Research article

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Vortex index identification and unidirectional propagation in Kagome photonic crystals

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Abstract: Vortex field in photonic metamaterials has been revealed in recent years, which provides an extra degree of freedom to control the behavior of electromagnetic waves, such as the unidirectional propagation in topological metamaterials and orbital angular momentum multiplexing in optical fibers. Achieving topologically protected unidirectionality needs an external source either with a vortex index of $m = \pm 1$ (i.e. $2\pi m$ phase winding around phase singularity) or with a spin index of ± 1 (i.e. right- or left-handed circular polarization). However, it is still an open question on the relationship between higher-order ($|m| > 1$) vortex field and topological metamaterials. Here, we study the excitation of valley bulk states by a source with a higher-order vortex index in Kagome photonic crystals. The selection rule for the excitation of valley bulk states is derived and can be applied to predict the selective excitation of valley bulk states by a source with a higher-order vortex index. Interestingly, we find that the Fourier spectrum and the averaged Fourier spectrum of the E_z component enable us to identify the vortex index of the source. Besides, it is shown that the unidirectional edge states can be excited by a source with a vortex index of 1 or 2 in a straight or 120° detour waveguide. Our work paves the way for the demonstration of the selection rule and may have potential applications in optical mode identification.

Keywords: topological metamaterials; vortex index; selection rule; unidirectional propagation.

1 Introduction

Topological insulators are electronic materials featuring an insulating bulk but conducting edge or surface states [1, 2]. As the analogues of topological insulators in electronic systems, photonic topological insulators (PTIs) also support topologically protected edge states, which enable the realization of the robust propagation of electromagnetic waves against sharp bend and disorder [3–8]. Thus far, two-dimensional PTIs have been realized in various photonic systems, such as photonic crystals (PCs) [9–15], coupled resonator optical waveguides [16–18], bianisotropic metamaterials [19–21], uniaxial metacrystal waveguides [22], and hyperbolic metamaterials [23]. Recently, a new degree of freedom, valley, has been introduced into the photonic and phononic crystals to manipulate the flow of electromagnetic and acoustic waves [24–31]. It has been theoretically demonstrated that valley PC (VPC) can be applied to emulate the quantum valley Hall effect and hosts robust edge states that are immune to sharp bending [24, 25]. Soon after, the valley-protected edge state has been experimentally demonstrated in several kinds of photonic systems such as PCs [32–36], designer surface plasmon crystals [37, 38], and photonic lattice [39].

Apart from the robust edge state, vortex field can exist in the eigenstates of PTIs and VPCs. For example, the bulk states around the K and K' valleys of VPC can carry phase vortices with opposite vortex indexes m (i.e. $2\pi m$ phase winding around the phase singularity) [25]. These valley-contrasting phase vortices enable the selective excitation of valley bulk states, which has been demonstrated by a source with a vortex index of $m = \pm 1$ [35, 40]. Different from the spin of light that is limited to $s = \pm 1$, the vortex index of the phase vortex can be higher and be any integer up to infinity in principle (e.g. $m = \pm 2, \pm 3$). However, it is still unknown whether the vortex states in PCs can be selectively excited by a source with a higher-order vortex index.

In this work, we study the excitation of valley bulk states by a source with a higher-order vortex index and

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the unidirectional excitation of topological edge states in a Kagome PC. We demonstrate that the excitation of valley bulk states obeys a selection rule that is verified by the spatial Fourier spectra of the E_z component. Furthermore, it is shown that the vortex index of the source can be identified by the features of the Fourier spectrum and the averaged Fourier spectrum of the E_z component. For the topological edge states, the phase vortex is observed in the edge state and the sign of its vortex index is locked to the propagation direction of the edge state. Excited by a source with a vortex index of 1 or 2, unidirectional light flow propagating toward the opposite direction is achieved in a straight or 120° detour waveguide. Our results pave the way for studying the relationship between higher-order vortices and topological metamaterials.

