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Zhang, Baile

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Topological refraction in dual-band valley sonic crystals

Ding Jia,^{1,2} Yong Ge,¹ Haoran Xue,³ Shou-qi Yuan,¹ Hong-xiang Sun,^{1,*} Yihao Yang,^{3,4,†} Xiao-jun Liu,² and Baile Zhang^{3,5,‡}

¹Research Center of Fluid Machinery Engineering and Technology, School of Physics and Electronic Engineering, School of Computer Science and Communication Engineering, Jiangsu University, Zhenjiang 212013, China

²Key Laboratory of Modern Acoustics, National Laboratory of Solid State Microstructures, Department of Physics and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China

³Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore

⁴Interdisciplinary Center for Quantum Information, State Key Laboratory of Modern Optical Instrumentation, College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China

⁵Centre for Disruptive Photonic Technologies, The Photonics Institute, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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Valley pseudospins, as quantum states of energy extrema in momentum space, have been introduced from condensed-matter systems into classical sound systems, and several valley sonic crystals (VSCs) have been realized experimentally. However, in the existing VSCs, topological kink states generally appear in a single band gap, which apparently has become an obstacle for multiband topological sound devices. To overcome this challenge, we here experimentally demonstrate dual-band VSCs, in which robust valley kink states exist in two separated bulk band gaps. More interestingly, two opposite valleys separately located in two band gaps are locked to a single propagation direction, which arises from the fact that the bands below two band gaps show opposite valley Chern numbers at the K/K' valley. This double valley-locking phenomenon has been demonstrated via measuring the topological refraction of the kink states into the ambient space at a zigzag termination. We observe positive refraction at the lower band gap, whereas the coexistence of positive and negative refraction at the higher band gap. Additionally, we observe the robust valley transport through the sharp corners at two band gaps. The designed VSCs with the dual-band topological refraction and robust valley transport could find potential applications in multiband and multidirectional devices.

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I. INTRODUCTION

In the recent years, valleytronics that studies valley pseudospin has become a hot topic owing to its great potential in information communication and energy transport [1–7]. Motivated by the valleytronics, considerable efforts have been made to introduce the concept of valley pseudospin into nonelectronic systems, such as photonics [8–17], mechanics [18–23], and acoustics [24–37]. In the acoustic community, researchers have demonstrated that domain walls between two valley sonic crystals (VSCs) with opposite valley Chern numbers can support robust valley transports with negligible intervalley scatterings [25,26,30,31]. With these unique features and advantages, several VSCs have been realized experimentally and presented potential applications in valley-selective acoustic emitters [25], valley-chirality locked beam splitters [26,35], sound delay lines [30], directional acoustic antennas [31], and acoustic concentrators [37].

Additionally, topological refractions of the kink states from domain walls between two VSCs have also been investigated extensively, which not only has the advantage of zero

reflection of sound, but also provides an explicit approach to distinguish two types of valleys. In previously demonstrated topological refractions, two excited kink states in opposite directions of the domain wall between two VSCs are generally locked to the valleys K and K' separately, which can be utilized to design a single-channel directional acoustic antenna [31]. Such a phenomenon is closely related to the fact that these valley kink states exist at a single band gap. However, the realization of locking the two valleys in a single propagation direction of the same domain wall based on multiband VSCs still remains elusive, which is very important for developing multiband and multidirectional sound devices.

To overcome this challenge, we here experimentally demonstrate dual-band VSCs, in which valley kink states appear in two different band gaps. Because the bands below two band gaps show opposite valley Chern numbers at K/K' valley, two valleys located in different band gaps are locked to the same propagation direction. This double valley-locking phenomenon has been numerically and experimentally demonstrated via measuring the topological refraction of the valley kink states from domain walls into the ambient space at a zigzag termination. We observe positive refraction at the lower band gap, whereas the coexistence of positive and negative refraction at the higher band gap. Furthermore, we directly measure the dispersions of the kink

