K_L$ are termed layer-polarized valley-Hall (LVH) phases, and the phases with non-zero $C^K_V$ are
termed conventional valley-Hall (CVH) phases. From the phase diagram, we can identify that \((0, 10°)\) is a CVH phase, while \((10°, 5°)\) is an LVH phase, indeed topologically different.

Figure 2. (a), (b) Projected band structures for supercells comprising different LVH phases \(C^\text{L}_v = \pm 1\) (a) and different CVH phases \(C^\text{V}_v = \pm 1\) (b), respectively. The gray shaded regions correspond to bulk bands. Red (blue) solid lines represent edge states with \(K\) (\(K'\)) valley index. Colored dots denote the edge states around \(K\) valley at 6.70 GHz indicated by the dashed lines. (c), (d) Simulated field maps (\(|E|\)) of the denoted states on the slices \(z = \pm 4\) mm. The yellow arrows denote the simulated energy flows.
Edge states between LVH phases are layer-polarized, either upper (U) or lower (L), but unpolarized between CVH phases. States around $K'$ valley can be obtained through time-reversal symmetry.

To explore the valley-Hall edge states, we assemble two different LVH phases $(\pm 15^\circ, 5^\circ)$ to form a supercell, and its projected band structure (Fig. 2(a)) shows two branches of the valley-Hall edge states around $K$ valley with opposite propagating directions. For comparison, we also assemble a supercell comprising two different CVH phases $(0, \pm 20^\circ)$, and its projected band structure (Fig. 2(b)) shows two branches with the same propagating direction around $K$ valley. To investigate their layer polarizations, we plot the field maps of the edge states on slices $z = \pm 4$ mm, namely, 2 mm above (below) the upper (lower) metallic layer, in Figs. 2(c) and 2(d), where energy flows are also plotted as the arrows. As shown, valley-Hall edge states between different LVH phases is layer polarized and the energy flows further indicate their layer polarizations are locked to their propagating direction around $K$ valley. This property may be termed ‘layer-chirality’. Since time-reversal transformation does not affect field distributions but reverses energy flows, the layer-chirality will be reversed at $K'$ valley. On the contrary, it can be seen that there is no such property for valley-Hall edge states between different CVH phases, since the field distribution is even not polarized to a single layer. Nevertheless, for these valley-Hall edges, backscattering is forbidden if no inter-valley scattering is introduced, which depends
on geometry of the interfaces [24,25,47]. A systematic study further confirms topological features of layer pseudospins under perturbation (see Note 7 [41]).

Figure 3. (a) Photograph of experiment setup. (b),(c) Central regions of the fabricated samples. The sample is composed of two different LVH (b) or CVH (c) phases on two sides of \( y = 0 \). The upper (lower) row shows the upper (lower) layers. White scale bar is 24 mm. (d), (e) Imaged field maps (\(|E_y|\)) around the interfaces between different LVH phases (c) or different CVH phases (d). (f)-(h) Layer-resolved dispersions obtained using FFTs, applied on the imaged fields around LVH interfaces (f,h) and CVH interfaces (g,i) on the upper slice (f,g) and lower slice (h,i), respectively. The white dashed lines denote the light cone, and the solid lines replicate the numerical results.
To directly observe the edge states between valley-Hall phases, we have performed near-field mappings and the experiment setup is shown in Fig. 3(a), two monopole antennas used as the source and detector, respectively. The samples are fabricated using standard printed circuit board (PCB) etching method, and each sample is composed of two PCBs tightened by plastic bolts (see Note 6 for details of samples and experiments [41]). Top-view photographs of the samples are shown in Figs. 3(b) and 3(c). On two sides of the interface $y = 0$ are different LVH or CVH phases, $(\alpha, \beta) = (\pm 15^\circ, 5^\circ)$ for LVH phases and $(\alpha, \beta) = (0, 20^\circ)$ for CVH phases. The imaged fields on upper and lower slices at 6.70 GHz are shown in Figs. 3(d) and 3(e), respectively (see Fig. S5 for other frequencies [41]). It is seen that excited field between LVH phases is polarized to the upper layer where source is placed, but between CVH phases it exhibits oscillation of amplitude on both slices due to the interferences of the symmetric and anti-symmetric CVH edge modes (see Fig. S10 [41]). We then perform fast Fourier transforms (FFT) on imaged fields and the corresponding FFT amplitude spectra are shown in Figs. 3(f)-(i), respectively. The bright regions in the layer-resolved spectra indicate dispersions of the edge states, and agree excellently with numerically calculations (solid lines). We have also measured the projected bands of the bulk phases, and only uncoupled plane wave-like modes exist in the bandgap (See Fig. S9 [41]).
Figure 4. (a) Diagram of layer convertor. (b) Central region of a fabricated sample. (c) Simulated field maps ($|E|$) at 6.70 GHz on slices $z = \pm 4$ mm, the distribution along the midline ($y = 0$) shown in (d), white scale bar 40 mm, shaded region denoting CVH phases. The yellow arrow represents the source. The yellow dashed rectangles denote the regions imaged in experiments. (e) Imaged field maps ($|E_y|$) at 6.70 GHz, the distribution along the midline ($y = 0$) shown in (f), white scale bar 30 mm.