2 Excitation of valley bulk states by a source with a higher-order vortex index

We choose the surface-wave PC [37] for the realistic design of a Kagome PC. The schematic of the designed Kagome PC is shown in Figure 1A. Figure 1A (left) shows the unit cell that consists of three aluminum rods (blue) standing on a metallic substrate (gray). Note that both the aluminum rods and the metallic substrate are considered as perfect electric conductors in the microwave region. The lattice constant a is 18.7 mm and the height of aluminum rod h is 14 mm. Figure 1A (right) illustrates the top view of the Kagome PC, where the rod diameter d is 3.7 mm. The distance between the unit cell center and the nearby

Figure 1: Bulk band structure of the Kagome PC and topological phase transition.

(A) The unit cell of the Kagome PC (left) consists of three aluminum rods standing on a metallic substrate (gray). The lattice constant a is 18.7 mm and the height of aluminum rod h is 14 mm. In the top view of the PC (right), the rod diameter d is 3.7 mm and R denotes the distance between the unit cell center and the neighboring aluminum rod. Parameters t_1 and t_2 are the amplitudes of the intracell and intercell interactions, respectively. (B) Bulk band structure of the PC when $R = R_0 = 5.4$ mm. The red dashed line denotes the light line. The degenerate bulk states at K are composed of dipole- and monopole-like modes, whose E_z field and phase φ_{E_z} are shown in (C). Top: E_z field at the plane 1 mm above the aluminum rod and at three vertical sides of the unit cell. Bottom: phase φ_{E_z} in the hexagon region. (D) Evolution of the two lowest bulk states at the K point when $\Delta R (= R - R_0)$ varies from -2 to 2 mm. The mode exchange occurs at $\Delta R = 0$ mm, indicating a topological phase transition. The insets show the top view of the unit cell with corresponding ΔR values labeled below. Here, we use different colors of rods to distinguish PCs with different ΔR values.

aluminum rod is denoted as R . We first consider the PC with $R=R_0=5.4$ mm in which the distance between the intracell aluminum rods and the distance between the intercell aluminum rods are the same. It guarantees the degeneracy between two lowest bands at the K point. This is confirmed in the calculated bulk band structure in Figure 1B, where the light line is denoted by the red dashed line. Linear Dirac cone dispersion is found around the K point and two degenerate modes are achieved at the frequency of 4.4 GHz (Figure 1B). For the degenerate bulk states at the K point, Figure 1C shows their eigenfield distributions [i.e. the out-of-plane electric fields (E_z) and their phases (φ_{E_z})]. The E_z fields on three vertical sides of the unit cell indicate that the electric fields are confined near the surface between the lower aluminum rods and the upper homogeneous air. The horizontal plane shows the fields on the plane 1 mm above the aluminum rods. It tells that the degenerate bulk states at the K point consist of one dipole-like and one monopole-like modes. For the monopole-like mode, the phase is homogeneous around the center of the unit cell; for the dipole-like mode, there is a phase vortex with $m=1$ around the center of the unit cell. Due to the time-reversal symmetry of the Kagome PC, there is also a dipole-like mode with a phase vortex of $m=-1$ at the K' point. These valley-contrasting phase vortices enable us to selectively excite the bulk states around the K or K' valley.

Next, we study the excitation of valley bulk states by a source with a higher-order vortex index. The coupling between the valley bulk state $E_z^{(m_b)}$ and the source $E_z^{(m_s)}$ can be described by the coupling parameter $C_{m_b, m_s} = \iint (E_z^{(m_b)})^* E_z^{(m_s)} d\mathbf{r}$ [26], where m_b and m_s are the vortex index of the valley bulk state $E_z^{(m_b)}$ and the source $E_z^{(m_s)}$, respectively. Due to the C_3 symmetry of the PC, the coupling parameter satisfies $\hat{C}_3 C_{m_b, m_s} = C_{m_b, m_s}$ where $\hat{C}_3$ is the $2\pi/3$ rotation operator. The $2\pi/3$ rotation introduces an extra phase term to the valley bulk state $E_z^{(m_b)}$ and the source $E_z^{(m_s)}$, namely, $\hat{C}_3 E_z^{(m_b)} = E_z^{(m_b)} e^{im_b 2\pi/3}$ and $\hat{C}_3 E_z^{(m_s)} = E_z^{(m_s)} e^{im_s 2\pi/3}$. Based on the above conditions, it can be deduced that $\hat{C}_3 C_{m_b, m_s} = C_{m_b, m_s} e^{i(m_s - m_b)2\pi/3} = C_{m_b, m_s}$, which is satisfied when $e^{i(m_s - m_b)2\pi/3} = 1$. Then, the selection rule for the excitation of bulk states is $m_s = 3N + m_b$ ($N \in \mathbb{Z}$). According to the selection rule, if the difference between m_s and m_b is an integral multiple of 3, sources with a vortex index of m_s can excite the bulk state with a vortex index of m_b . To demonstrate the selection rule, we choose the PC with $\Delta R = R - R_0 = 1.5$ mm as an example. The bulk band structure of the PC is shown in Figure 2A (right) and the complete band gap ranges from 4.29 to 4.59 GHz. The nonzero value of ΔR results in the breaking of degeneracy