*jsdxshx@ujs.edu.cn

†yangyihao@zju.edu.cn

‡blzhang@ntu.edu.sg

FIG. 1. (a) Structure of a VSC consisting of triangular-lattice TLRs. Two insets represent different views of the TLR. a is the lattice constant; l and d are the length and the width of the leg, respectively; α is the angle between two neighbor legs; h is the thickness of the TLR. Here, $a = 20.0$ mm, $l = 8.0$ mm, $d = 3.2$ mm, $h = 8.0$ mm, and $\alpha = 120^\circ$. (b) Photograph of the topological domain wall fabricated with photopolymer. Green line is the domain wall between VSC-A and VSC-B consisting of the TLRs with opposite rotation angles. Blue TLRs in two insets represent the original configuration ($\theta = 0^\circ$), and red TLRs exhibit the rotated structures in VSC-A (θ) and VSC-B ($-\theta$).

states and the robustness of valley transport against sharp corners. Our work paves a way to high-performance multi-band and multidirectional sound devices for robust sound communications and energy transport.

II. RESULTS AND DISCUSSION

A. Design of dual-band VSCs

As shown in Fig. 1(a), we design a VSC consisting of a triangular-lattice array (with the lattice constant of $a = 20.0$ mm) of scatters in air. Each scatter (with a height of $h = 8.0$ mm) consists of three legs with a length of $l = 8.0$ mm and a width of $d = 3.2$ mm, and the angle between two neighbor legs is $\alpha = 120^\circ$ [two insets in Fig. 1(a)]. In our implementation, we construct a domain wall that is composed of two types of units, i.e., VSC-A and VSC-B, consisting of three-legged rods (TLRs) with the rotation angle of θ and $-\theta$, respectively [Fig. 1(b)].

B. Dual-band acoustic valley Hall phase transitions

Figure 2(a) shows the dispersions of the VSCs with $\theta = 0^\circ$ and 5° . In the case of $\theta = 0^\circ$ (black solid lines), two Dirac cones protected by the C_{3v} point-group symmetry of the VSC exist at the point K (K') at different frequencies. However, when $\theta = 5^\circ$ (color dashed lines), the broken inversion symmetry of the VSC (the corresponding group symmetry is reduced to C_3) destroys the twofold point degeneracy and band gaps open for both Dirac cones. The formed band gaps I and II (yellow shaded regions) can support topological valley transport of sound. Figure 2(b) shows the band-edge eigenfrequencies of the VSCs with different values of θ at K valley. Note that the band gaps I and II at K valley close and reopen when rotating TLRs across 0° , and acoustic valley Hall (AVH) phase transitions take place.

Based on the $\mathbf{k} \cdot \mathbf{p}$ perturbation method [25], the Berry curvatures of the bands below the band gaps I and II can be calculated as $\Omega(\delta\mathbf{k}) = \frac{m_i v_{Di}}{2(\delta k^2 + m_i^2 v_{Di}^2)^{3/2}}$, where v_{Di} is the Dirac velocity of the conic dispersion at $\theta = 0^\circ$; $\delta\mathbf{k}$ is the momentum deviation from the K point, and $m_i = (\omega_{q+}^i - \omega_{p-}^i)/2v_{Di}^2$ represents the effective mass and is proportional to the frequency interval between two eigenstates φ_{q+}^i and φ_{p-}^i . The

valley Chern number can be obtained by the numerical integration of the Berry curvature around the valley, $C_K^i = \frac{1}{2\pi} \int \Omega(\mathbf{k}) d^2k = \frac{1}{2} \text{sgn}(m_i)$. As shown in Fig. 2(b), the signs of m_i are opposite for the band gaps I and II. At the domain wall between two VSCs with opposite AVH phases, the difference between the valley Chern numbers of two VSCs are quantized (that is, $|\Delta C_K^i| = 1$), which guarantees a pair of topological kink states propagating along the domain wall at each band gap.

