Tunable topological valley transport in two-dimensional photonic crystals

Yujing Wang, Weixuan Zhang and Xiangdong Zhang

Key Laboratory of Advanced Optoelectronic Quantum Architecture and Measurements of Ministry of Education, School of Physics, Beijing Institute of Technology, 100081, Beijing, People’s Republic of China
E-mail: zhangxd@bit.edu.cn

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1. Introduction

During the past few years, there has been a great deal of interest in studying valleytronics, where the valley degree of freedom (DOF) is used as a new carrier to process information in electronic devices [1–9]. Many intriguing phenomena have been unveiled in the electronic crystals such as the valley Hall effect, valley-selective excitation, topologically protected valley edge states and so on [3, 10–13]. Meanwhile, the control of currents by manipulating the valley DOF has been successfully realized in novel electronic devices such as the valley splitter and the valley valve [1, 14].

Analogous to the valleytronics, the study of valley DOF for classical waves, which existed in photonic (PCs) and sonic crystals, has also received increasing amount of attentions in recent years. Numerous fascinating phenomena associated with the bulk valley transport have been demonstrated, such as the notable vortex nature in eigen-states, valley-selective excitation, and chirality-locked beam splitting behavior [15–17]. In addition, the valley-projected edge states have also been theoretically proposed and experimentally observed in the photonic [18–21] and acoustic systems [22, 23], where the reflection immunity to the sharp corners has been clearly demonstrated. However, these phenomena were observed in the structures with fixed parameters. In fact, in many practical applications, it is expected that the phenomena can be tuned by external factors such as external electric fields. Therefore, it is extremely necessary to develop a solution that the valley transport of electromagnetic fields can be dynamically modified without changing structural parameters. In this consideration, the tunable electromagnetic flow control in microwave region has been demonstrated by employing the valley DOF in a topological photonic crystal waveguide [24] and a reconfigurable valley PC composed of barium titanate has also been proposed [25].

Owing to the electro–optics effect, liquid crystal (LC) is usually selected as an electric–controlled material to manipulate electromagnetic fields. The orientation of the principal axis of nematic LC molecules, which decides the corresponding anisotropic permittivity, depends on the external electric field when the external voltage is larger than the critical voltage [26]. Thus, the refractive index of LCs is easily to be controlled by the external electric field. Based on this unique characteristic, LC is often used to achieve electrically tunable photonic...
The question is whether LCs can be used to design valley PC with tunable bulk and edge states? In this work, we introduce LCs into the design of valley PCs and explore the possibility to realize electrically tunable valley-based photonic devices. Electrically controlled valley-selective excitation, valley-locked beam splitting behavior and valley-projected edge transport of electromagnetic fields have been numerically demonstrated with finite element methods. Moreover, a switchable valley filter device has also been designed. The advantage of these devices is that they can work in a broad range of terahertz (THz) frequency region. THz waves are actively explored for fundamental research and applications. However, due to the lack of materials and technology, it is difficult to fabricate efficient and widely tunable THz devices. Thus, the present work is of great significance in the THz research. The rest of the paper is organized as follows: the numerical results of tunable bulk valley transport are provided in section 2. The discussion on tunable topological interface states is given in section 3. The design of valley-based device is described in section 4, together with a brief summary in section 5.

2. Tunable bulk valley transport

Note that bulk valley transport has been recently demonstrated for electromagnetic fields in valley PCs. In this section, we propose a tunable valley PC by using a hexagonal array of regular triangular metal rods immersed in LC environment and enclosed between two conducting electrodes, as shown in figure 1 (a). The steerable functionality is realized by tuning the refractive index of the background LCs with the help of an external electric field supplied by the electrodes. The above tuning mechanism we used is applicable in the mid-infrared regime where the typical size of a PC cell size is of the order of a few micrometers. In practical, reorientation of the LC molecules infiltrating the structures on this scale has been shown to be feasible [32–35]. Here, only transverse-electric-polarized waves are considered. In this case, a simplified two-dimensional model can be used to characterize the wave behavior.

