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Research Highlight

Zero chiral bulk modes in 3D Weyl metamaterials

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In the Weyl semimetals, a special type of one-way chiral zero mode (CZM) can be supported if a strong magnetic field is applied. The corresponding CZM is related to the zero-order Landau level for relativistic particles in Dirac or Weyl systems. This special energy level can lead to chiral anomaly, which describes the phenomenon of breaking the conservation of chirality [1]. Under the action of an effective magnetic field, the zeroth Landau mode can be expected to propagate only in the chiral direction according to the chirality (left-handed or right-handed) of the Weyl points and the magnetic field direction. Distinguished from the topological insulators, such a one-way propagation mode is a bulk state rather than a surface state or edge state that travels along the interface. Recently, the discovery of Dirac or Weyl degeneracies in the electronic and photonic systems brings opportunities for experimental detection of the chiral zeroth Landau levels [2,3]. Notwithstanding, the chiral Landau level in the 3D photonic system has not been observed yet.

To form the CZM, it is crucial to establish an effective magnetic field, which is closely correlated with the structure of metamaterials. In periodically microstructured systems, the degenerate Weyl point is in twofold linear degeneracy between two energy bands in the 3D systems [4,5]. Since the corresponding spatial dimension is the same as that of the Pauli matrices, the Weyl point is highly robust and cannot be eliminated unless two partners with positive and negative chiralities annihilate each other in the momentum space [6]. As the currently known types of Weyl degeneracy all belong to the category of accidental degeneracy, the positions of Weyl points can be flexibly modulated in the momentum space, which provides a good opportunity for engineering artificial gauge fields [7]. The main method of designing the effective magnetic field reported previously is based on the mechanical strain [8,9]. According to the tight-binding approximation, the stress tensor can be expressed as a vector potential, which results in the desired magnetic field. This method has been widely used in 2D systems. However, owing to the weak scalability, the effect of stain is seriously restricted in 3D systems. Because of this limitation, artificially induced fields have only been experimentally realized in 2D systems. It is still a challenge to construct 3D effective magnetic field.

Jia et al. [10] recently reported a novel approach to establishing the artificial magnetic field in spatial inhomogeneous 3D Weyl photonic metamaterial systems by designing the microstructures of unit cells. Instead of the traditional method of designing fields with the tight-binding approximation theory, they achieved the aperiodic modulation of the unit cells based on the effective medium theory [11]. Thus the adiabatic evolution of the locations of Weyl points in the momentum space is realized, which results in an equivalent gauge field. They have designed a hexahedron unit cell (3 mm × 3 mm × 4.5 mm), and the inner structure of each unit cell is a saddle-shaped connective metallic coil embedded in a dielectric block with the permittivity 2.2, as is shown in Fig. 1a. The positions and the frequency of the Weyl points can be adjusted through changing the rotational angle θ and the offset distance d. For a detailed illustration, a uniform angular step $\Delta\theta = 0.2^\circ$ along the x direction is set, which leads to a linear relation $\theta = ax$ ($a = -1.1636$ rad/m). If the total number of unit cells is set to be 101, θ will range from 10° to −10°. Moreover, to ensure equal frequency Weyl points in the whole structure, the parameter d should be carefully engineered throughout the system. Correspondingly, the band structure is calculated, and the Weyl points are shown in Fig. 1b. From the figure, it can be seen that this system supports four type I Weyl points (Q1–Q4).