Figures 2(c) and 2(d) show the distributions of the pressure amplitude field of the eigenstates $K1$ – $K8$ [Fig. 2(b)]. For the band gap I [Fig. 2(c)], the pressure amplitude distributions for the eigenstates $K1$ and $K4$ are almost the same, and so are the eigenstates $K2$ and $K3$. Moreover, the sound vortices are centered at the phase singular point p (blue circular arrows) for the $K1$ and $K4$, but at the point q (red circular arrows) for the $K2$ and $K3$, which shows the typical characteristic of band inversion for the two VSCs with opposite rotation angles. The corresponding sound vortices of the eigenstates can be adopted to mimic spin states of electron. For the band gap II [Fig. 2(d)], the characteristics of the eigenstates $K5$ – $K8$ are opposite to those of the eigenstates $K1$ – $K4$ [Fig. 2(c)], which demonstrates that the signs of m_i of the band gaps I and II are opposite. The AVH phase transitions between both VSCs for the band gaps I and II can be adopted to realize the topological valley transport. Moreover, different from the band gap I, there exists another type of acoustic vortex in each eigenstate for the band gap II, in which its chirality (green circular arrows) is opposite to that at the corresponding point p or q .

C. Dispersion and robustness characteristics of valley kink states

The experimental sample consisting of the VSC-A and VSC-B are shown in Fig. 3(a), and the simulated dispersions around the band gaps I and II are shown in Figs. 3(b) and 3(c), respectively. As shown in Fig. 3(b), for the band gap I, a pair of kink states (φ_1^- and φ_1^+) exist inside the bulk band gap. Note that both kink states have the same acoustic velocity, but propagate in the opposite directions. As an example, the group velocity of φ_1^+ (corresponding to the projection of the valley K) is positive, because the valley Chern numbers of the lower

FIG. 2. (a) Dispersions of VSCs consisting of TLRs with $\theta = 0^\circ$ (black solid lines) and $\theta = 5^\circ$ (color dashed lines). Yellow regions are the band gaps I and II for $\theta = 5^\circ$. Inset on the left shows blue and red TLRs with $\theta = 0^\circ$ and 5° , respectively, and labels p and q are two inequivalent triangular-lattice centers. Inset on the right is the first Brillouin zone. (b) Band-edge eigenfrequencies of two states at the K point with different θ . Different acoustic insulating phases are determined by their signs of the effective mass $\text{sgn}(m) = \text{sgn}(\omega_{q^+} - \omega_{p^-})$, in which the subscripts q^+ and p^- represent the anticlockwise and clockwise vortex pseudospins of energy flux around the points q and p , respectively. Simulated distributions of pressure amplitude field of the eigenmodes (c) at the points $K1$ – $K4$ for the band gap I and (d) at the points $K5$ – $K8$ for the band gap II in (b). Blue and red circular arrows are energy flow directions at the points p and q , respectively, and green circular arrows in (d) are energy flow directions of another acoustic vortex.

band for the VSC-A and VSC-B around the valley K are $1/2$ and $-1/2$, respectively, and thus the variation of the valley Chern number $\Delta C_K^I = C_K^I(\text{VSC-A}) - C_K^I(\text{VSC-B}) = 1$. However, for the band gap II [Fig. 3(c)], the slope signs of the dispersion bands are opposite to their counterparts of the band gap I. This is because the valley Chern numbers of the corresponding lower band for the VSC-A and VSC-B around the valley $K(K')$ are $-1/2(1/2)$ and $1/2(-1/2)$, respectively, and therefore the corresponding variations of the valley Chern numbers are contrary to those of the band gap I. More interestingly, due to the opposite valley Chern numbers at K/K' valley for the two band gaps, it provides feasibility basis for obtaining a double valley-locking phenomenon in a single propagation direction of the domain wall.