at the K point, and the dipole-like mode appears at the lower band (Figure 1D). Figure 2A schematically illustrates the top view of the simulated structure for the excitation of bulk states. The green circle denotes the source. In the simulation, we set several equal-amplitude E_z point sources with proper phases to mimic a source with phase vortex. We first consider the case of the source with $m_s = -1$ at the frequency of 4.28 GHz, whose phase distribution is shown in Figure 2B₁ (left). The height of the source here and the height of the source in other simulation results are the same as the aluminum rod. The simulated electric field distribution is also shown in Figure 2B₁, where the white star at the center denotes the source. The field pattern in Figure 2B₁ and the following figures are obtained from the x - y plane 1 mm above the aluminum rod. Figure 2B₂ exhibits the φ_{E_z} pattern in the unit cell highlighted by the black box in Figure 2A. The black arrow indicates the direction of the phase gradient and m_b denotes the vortex index of φ_{E_z} . Because the vortex index of the source is the same as that of the lowest dipole-like bulk states around the K' valley, it can be inferred that the lowest dipole-like bulk states around the K' valley are excited. Therefore, the vortex index of the phase pattern in Figure 2B₂ is the same as that of the lowest dipole-like bulk states around the K' valley. In addition, the spatial Fourier spectrum amplitude of the E_z component in Figure 2B₁ gets the maximum around the K' valley in the momentum space (Figure 2B₃). It is consistent with the conclusion that the lowest dipole-like bulk states around the K' valley are excited. To characterize the variation trend of the Fourier spectrum amplitude, we define an averaged Fourier spectrum $I(k)$. $I(k)$ is calculated by integrating the Fourier amplitude in a ring region ($k - \delta k$, $k + \delta k$) and then dividing the result by the area, $2\pi k \times 2\delta k$, where $\delta k = 2\pi/(15a)$. As expected, $I(k)$ gets the maximum around the corner of the first Brillouin zone, as labeled in Figure 2B₄. Similar to the source with $m_s = -1$, sources with $m_s = 2$ and 5 also satisfy the condition $m_s = 3N - 1$ ($N \in \mathbb{Z}$), and all of them can excite the K' valley bulk states with the vortex index of -1 . Therefore, from the phase patterns in Figure 2B₂, E_2 , and H_2 , one can see that all the corresponding vortex indexes are -1 . Besides, from the Fourier spectra around the first Brillouin zone (Figure 2B₃, E_3 , and H_3), it can be seen that the bulk states around the K' valley are excited and the bulk states around the K valley are suppressed. The simulation results agree well with the conclusion inferred from the selection rule. However, from the averaged Fourier spectra in Figure 2B₄, E_4 , and H_4 , one can see that their averaged Fourier spectra are different. Compared to the averaged Fourier spectrum in Figure 2B₄, a peak emerges at $k = 6\pi/a$ in Figure 2E₄ and $12\pi/a$ in Figure 2H₄. It indicates that the Fourier amplitude

Figure 2: Excitation of valley bulk states by sources with higher-order vortex index at the frequency of 4.28 GHz.