After our findings soundly confirmed, it is time to exploit this new DOF to design interesting photonic devices. First, we note the layer-chirality of layer-polarized edge states between LVH phases and lack of the property between CVH phases. This
contrast suggests a layer convertor using the CVH phases as the bridge to compel an interlayer transport. The schematic diagram of the layer convertor is shown in Fig. 4(a). A photograph of the central region of the fabricated sample is shown in Fig. 4(b). First, we perform simulations for this device and the simulated field maps at 6.70 GHz are shown in Fig. 4(c) (see Fig. S6 for other frequencies [41]). To characterize the topological protection on interlayer transports, the simulated field profile along the midline is explicitly shown in Fig. 4(d). Simulated temporal dynamics of the transport also show a negligible backscattering (see Fig. S13 and Movie S1 [41]). We then perform near-field mappings with aforementioned experiment setup and image the region enclosed by the yellow dashed rectangle in Fig. 4(c). The measured field maps at 6.70 GHz are shown in Fig. 4(e) and the its field profile along the midline is shown in Fig. 4(f). The shaded regions in Figs. 4(d) and 4(f) denote the interval occupied by transitional CVH phases. The simulation and experimental results agree quite well and clearly show that a smooth interlayer transport happens when the layer-polarized edge state passes through CVH phases where the edge state becomes layer-mixed, validating the proposed mechanism. Compared with conventional vertical couplers used for interlayer communications in photonics [48-50], which need geometric optimizations to refine the performance focusing on a single frequency, our layer convertor based on layer pseudospins function smoothly in the bandgap (see Fig. S7 [41]). Therefore, it could potentially simplify fabrication process of devices with interlayer communications, relaxing fabrication tolerance, and may improve their
Figure 5. (a) Diagram of Layer-selected delay line. Signals is excited at input and dwell time is measured around output. Blue and red dashed lines denote topologically different interfaces between LVH and CVH phases. (b) Measured dwell time (scatters) when source is attached at the upper or lower face. Fitted lines manifest different intercepts, featuring the layer-selected delay. (c), (d) Simulated field maps (|E|) at 6.70 GHz when source (yellow arrow) is placed at the upper (c) or lower (d) face, white scale bar 60 mm. The yellow dashed rectangles denote the regions imaged in experiments. (e), (f) Imaged field maps (|E_y|) at 6.70 GHz, white scale bar 30 mm.
Further, layer-polarized edge states also exist between neighboring LVH and CVH phases (see Note 4 [41]). For example, when a CVH phase (0, 20°) at left meets an LVH phase (±15°, 5°) at right, the forward-going edge state at K valley is polarized to the upper (lower) layer (see Fig. S4 and Table S1 for summary [41]). This intriguing interplay inspires a layer-selected topological delay line, whose schematic diagram is shown in Fig. 5(a). At the interfaces between LVH and CVH phases denoted by dashed lines, the red (blue) dashed line highlights upper (lower) layer-polarized edge state. The edge state around K-valley (K'-valley), upper (lower) layer-polarized, follows the path indicated by the red (blue) dashed line and undergo a (no) detour. Consequently, the upper (lower) layer-polarized edge state will (not) be delayed. We then quantify this layer-selected delay by measuring their dwell time [47,51] (see Note 6 for experiment setup [41]). The measured data plotted as functions of the distance to source (Fig. 5(b)) show good linear dependence ($R^2 > 0.90$), confirming the ballistic transport of the edge states [51]. Further, the fitted lines exhibit similar slopes representing similar group velocities, but the upper layer-polarized one has a significantly larger intercept ($\sim 0.95$ ns), suggesting it has undergone a layer-selected delay caused by the detour. For better understanding, we perform simulations for this situation, and simulated field maps (Figs. 5(c) and 5(d)) shows that upper layer-polarized edge state indeed travels through the detour while lower layer-polarized edge state go straightforward. Further, we also experimentally imaged the region around the detour, and the imaged field maps (Figs. 5(e) and 5(f))
also agree with this picture. Therefore, a layer-selected topological delay line is successfully realized. The delay on each side can be separately adjusted by tailoring the shapes of the detours and whispering-gallery-type resonators can be employed if a long dwell time is necessary [47]. Compared with previous topological delay lines [30,51], the layer-selected delay line could offer delays in very different ranges on two sides of the device, which doubles the space utilization in a simple manner.