We then experimentally demonstrate the existence of the valley kink states at both band gaps, and the experimental setup is shown in the Supplemental Material [38]. Figures 3(d) and 3(e) show the measured dispersions of the kink states in

the band gaps I and II, respectively, in which the dark and bright thermal colors refer to the low and high amplitudes of the spectra. By scanning the pressure distributions along the domain wall of the VSCs [green dashed line in Fig. 3(a)], the measured dispersions can be obtained by applying Fourier transform. As shown from Figs. 3(d) and 3(e), the measured results (thermal colors) agree well with the simulated dispersions (green lines) for the left-moving (φ_1^- and φ_2^-) and right-moving states (φ_1^+ and φ_2^+) in the band gaps I and II [Fig. 3(d)], which verifies the existence of the valley kink states for both band gaps. Furthermore, we simulate the dispersions of the valley kink states along another type of domain wall, in which the VSC-B is placed on the upper side of VSC-A (see Appendix A). The characteristics of the kink states at the domain wall are opposite to those in Figs. 3(b) and 3(c).

Beyond that, we conduct another experiment to demonstrate the robustness of the kink states along the straight and

FIG. 3. (a) Photograph of the fabricated sample consisting of VSC-A ($\theta = 5^\circ$) and VSC-B ($\theta = -5^\circ$). Green dashed line and star represent the domain wall between VSC-A and VSC-B and the point sound source, respectively. Dispersions of valley kink states along the domain wall in **a** around the bandgaps (b) I and (c) II, respectively. Dark gray regions and red solid lines represent the bulk states and the kink states $\varphi_1^\pm$ and $\varphi_{II}^\pm$ at the domain wall. Experimentally measured dispersions (thermal color) for the kink states (d) $\varphi_1^\pm$ and (e) $\varphi_{II}^\pm$, compared with the simulated ones (green solid lines).

V-shaped domain walls in two types of samples (see Appendix B). The results show that, in the band gaps I and II, the kink states can transmit through the straight and V-shaped domain walls with high transmission, and the measured transmittances for both types of the domain wall are close, indicating high robustness of the kink states.

D. Dual-band reflection-free topological refractions

Next, we experimentally demonstrate the dual-band topological refraction of the kink states from the domain wall into the ambient space at the zigzag termination. In the experiment, a point sound source at 7.9 and 19.7 kHz (the selected frequencies in the band gaps I and II) is placed at the left side of

FIG. 4. (a) Schematic of the outcoupling of the kink state projected from the valley K transmitting through the zigzag termination at 7.9 kHz based on the phase-matching condition. Black solid regular hexagon and red solid circle represent the first Brillouin zone and the equifrequency curve of air, respectively. Green star represents a point sound source. Two bottom insets are the simulated and measured distributions of intensity field transmitting through the zigzag termination at 7.9 kHz. (b) Schematic of the outcoupling of the kink state projected from the valley K' at 19.7 kHz. Measured momentum space of the kink states through the zigzag termination at (c) 7.9 and (d) 19.7 kHz. Two red dashed ellipses represent where the reflected sound energy may locate.

FIG. 5. (a) Schematic of another type of acoustic valley topological material consisting of VSC-B ($\theta = -5^\circ$) and VSC-A ($\theta = 5^\circ$), in which the VSC-B is placed on the upper side of VSC-A. Green dashed line and star represent the domain wall between two VSCs and the point sound source. (b), (c) Simulated dispersions of valley kink states along the domain wall in **a** around the band gaps I and II, respectively.

the sample consisting of the VSC-A and VSC-B. As shown in Fig. 4(a), the right-propagating kink states are projected from the valley K at 7.9 kHz. Measured and simulated far-field sound intensity distributions are shown in the bottom insets. Note that the valley kink states positively refract from the straight domain wall into the air at the zigzag termination. Moreover, we simulate the propagation characteristics of the left-propagating kink states at 7.9 kHz [38], in which the kink states are obviously projected from the valley K' .