(A) Left: top view of the Kagome PC with $\Delta R = 1.5$ mm. The green circle in the inset denotes the source. Right: bulk band structure of the Kagome PC shown in the left. (B₁) Electric field distribution of the valley bulk states excited by the source with $m_s = -1$, whereas the magnitude of the source is constant. The white star at the center denotes the source and the left inset shows the phase pattern of source. (B₂) Phase of E_z in B₁ in the unit cell highlighted by the bold black hexagon in A. The black arrow indicates the direction of phase gradient. (B₃) Spatial Fourier spectrum of the E_z component in B₁. The gray solid hexagon denotes the first Brillouin zone of the PC. (B₄) Variation trend of the averaged Fourier spectrum $I(k)$ along the radial direction in momentum space. (C–H) Same as in B but for the sources with m_s ranging from 0 to 5. Here, m_s and m_b represent the vortex index of the source and the valley bulk state, respectively.

at the momentum that is far away from the first Brillouin zone is dominant (not shown here). These differences in the averaged Fourier spectra result from the differences between vortex indexes of the sources and can help us to identify the sources with $m_s = -1, 2$, and 5.

In contrast to the case of $m_s = -1$, the lowest dipole-like bulk states around the K valley can be excited for the case of $m_s = 1$. Thus, the vortex index of the phase pattern is 1 (Figure 2D₂) and the amplitude of the spatial Fourier spectrum gets the maximum around the K valley (Figure 2D₃). Considering that both $m_s = 1$ and 4 satisfy the condition $m_s = 3N + 1$ ($N \in \mathbb{Z}$), sources with $m_s = 1$ and 4 can excite the bulk states around the K valley. Both the simulated phase pattern in Figure 2G₂ and the Fourier spectrum in Figure 2G₃ indicate that the bulk states around the K valley are excited by the source with $m_s = 4$. Compared to the case of $m_s = 1$ (Figure 2D₄), the position of the maximum value of the averaged Fourier spectrum shifts to the k value around $10\pi/a$ in the case of $m_s = 4$ (Figure 2G₄). This difference also enables us to identify the sources with vortex indexes of 1 and 4. Finally, for the case of $m_s = 0$ or 3, neither $m_s = 3N + 1$ nor $m_s = 3N - 1$ ($N \in \mathbb{Z}$) can be satisfied, so a source with $m_s = 0$ or 3 cannot excite the bulk states around the K or K' valley. Thus, for cases of $m_s = 0$ and 3, the electric fields are localized around the source (Figure 2C₁ and F₁) and the amplitude of the Fourier spectrum (Figure 2C₃ and F₃) is near zero at both K and K' valleys. The excitation is totally suppressed at K and K' points, whereas the surrounding states are weakly excited due to the finite-size effect of the PC. For the case of $m_s = 0$, the averaged Fourier spectrum gets the maximum around the corner of the first Brillouin zone (Figure 2C₄), whereas the averaged Fourier spectrum for the case of $m_s = 3$ gets the maximum around $k = 8\pi/a$ (Figure 2F₄). This difference enables us to identify the sources with vortex indexes of 0 and 3. According to the above results, the vortex index of the source (from $m_s = -1$ to 5) can be identified by the Fourier spectrum around the first Brillouin zone and the averaged Fourier spectrum. First, according to the Fourier spectra around the first Brillouin zone, we can identify whether m_s belongs to $3N - 1$, $3N$, or $3N + 1$ ($N \in \mathbb{Z}$). Then, for the cases with similar corresponding Fourier spectra around the first Brillouin zone, such as $m_s = -1, 2$, and 5, they can be identified by their corresponding averaged Fourier spectra.