According to such a system, the interaction Hamiltonian can be written as $H_\mathrm{W} \approx \mathbf{w}\cdot\left(\mathbf{k}-\mathbf{k}_0^\mathrm{W}-\mathbf{A}\right)\mathrm{I}_2+\sum v_{ij}\left(k_i-k_{0i}^\mathrm{W}-A_i\right)\sigma_j$, where I_2 is the 2×2 identity, σ_j are the Pauli matrices, v_{ij} belongs to an anisotropic velocity tensor. Moreover, $\mathbf{w}$ is the tilt factor of the Weyl cone, $\mathbf{k}$ is the wave vector, and $\mathbf{k}_0^\mathrm{W}$ describes the location of the Weyl point in the momentum space. In this equation, the gauge field is denoted by $\mathbf{A}$, whose expression is $\mathbf{A} = \Delta\mathbf{k}^\mathrm{W} \approx [axk_0^\mathrm{W}/\sqrt{2}, -axk_0^\mathrm{W}/\sqrt{2}, 0]^\mathrm{T}$. Thus the artificial magnetic field can be derived by $\mathbf{B} = \nabla\times\mathbf{A}$ as $\mathbf{B} = [0, 0, -axk_0^\mathrm{W}/\sqrt{2}]^\mathrm{T}$. Based on the near-field scanning technique, the corresponding system is detected. The results show that the Weyl points Q1 to Q4 move in the momentum space following the blue arrows (left panel in Fig. 1c) as the increase of x. Correspondingly, the generated effective magnetic field for each Weyl point lies along the $+z$ or $-z$ direction, as is shown in the right panel of Fig. 1c.

The artificial magnetic field can induce chiral Landau energy levels, and the directions of group velocity are different for these Weyl points. Specifically, owing to the positive topological charge,

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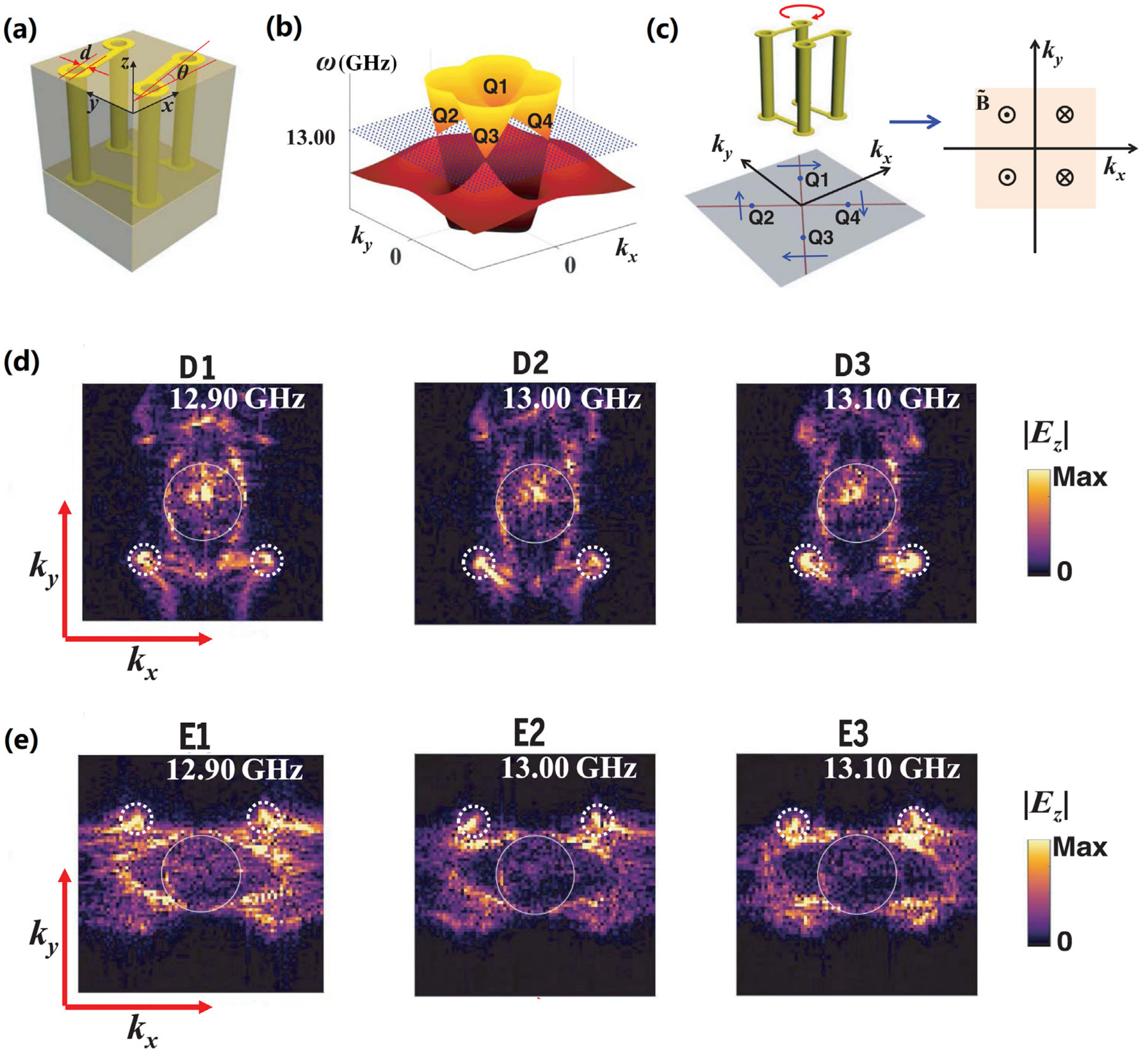