However, as shown in Fig. 4(b), we can see that the right-propagating kink states are projected from the valley K' at 19.7 kHz, which is different from the counterpart at the band gap I. Here, it is worth mentioning that a double valley-locking phenomenon is realized in the same propagation direction of the domain wall. Additionally, there exist two directional outcoupling sound beams, showing the coexistence of positive and negative refraction. The measured results agree well with the simulated ones. To interpret this phenomenon, we introduce the first Brillouin zone and the equifrequency contour of air [black solid regular hexagons and red solid circles in Figs. 4(a) and 4(b)] which represents the relative values of the incident and refracted wave vectors (denoted as $\mathbf{K}$ and $\mathbf{k}$), respectively. By introducing the phase-matching condition to the termination interface parallel to $\mathbf{e}_{\text{zig}}$, we theoretically calculate the refraction angle θ_r of the output beams based on $\mathbf{k} \cdot \mathbf{e}_{\text{zig}} = \mathbf{K} \cdot \mathbf{e}_{\text{zig}}$ (shown in Appendix C). The resulting refraction angles θ_r are 16.4° at 7.9 kHz, and 5.5° and -46.9° at 19.7 kHz (black hollow arrows in the bottom insets), consistent with both the experimental and numerical results.

To further demonstrate the reflection-free topological refraction, we obtain the measured momentum space of the kink states at the domain wall by applying the one-dimensional spatial Fourier transform to the measured pressure distribution [Figs. 4(c) and 4(d)]. One can see that the incidence wave energy is dominant in the momentum space, but the reflection wave energy is almost negligible at both frequencies, showing an obvious reflection-free characteristic of the topological refraction. Therefore, we experimentally observe the dual-band reflection-free topological refraction of the valley kink states in our VSCs. The positive refraction at the lower band gap and the coexistence of both negative and positive refraction at the higher band gap manifest that opposite valleys separately located in two band gaps are locked to the same propagation direction, which may have potential applications in the multi-band and multidirectional topological acoustic antennas.

Finally, due to the proposed VSC-A and VSC-B constructed by the rods with two different rotation angles (θ and $-\theta$), we can realize the modulation of propagation paths arbitrarily and the design of beam splitters by simply rotating the rods, for which the simulated results are shown in the Supplemental Material [38].

III. CONCLUSIONS

In summary, we have experimentally demonstrated VSCs with topological refraction at two separated band gaps. The designed VSCs show double valley-locking phenomenon, that is, two opposite valleys are locked to the same propagation direction, but located in different band gaps. The measurement

FIG. 6. (a), (b) Simulated distributions of intensity field near the straight domain wall at 7.9 and 19.7 kHz, respectively. (c), (d) Simulated distributions of intensity field near the V-shaped domain wall at 7.9 and 19.7 kHz, respectively. Green dashed lines, arrows, and stars represent the domain walls between VSC-A and VSC-B, the acoustic propagation paths of the kink states and the point sound sources, respectively. (e), (f) Measured transmittance spectra around the band gaps I and II (black shaded regions).

of the outcoupling of the kink states into the ambient space at a zigzag termination indeed manifests the double valley-locking phenomenon. In addition, the dispersions of the kink states as well as the robust valley transport through the sharp corners at two band gaps are experimentally demonstrated. The verified VSCs with dual-band topological refraction and the robust valley transport find many practical applications, such as multiband and multidirectional sound antennas and advanced communication devices (hand-free smartphones and hearing aids with noise immunity).

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APPENDIX A: DISPERSIONS OF A SUPERCELL COMPOSED OF VSC-B AND VSC-A

Figure 5(a) shows another type of acoustic valley topological material, in which the VSC-B is placed on the upper side of the VSC-A, and the green dashed line represents its domain wall. Figures 5(b) and 5(c) present the dispersions of the valley kink states around the band gaps I and II, respectively. Similar to the results in Figs. 3(b) and 3(c), a pair of valley kink states exists inside the band gaps I and II. However, the characteristics of the valley kink states at the domain wall are opposite to those in Figs. 3(b) and 3(c).