The lattice constant of the unit cell is taken as $a = 6.5 \text{ um}$ throughout the paper and the side length of each triangular rod is marked as $b$. The angle $\alpha$, measured with respect to the $x$-axis, characterizes the orientation of
the meta-atom, which provides a flexible control of the band-gap by gradually breaking the in-plane mirror symmetry of the valley PC system [36]. For $\alpha = m\pi/3$, with $m$ being an integer, the point group at $K$ (and $K'$) is featured by $C_3v$ symmetry because of the perfect match of the in-plane mirror symmetry between the triangular-lattice and the meta-atom. Except for the specific angles, the mirrors are mismatched and the symmetry reduces to $C_3$. Thus, a two-fold Dirac degeneracy is protected at $K$ (and $K'$) for any valley PC with $\alpha = m\pi/3$, while an omnidirectional gap would be opened for any other rod orientation because of the broken mirror symmetry. Additionally, there are many other methods to break the $C_3v$ symmetry of the system. For example, using different structural parameters of two cylinders in the unit cell for honeycomb lattice to open a gap at $K'(K')$ [37, 38]. Both of these methods are aimed to break the $C_3v$ symmetry, while, the method of rotating the triangles is more simple and intuitive.

The dynamic regulation of the valley state can be realized by modifying the orientation of the LC molecules. When the external voltage is applied to the two electrodes, the orientations of nematic LC molecules can be aligned along the z-direction (corresponding to the ON-state), as shown in figure 1(b). In this case, the background refractive index of $n_{bkg} = 1.45$. If no voltage is applied, the orientation of nematic LC molecules is perpendicular to the trigonal rods (corresponding to the OFF-state), as shown in figure 1(c). The background refractive index $n_{bkg} = 1.75$. Based on the tunable property of the LC permittivity, the tunable excitation of bulk valley states and switchable chirality-locked beam splitting can be realized.

Figure 2(a) shows calculated photonic band structures for LC-embedded valley PCs, as displayed in figure 1(a), using finite-element methods (COMSOL Multiphysics). Here the rotation angle and side length of each triangular rod are taken as $\alpha = 10^\circ$ and $b = 0.78a$, respectively. The blue (red) line corresponds to the case where the external voltage is turned on (off) with the refractive index of LC being $n_{bkg} = 1.45$ ($n_{bkg} = 1.75$). Due to the mismatch of mirror symmetries between the lattice and scatterers ($\alpha = 0^\circ$), the original degenerate Dirac points located at the two valleys ($K$ and $K'$) were gapped [36]. Here, only $K$-valley is presented. The gapped valley states are labeled by $K_a(14.06$ THz) and $K_b(16.99$ THz) for the case of $n_{bkg} = 1.45$. And, those are expressed by $K_a(11.64$ THz) and $K_b(14.06$ THz) when $n_{bkg} = 1.75$. By suitably designing the structure parameters, it is interesting to show that the frequencies for $K_a$ and $K_b$ states can be tuned identically. Consequently, we can selectively excite either $K_a$ or $K_b$ state at the same frequency just by turning on/off the external voltage. It is worthy to note that the change of the background index does not modify the topological properties of the valley state, but shifts the spectral position of the band gap.

Similar to the previous investigations of electronic valley states, these photonic valley states also exhibit exotic chirality. This can be directly observed from distributions of the corresponding eigen-fields, as shown in figure 2(b), where the top and bottom panels display the phase and amplitude of the eigen-fields at $K_a$ and $K_b$ states. It is clearly shown that the right- (left-) hand phase singularity appears at the spatial position of $q (p)$ point for $K_a (K_b)$ states. The typical chiral feature can also be clearly presented with time-averaged Poynting vectors, as shown in the lower panels of figure 2(b) with black arrows. The Poynting vector rotates clockwise for the $K_a$ valley state and anticlockwise for the $K_b$ valley state, which means that the chirality of $K_a$ state and $K_b$ state is reversed. Similar phenomena can also be observed for the $K_c$ state and $K_d$ state. According to the analysis in [15], these phase singularities can be characterized by the nonzero angular quantum numbers (AQNs) $n$. Here, $n = -1$ for $K_a$ and $K_c$ states and $n = +1$ for $K_b$ and $K_d$ states.