3 Unidirectional excitation of topological edge states

For the Kagome PC, a topologically trivial or nontrivial band gap can be obtained by shrinking or expanding the

aluminum rods within the unit cell. A two-band effective Hamiltonian can be adopted to describe the band topology of the two lowest bands. Around the K point, the two-band effective Hamiltonian can be expressed in a general form [41, 42]:

$$H = \begin{pmatrix} d_z & d_x - id_y \\ d_x + id_y & -d_z \end{pmatrix} = \vec{d}(k) \cdot \vec{\sigma}, \quad (1)$$

where

$$\begin{aligned} d_x &= \frac{t_2}{3} \left[\cos\left(\frac{k_x a}{2}\right) \cos\left(\frac{\sqrt{3}k_y a}{2}\right) + \sqrt{3} \sin\left(\frac{k_x a}{2}\right) \cos\left(\frac{\sqrt{3}k_y a}{2}\right) \right. \\ &\quad \left. - \cos(k_x a) + \sqrt{3} \sin(k_x a) \right], \\ d_y &= \frac{t_2}{\sqrt{3}} \left[\sqrt{3} \cos\left(\frac{k_x a}{2}\right) \sin\left(\frac{\sqrt{3}k_y a}{2}\right) - \sin\left(\frac{k_x a}{2}\right) \sin\left(\frac{\sqrt{3}k_y a}{2}\right) \right], \\ \text{and } d_z &= \frac{3t_1}{2} + t_2 \left[\frac{1}{2} \cos(k_x a) - \frac{\sqrt{3}}{3} \sin\left(\frac{k_x a}{2}\right) \cos\left(\frac{\sqrt{3}k_y a}{2}\right) \right. \\ &\quad \left. + \cos\left(\frac{k_x a}{2}\right) \cos\left(\frac{\sqrt{3}k_y a}{2}\right) + \frac{\sqrt{3}}{6} \sin(k_x a) \right] \end{aligned}$$

$\vec{\sigma}$ are the Pauli matrices. t_1 and t_2 signify the amplitudes of the intracell and intercell interactions, respectively. For this Hamiltonian, the Berry curvatures of the upper band (+) and lower band (−) are $\vec{\Omega}_{\pm} = \mp \frac{1}{2} \frac{\vec{d}}{|\vec{d}|^3}$ [43]. Then, we can define the winding number as [41]

$$w_{\pm} = \frac{\iint_S \vec{\Omega}_{\pm} \cdot d\vec{s}}{4\pi} = \pm \frac{1 - \text{sign}(t_1 - t_2)}{2}, \quad (2)$$

where S is the orientated area in Pauli vector space. One can see that the winding number is determined by the difference between the intracell interaction amplitude t_1 and the intercell interaction amplitude t_2 . When $t_1 = t_2$, two bands are degenerate at the K point and there is no band gap. A gap will open for PCs with $t_1 \neq t_2$. When $t_1 > t_2$, we have zero winding numbers $w_{\pm} = 0$, meaning that the gap is topologically trivial. On the contrary, when $t_1 < t_2$, $w_{\pm} = \pm 1$, which indicates that the gap is topologically nontrivial. Note that the magnitude of t_1 (t_2) is inversely proportional to the distance between the intracell (intercell) aluminum rods. Thus, a topologically trivial or nontrivial band gap can be obtained by tuning the distance between the aluminum rods. For example, starting from the case of $t_1 = t_2$, a topologically nontrivial band gap can be obtained by expanding the three aluminum rods inside the unit cell. To show the topological phase transition, we calculate

the evolution of two lowest modes at the K point as a function of ΔR (i.e. $R - R_0$; Figure 1D). These two modes are classified into monopole- or dipole-like mode by checking their phase patterns. When $\Delta R < 0$ (i.e. shrinking three aluminum rods inside the unit cell), a topologically trivial band gap opens. The frequency of the monopole-like mode (blue curve) is lower than that of the dipole-like mode (red curve). On the contrary, when $\Delta R > 0$ (i.e. expanding three aluminum rods), the frequency of the monopole-like mode is higher than that of the dipole-like mode. It indicates that, after the band inversion, a topologically nontrivial band gap is obtained. Topologically nontrivial band gap guarantees the existence of topological edge states at the edge between PCs with nontrivial and trivial band gaps. Here, we use the PCs with $\Delta R = -1.5$ and 1.5 mm to construct the edge (Figure 3A). The band dispersion is shown in Figure 3B, where the gray regions shade the bulk modes. Two red dots highlight the edge states with the frequency of 4.36 GHz at $k_x = \pm 0.32 \times 2\pi/a$. We plot the $|E_z|$ and φ_{E_z} patterns of these two edge states (Figure 3C). From the $|E_z|$ patterns, one can see the electric field is confined near the edge. For the φ_{E_z} patterns,