**Discussion**

In summary, a composite DSP crystal is proposed to realize layer pseudospins in photonic valley-Hall phases. Layer-polarized valley-Hall phases emerge after deliberately twisting anisotropic slots on vertically coupled metallic layers. The layer-polarized edge states arising from these phases show fundamentally different transport behaviors compared with those found in 2D materials. Direct experimental observations, including imaged field maps and their Fourier spectra, rigorously confirm our scheme and show DSP crystals are ideal platforms to thoroughly explore the new physics. We also realize photonic devices utilizing layer pseudospins, which demonstrate more versatile control over valley-Hall edge states, in comparison with conventional devices and previous valley-Hall devices.

In future, realizing layer pseudospins in higher frequency regimes would offer new potentials for integrated photonic devices. The scheme should be direct, as our scheme relies on symmetries instead of material properties and can be directly scaled
down until the far-infrared regime, in which DSPs still dominate over real surface plasmons on patterned metallic surfaces. Moreover, coupling layer pseudospins with other kinds of pseudospins, such as hybridized TE/TM modes [19,26] or dipole/quadrupole modes[20,23], would also stimulate designs for subtle and interesting topological systems which have not been found in quantum systems.

Acknowledgements

X. Wu would like to thank Prof. J. H. Jiang and Dr. R.-Y. Zhang for fruitful discussions. The work is supported by an Areas of Excellence Scheme grant (AoE/P-02/12) from Research Grants Council (RGC) of Hong Kong, and grants from Natural Science Foundation of China (NSFC) (No. 11474212), Open Fund of the State Key Laboratory of Integrated Optoelectronics (IOSKL2017KF05), and the Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions.

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[41] See Supplementary Material at [inserted URL] for (1) derivation of perturbation Hamiltonian, (2) band structures from perturbation Hamiltonian, (3) layer-projected valley Chern numbers, (4) edge states between LVH phase and CVH phase, (5) simulation setup in frequency domain and time domain, (6) sample fabrication and experiment setup, (7) preservation of layer pseudospins under perturbation, and more other details.

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