In electronic system, circularly polarized light couples only to a specific valley and thus different valley can be excited [39]. Similarity, photonic valley states with different chirality can be directly excited by a point-like source with proper chirality based on the azimuthal phase matching condition (i.e. a valley state can be picked out only if its AQN is identical to that of the source located at the specific triangular lattice center) [15, 37]. The point-like chiral source can be realized by a subwavelength circular array of identical point-sources with proper phase lags. As shown in the panel of figures 2(c), (d), the source with AQN being $n = -1$ (+1) is designed using a $\pi/2$ phase delay among neighboring antennas anticlockwise (clockwise). In experiments, this chiral source has also been realized by using a four-antenna array with discontinuous phases [40]. In this consideration, to excite the $K_a$ state, a point-like right-handed chiral source ($f = 14.06$ THz) with AQN being $n = -1$ needs to be positioned at the $q$ point in the center unit cell of the designed PC and the external voltage should be turned on. The corresponding numerical result is shown in the figure 2(c). When the external voltage is turned off, the $K_b$ state is able to be stimulated at the same frequency with a left-handed chiral source (AQN being $n = +1$) locating at the $p$ point in the center unit cell of the PC structure, as shown in the figure 2(d). From the above result, we find that the tunable excitation of valley bulk states can be easily achieved by turning on/off the external voltage at the fixed frequency. Note that in order to avoid the inter-valley scattering at the boundary of PCs, a regular triangle sample should be selected so that the surface orientation is along the $\Gamma M$ direction [15, 37].

The vortex nature is not only limited to the valley point at the corner of the FBZ ($K$ and $K'$), but remains rather well with slightly deviating from these corner points. Intriguingly, as the frequency deviates from the band edge, the trigonal warping effect gradually emerges, which makes it possible to separate the vortex states with
opposite chirality to different spatial regions, e.g. the valley-chirality locked beam-splitting effect [15]. Based on this novel effect, we further use the structure, shown in figure 1(a), to realize the dynamic control of the chirality-locked beam splitting phenomenon. As shown in figure 3(a), we calculated the band structure with different background refractive index (red line for \(n_b = 1.75\) and blue line for \(n_b = 1.45\)) of the valley PC with \(\alpha = 10^\circ\) and \(b = 0.45a\). The corresponding isofrequency contours (\(f = 15.96\) THz, labeled with the dashed line in figure 3(a)) are shown in figures 3(b) and (c). It is clearly shown that the trigonal warping effect can always happen at this frequency with appropriate structure design no matter the external voltage being applied or not.

To simulate the beam-splitting effect locked by valley-chirality, an incident Gaussian beam (of a width \(\sim 3a\) and frequency of 15.96 THz), which is narrow enough to cover a broad range of momentum distribution, should be used to illuminate the bottom boundary of valley PC based on the principle of momentum conservation [15, 16, 38]. Figure 3(d) shows the results with the external voltage being turned off. We find that the bulk states around the \(K\) and \(K'\) points are excited simultaneously and separated in different spatial regions. If we turn on the external voltage, the bulk valley states around the \(K\) and \(K'\) points can also be excited, as shown in figure 3(e). However, the directions of their propagation are interchanged, e.g. the \(K'\) and \(K\) valleys are responsible for the right- and left-moving beams, respectively. In this case, the emitted beam can also change from negative refraction to positive refraction.

The tunable valley-chirality locked beam-splitting effect can be clearly understood based on the group velocity analysis. The propagation direction of the incident wave is perpendicular to the isofrequency contour and points to the direction in which the frequency is increased. When the external voltage is turned off, only the valley state on the second energy band can be excited at 15.96 THz. In this case, the direction of frequency

![Figure 2. Electrically controlled valley-selective excitation. (a) The band structures of the PC for the cases of applying voltage (blue line) and no voltage (red line), with the rotation angle \(\alpha = 10^\circ\) and the length \(b = 0.78a\). Specially, \(f_{K_A} = f_{K_B} = 14.06\) THz. (b) Field distributions for the valley states \(K_A\) (left) and \(K_B\) (right), where the top and bottom panels display (by color) the phase and amplitude patterns, respectively. The additional arrows in the bottom panels indicate the corresponding Poynting vectors. (c) The field distribution stimulated by a chiral source of AQN \(n = -1\) and frequency \(f = 14.06\) THz positioned in the center of PC (i.e. one of the equivalent \(q\) points) when applied voltage. The upper-left panel is the schematic diagram of the chiral source (AQN \(n = -1\)) designed using a four-antenna array with discontinuous phases, where the phase increases anticlockwise between neighbors by \(\pi/2\). (d) The field distribution stimulated by a chiral source of AQN \(n = 1\) with same frequency positioned in the one of the equivalent \(p\) points for the case when there is no voltage applied. The upper-right panel is the schematic diagram of the chiral source (AQN \(n = 1\)) designed using a four-antenna array with discontinuous phases, where the phase increases clockwise between neighbors by \(\pi/2\).]
increased points away from the valley center with red (K) and green (K') arrows, as shown in figure 3(b).