the plot regions are highlighted by the white dashed box and the black arrow indicates the direction of phase gradient. A phase vortex with $m_e = -1$ ($m_e = 1$) is observed for the edge state at $k_x = -0.32 \times 2\pi/a$ ($k_x = 0.32 \times 2\pi/a$). Because edge states with opposite k values have opposite group velocities, the propagation direction and the sign of the vortex index are locked together. It indicates the unidirectional edge state can be selectively excited by the source with a vortex index of 1 or -1 .

To demonstrate the excitation of the unidirectional edge state, we consider a straight edge (Figure 4A). The region denoted by the black dashed box is zoomed in to show the position of the source (green circle), which lies at the phase singularity in Figure 3C. The electric field of the edge state excited by a source with $m_s = 1$ is shown in Figure 4B, where the white star denotes the source and the white arrow indicates the direction of the excited edge state. Note that the energy flow propagates toward right, indicating the selective excitation of the rightward edge state. Figure 4B (inset) shows the φ_{E_z} pattern in the region denoted by the white dashed box. It shows that the phase vortex still exists as the unidirectional edge state propagates. Interestingly, for the

Figure 3: Topologically protected edge states in the Kagome PC.

(A) Top view of the edge formed by the PC with $\Delta R = 1.5$ mm (blue) and -1.5 mm (purple). (B) Band dispersion of the edge states, where two red dots highlight the representative edge states with the frequency of 4.36 GHz at $k_x = \pm 0.32 \times 2\pi/a$. The gray region shades the other modes. (C) $|E_z|$ and φ_{E_z} of the edge states at $k_x = -0.32 \times 2\pi/a$ (left) and $k_x = 0.32 \times 2\pi/a$ (right). The black arrow indicates the direction of phase gradient.

Figure 4: Excitation of unidirectional edge states at the frequency of 4.36 GHz.

(A) Schematic of the straight edge in the x - y plane. The magnified region in the right side shows the position of the source. (B) Rightward and (C) leftward unidirectional edge states excited by the source with $m_s = 1$ and 2 , respectively. The white star denotes the source and the white arrow indicates the direction of the energy flow. The inset shows the φ_{E_z} distribution in the region denoted by the dashed white box. The black arrows denote the direction of the phase gradient. Schematic of a 120° sharp bend edge with the bend in the (D) right and (F) left sides of the source. (E) Rightward and (G) leftward unidirectional edge states excited by the source with $m_s = 1$ and 2 , respectively.

source with $m_s = 2$, it can excite the edge state that propagates leftward (Figure 4C). The origin of this phenomenon needs further investigation. Figure 4C (inset) shows the φ_{E_z} pattern in the region denoted by the white dashed box. It also shows that the phase vortex still exists as the unidirectional edge state propagates leftward. We also design an edge with a 120° sharp bend to demonstrate the robustness of topological edge states (Figure 4C and F). In the case of $m_s = 1$ and 2 , the unidirectional edge state can circumvent the 120° sharp bend and propagate forward (Figure 4E and G), verifying the edge state's robustness. Figure 4E and G (inset) shows the φ_{E_z} patterns in the regions denoted by the white dashed box and indicates that the phase vortex still exists even when the unidirectional edge state circumvents the sharp bend.

4 Conclusion

In conclusion, we demonstrate a selection rule for the excitation of valley bulk states by a source with a

higher-order vortex index. With the help of the selection rule, it is possible to identify the vortex index of the source by the Fourier spectrum and the averaged Fourier spectrum of the E_z component. Besides, the excitation of unidirectional edge states by a source with $m_s = 1$ or 2 in both the straight and 120° sharp bend edges is demonstrated. It is shown that the phase vortex in the edge state still exists as the unidirectional edge state propagates. Our design paves the way for the direct observation of valley bulk state excitation by a source with a higher-order vortex index. Furthermore, our work also provides another perspective for distinguishing the phase vortex with different vortex indexes.

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