APPENDIX B: ROBUSTNESS OF VALLEY KINK STATES

To verify the robustness of the valley kink states, we make two samples consisting of the VSC-A (upper side) and VSC-B (lower side) with the straight and V-shaped domain walls (green dashed lines), respectively. In the measurement, a point sound source (green star) at 7.9 and 19.7 kHz (the selected frequencies in the band gaps I and II) is placed at the left side of the domain wall. Comparing the results of both straight and V-shaped domain walls [Figs. 6(a)–6(d)], the kink states pass through the V-shaped domain wall with high transmission for both frequencies, and the measured transmittance spectra in the band gaps I and II (black shaded regions) for both types of domain walls are close [Figs. 6(e) and 6(f)], verifying the robustness of the valley kink states.

FIG. 7. Schematic of the calculation of the theoretical refractive angles based on the phase-matching condition at (a) 7.9 and (b) 19.7 kHz.

Moreover, as shown in Figs. 6(a)–6(d), the kink states at 19.7 kHz are much more tightly confined around the domain walls than those at 7.9 kHz. This is because the kink state has the general form $\phi = (c_1\varphi_{p^-}^i + c_2\varphi_{q^+}^i)e^{j\delta k_x x - |m_i v_{\text{DI}}| y}$, in which $|m_i v_{\text{DI}}| = |(\omega_{q^+}^i - \omega_{p^-}^i)/2v_{\text{DI}}|$ determines the exponential decay depth of the pressure amplitude away from the domain wall. The bandwidth of the gap II ($\omega_{q^+}^{\text{II}} - \omega_{p^-}^{\text{II}} = 1541$ Hz) is larger than that of the gap I ($\omega_{q^+}^{\text{I}} - \omega_{p^-}^{\text{I}} = 901$ Hz), while the Dirac velocity $v_{\text{DI}}(76.5$ m/s) is smaller than $v_{\text{DI}}(165.3$ m/s). Therefore, we obtain $\frac{|m_i v_{\text{DI}}|}{|m_{\text{II}} v_{\text{DI}}|} \approx 0.27$, which demonstrates that the decay depth of the kink states for the band gap II is much smaller than that for the band gap I.

APPENDIX C: THEORETICAL REFRACTION ANGLES

The theoretical refractive angles can be obtained based on the phase-matching condition. As shown in Fig. 7(a), the

right-moving kink state along the domain wall at 7.9 kHz is projected from the K valley, in which the value of wave vector is $|\mathbf{K}| = 4\pi/3a$. Besides, the equifrequency curve in air satisfies $|\mathbf{k}| = 2\pi f/c$. By applying the phase-matching condition to the termination interface parallel to $\mathbf{e}_{\text{zig}}$, we theoretically calculate the refraction angle θ_t of the output beams based on $\mathbf{k} \cdot \mathbf{e}_{\text{zig}} = \mathbf{K} \cdot \mathbf{e}_{\text{zig}}$.

As shown in Fig. 7(a), the theoretical refraction angle θ_{r1} can be calculated as $|\mathbf{k}|\cos(60^\circ - \theta_{r1}) = |\mathbf{K}|\cos 60^\circ$ at 7.9 kHz. Considering the lattice constant $a = 2$ cm and the air velocity $c = 343$ m/s, the refraction angle at 7.9 kHz can be calculated as 16.4° . By applying the same method, we can theoretically calculate the refraction angle θ_{r2} and θ_{r3} at 19.7 kHz [shown in Fig. 7(b)] as follows: $|\mathbf{k}|\cos(60^\circ - \theta_{r2}) = |\mathbf{K}|$ and $|\mathbf{k}|\cos(120^\circ + \theta_{r3}) = |\mathbf{K}|\cos 60^\circ$. Thus, the refraction angles θ_{r2} and θ_{r3} at 19.7 kHz are 5.5° and -46.9° , respectively.

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- [38] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevB.103.144309> for the experimental setup, the propagation characteristics of kink states projected from valleys K and K' at 7.9 kHz, and the modulation of propagation paths and design of beam splitters.