Fig. 1. (Color online) (a) Schematic of the saddle-shaped metallic coil; (b) Diagram of the four Weyl points in the band structure; (c) Shifting of the locations of Weyl points (left panel) and the directions of artificial magnetic field (right panel); (d and e) The measured equifrequency contours exhibit the up-going and down-going chiral zero modes, respectively (modified from Jia et al. [10]).

the group velocities of the zeroth Landau levels in Q3 and Q4 are in the +*z* direction, which are along the magnetic field. In contrast, Weyl points Q1 and Q2 have CZMs with group velocity against the magnetic field in the −*z* direction. Therefore, for the excitation applied on the bottom surface, there are only up-propagating zeroth Landau levels in Q3 and Q4, which can be detected on the top surface. The conservation of in-plane momentum prevents the reflection at the top surface from coupling to down-going modes in Q1 and Q2, which makes Q3 and Q4 much brighter than Q1 and Q2 on the measured field patterns in the vicinity of the Weyl frequency (panels D1–D3 in Fig. 1d). On the contrary, if the point source locates on the top surface, Q1 and Q2 are more obvious than Q3 and Q4 (panels E1–E3 in Fig. 1e). Based on these results, the chiral propagation of zeroth Landau levels is confirmed. Furthermore, the robust unidirectional transport of CZMs against backscattering originating from a defect layer of dielectric slab or the air in the middle of the sample is also verified.

The capability to tailor the micro/nano-structures of Weyl semimetals provides a powerful method of engineering the pseudo–gauge field in 3D photonic systems. This type of metamaterial provides a good platform to explore various novel topological phenomena induced by strong magnetic fields. Moreover, the observed CZM is of great value in designing new photonic devices owing to its unidirectional transport characteristic in the bulk medium.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

[1] Son DT, Spivak BZ. Chiral anomaly and classical negative magnetoresistance of Weyl metals. Phys Rev B 2013;88:104412.
[2] Liu ZK, Zhou B, Zhang Y, et al. Discovery of a three-dimensional topological Dirac semimetal, Na_3Bi. Science 2014;343:864–7.
[3] Guo Q, Yang B, Xia L, et al. Three dimensional photonic Dirac points in metamaterials. Phys Rev Lett 2017;119:213901.

[4] Furusaki A. Weyl points and Dirac lines protected by multiple screw rotations. Sci Bull 2017;62:788–94.
[5] Wang H, Wang HC, Chen Y. Discovery of tip induced unconventional superconductivity on Weyl semimetal. Sci Bull 2017;62:425–30.
[6] Wan X, Turner AM, Vishwanath A, et al. Topological semimetal and Fermi-arc surface states in the electronic structure of pyrochlore iridates. Phys Rev B 2011;83:205101.
[7] Westström A, Ojanen T. Designer curved-space geometry for relativistic fermions in Weyl metamaterials. Phys Rev X 2017;7:041026.
[8] Guinea F, Katsnelson MI, Geim AK. Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering. Nat Phys 2010;6:30–3.
[9] Mañes JL. Symmetry-based approach to electron-phonon interactions in graphene. Phys Rev B 2007;76:045430.
[10] Jia H, Zhang R, Gao W, et al. Observation of chiral zero mode in inhomogeneous three-dimensional Weyl metamaterials. Science 2019;363:148–51.
[11] Zhao R, Koschny T, Soukoulis CM. Chiral metamaterials: retrieval of the effective parameters with and without substrate. Opt Express 2010;18:14553–67.

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