Consequently, the left-moving (right-moving) beams inside the valley PC corresponds to the bulk state near the K' (K) point. If we turn on the external voltage, only the valley state on the first energy band can be excited at the same frequency. In this case, the increased frequency within the isofrequency contour points to the valley center (shown in figure 3(c) with red (K) and green (K') arrows). Hence, the propagation directions of K and K' states are interchanged. The electrically controlled valley-dependent beams could be used to control the flow of electromagnetic fields and might be applied to carry information in valley polarized beam splitter, collimator or guiding device.

3. Tunable topological interface states

The above discussions only focus on the tunable bulk valley transportation. In fact, we have also designed the valley PCs with tunable topological interface states. Different from the bulk state excitation, two valley PCs with distinct valley Hall phase should be spliced. In this case, the valley-dependent topological interface states are supported [37]. It has been demonstrated that the valley Hall phase transition can be triggered by simply rotating scatterers [15]. As shown in figure 4(a), we design such a domain wall along the x direction marked by the black dashed line. The two parts with different valley phases A (the angle of rotation is \( \alpha_1 = 30^\circ \)) and B (the angle of rotation is \( \alpha_2 = -30^\circ \)) are both immersed in LC environment and enclosed between conducting electrodes. The side length of each triangular rod is taken as \( b = 0.78a \).

Figures 4(b) and (c) present calculated dispersion relations (color lines) for the PC interfaces separating two topologically distinct AVH insulating phases when the external voltage is turned on and off, respectively. Specifically, states labeled by \( \phi^0_{AB} \) and \( \phi^0_{AB}' \) correspond to the edge states predicted on the interfaces AB in the two cases, where the signs ± indicate the interface modes traveling along the \( \pm x \) directions. The AQN \( n = +1 \) can be found to be carried by \( \phi^0_{AB} \) and \( \phi^0_{AB}' \) states, while \( n = -1 \) is carried by \( \phi^0_{AB} \) and \( \phi^0_{AB}' \) states. Thus, the propagating direction of the interface state also depends on the carried AQN. Similar to the tunable bulk valley state, in the following, we numerically prove that the topological edge states can also be selectively excited by just turning on/off the external voltage at a fixed frequency (\( f = 18.50 \) THz). Firstly, we locate a left-handed chiral source with the AQN being \( n = +1 \) at the p point near the interface between domain A and B when the external voltage is applied \( (n_{bg} = 1.45) \). In this case, only \( \phi^0_{AB} \) valley state can be selectively excited due to the AQN matching well with the applied chiral source. As shown in figure 4(d), the unidirectional wave propagation (along +x direction) appears. The excited valley edge can be easily disturbed by just turning off the external voltage \( (n_{bg} = 1.75) \). In this case, the spectral gap gets red shift so that the bulk state is excited, as shown in

**Figure 3.** Electrically controlled valley-locked beam splitting behavior. (a) The band structures of the PC for the cases of applying voltage (blue line) and no voltage (red line), with the rotation angle \( \alpha = 10^\circ \) and the length \( b = 0.45a \). At frequency 15.96 THz (dashed line), the notable trigonal warping effect emerges in the isofrequency contour whether the voltage is applied or not. (b) and (c) The trigonal-like equifrequency contours at a frequency slightly above \( K_B \) (b) or below \( K_c \) (c), i.e. 15.96 THz. Directions of group velocity for \( K(K') \) valley are marked with red (green) arrows. (d) and (e) Amplitude distribution of the field simulated for a narrow Gaussian beam incident normally from the bottom at 15.96 THz when the external voltage is turned off and on, respectively.
Similarly, the switchable excitation for the other valley edge state ($\phi^{+\text{AB}}$) can also be realized with the same scheme where the applied right-handed chiral source ($n = -1$) should be used, as shown in figures 4(f) and (g). This controllable one-way valley edge state can be regarded as a topological optical switch. In addition, for the tunable topological interface states, the source is allowed to have a certain bandwidth as long as it locates within the bandgap of the system. This is due to the fact that the unidirectional interface states almost exist in the whole bandgap.

Compared with non-topological photonic crystals with nematic control, the unidirectional edge states are robust to some structural defects, which are clearly displayed in figures 4(d) and (f). It is clearly shown that the excited valley edge state can pass through the sharp corner without backscattering. This system has a certain anti-jamming ability, which has more practical application significance. For example, a topological optical switch can be proposed and realized using above tunable topological interface states because of a balance between the flexibility of devices and the robustness of topological properties.
4. The design of the valley devices

In the previous investigations, the valley devices have been designed based on PCs with fixed parameters. Here, we combine the tunable bulk valley transport and topological interface states discussed above to realize a tunable bulk valley filter. We design a composite PC module as depicted in figure 5(a), which consists of A, B, C1 and C2. Here, C1 and C2 (turning C1 over 180°) represent PCs similar to the structure depicted in figure 1(a) except that the rotation angle and side length of each triangular rod are taken as $\alpha = 15^\circ$ and $b = 0.377a$, respectively. A domain wall is constructed by PC A and B (the same structural parameters as section 3) to conduct information of valley and it is connected to the PC C1 and C2. Figure 5(b) displays the band dispersion for the structure C1 (C2) when the external voltage is turned on (blue line) and off (red line). (c) and (d) The simulated fields show that the $K_a$ ($K'_a$) valley state of PC C1 (C2) is excited by the topological interface state $\phi_{AB}$ ($\phi'_{AB}$) using a chiral source with AQN being $n = -1 (+1)$ when the external voltage is turned on. (d), (f) The excited $K_a$ ($K'_a$) valley state can be easily disturbed by just turning off the external voltage.

5. Discussion and conclusion

Although our work focuses on the theoretical design of the tunable valley state excitations, it can also be achieved practically. As many previous works about the realization of tunable nano-devices based on the electro-optics effect of LCs [41, 42], our proposed structures are also able to be fabricated with the help of modern nano-
machining technologies. In addition, the special requirement for the excitation of valley states can be easily solved by using point-like chiral sources composed of four-antenna with proper phase lags and narrow Gaussian beams. Recently, a very clever way to effectively excite the valley states in near-infrared range has been proposed, where a microdisk is used as a phase vortex generator [38].

Our designed structures can be scaled to work in a broad range of THz frequency region. The THz technology is of great importance in information technology, medicine and nondestructive evaluation [43–45]. For example, the THz spectral region offers higher available bandwidth that is imperative for meeting the ever-growing demand for higher data rates and the THz spectral band has the potential to achieve terabits/s data rates over a kilometre distance [46, 47]. Constructing THz communication systems, some THz devices such as switchable beam splitter and filter are indispensable. However, such devices have always been scarce at present. Besides, these devices possess weak anti-jamming capability, which is susceptible to external disturbances, reducing the signal-to-noise ratio. The devices we designed, such as topological switch, can solve this problem very well and improve communication efficiency. Thus, our designed tunable THz valley devices are expected to play an important role in future THz communication.

In conclusion, we have designed a tunable valley PC using an array of regular triangular metal rods embedded in LCs. By using the electro-optic effect of LC, the dynamic control of valley transport in the PCs has been studied systematically and comprehensively, including electrically controlled valley-selective excitation, valley-locked beam splitting behavior and valley-projected edge transportation, so as to flexibly control the propagation of electromagnetic fields inside bulk PCs and the interface between two PCs with distinct valley Hall phase. This is highly beneficial to the design of photonic devices, such as a topological optical switch, because the flexibility of devices and the robustness of topological properties have been realized successfully.

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ORCID iDs

Weixuan Zhang @ https://orcid.org/0000-0003-2459-8134
Xiangdong Zhang @ https://orcid.org/0000-0002-7725-8814

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