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DOI:
10.1103/PhysRevApplied.9.054033

Spin-orbit Coupling Induced Circular-polarization-selective Transmission in a Helical Tape Waveguide

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Spin-orbit coupling (SOC) of light, describing the interaction between the polarization (spin) and spatial degrees of freedom (orbit) of light, plays an important role in subwavelength scale systems and leads to many interesting phenomena, such as spin Hall effect of light. Here, based on the SOC, we design and fabricate a helical tape waveguide (HTW) which can realize a circular-polarization-selective process. When the incident circularly-polarized wave is of the same handedness as the helix of the HTW, a nearly complete transmission is observed; in contrast, a counter-rotating circular polarization of incident wave results in a much lower transmission or is even totally blocked by the HTW. Indeed, both simulations and experiments reveal that the blocked component of power leaks through the helical aperture of the HTW and forms a conical beam analogous to helical Cherenkov radiation due to the conversion from the spin angular momentum to the orbital angular momentum. Our HTW structure demonstrates its potential as a polarization selector in a broadband frequency range.

I. INTRODUCTION

Spin-orbit coupling (SOC), also called spin–orbit interaction, is an interaction between the spin and motion of a particle. Similar to the SOC of electrons in solids and quantum gases [1−5], light carries both spin angular momentum (i.e., circular polarization) and orbital angular momentum (i.e., spatial degrees of freedom of light), and its SOC can appear when light carrying intrinsic angular momentum interacts with a medium [6,7]. Having been widely studied in bianisotropic and inhomogeneous metamaterials [8−10], plasmonic metalenses [11], metasurfaces [12−15], etc., the SOC was demonstrated to accurately control and distinguish the polarization of light [16−21]. In addition, the SOC of light leads to a number of interesting phenomena, including the spin Hall effect [6,22,23], spin-controlled shaping and control of light [24−28], and robust spin-directional coupling via evanescent near fields [29−34]. Among them, a controlled steering Cherenkov wake determined by the photon spin angular momentum of the incident radiation was realized in a one-dimensional metamaterial recently [35].

Cherenkov radiation occurs when a charged particle enters an ordinary medium at a velocity higher than the velocity of light in such a medium. Cherenkov radiation has already been widely applied in high-energy physics such as detectors in particle physics [36] and microwave generation [37,38]. There have been also numerous investigations on the generation of Cherenkov radiation and reversed Cherenkov radiation in metamaterials [39−46]. As a specific Cherenkov radiation, helical Cherenkov radiation effect is a very interesting physical phenomenon, which could possibly be used as a detector of radiation by energetic electrons that are trapped in a medium by strong magnetic fields. Helical Cherenkov radiation was firstly theorized by Soln [47,48]. Soln demonstrated that the helical Cherenkov radiation can only be observed in the visible spectrum when an external magnetic field value is larger than 100 T [48]. Due to this extreme condition, helical Cherenkov radiation is rarely observed in experiment.

Here, we design and fabricate a helical tape waveguide (HTW) with circular-polarization-selective transmission induced by the SOC. Our simulations and proof-of-concept experiments show that when a right-handed circularly polarized (RCP) electromagnetic wave is incident into the HTW, a nearly complete transmission is obtained. On the contrary, when a left-handed circularly polarized (LCP) wave is incident, HTW behaves as a leaky wave helical antenna with conical radiation pattern [49,50] akin to a vortex radiation. Originated from the strong SOC (i.e., spin angular momentum to orbital angular momentum conversion), this leaky vortex radiation for LCP is in analogy to a helical Cherenkov radiation. Our HTW demonstrate the results at microwave frequencies; nevertheless, the proposed structure can be scalable to other frequency ranges given its simplicity.

II. DESIGN AND THEORETICAL ANALYSIS

The configuration and the dimensions of the HTW are shown in Fig. 1(a). We study first the electromagnetic behavior of the HTW by numerical simulations. To this end, the transient solver of the commercial software CST Microwave Studio® is used. Open boundary conditions are applied in all directions, ensuring convergence of the results. Metal is model as perfect electric conductor. The solver-defined adaptive grid is employed with a convergence accuracy of 0.001. A circularly polarized (CP) electromagnetic wave propagating along the -z direction is excited at one end of the HTW using the software-defined waveguide port, whereby two degenerate orthogonal linear modes ($TE_{\perp}$ and $TE_{//}$) with equal amplitude and ±90° phase difference are excited (+90° for RCP and -90°

for LCP) within the HTW. Another waveguide port is defined at the other end of the HTW to calculate the transmission coefficient S_{21}. The total fields inside the whole simulation volume as well as the radiation characteristic are recorded with the software-defined E-field and far-field monitors.

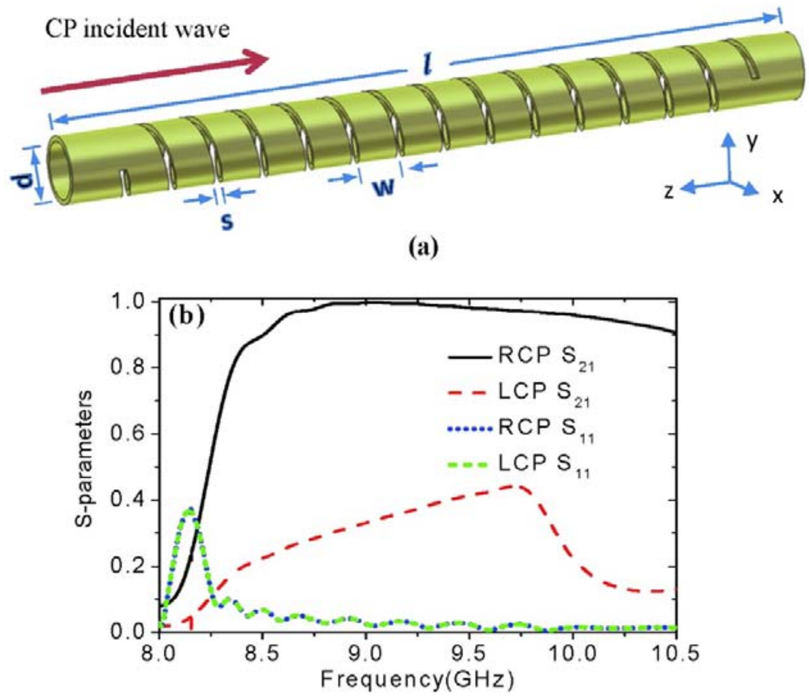

FIG. 1. (a) Schematic diagram of the proposed HTW. The geometric parameters of the HTW are: diameter d = 21.6 mm, metallic copper thickness t = 0.5 mm, slit width s = 4 mm, metallic width w = 15 mm, lattice constant $a = s + w$ = 19 mm, and the number of turns n = 14, which corresponds to a length of l = 290 mm. (b) Simulated transmission S_{21} and reflection S_{11} for LCP and RCP incident waves.

Figure 1(b) display the transmission S_{21} and reflection S_{11} for LCP and RCP incident waves. The HTW operates above ~8.3 GHz as a transmission line for RCP wave given the high transmission and low reflection observed. For LCP wave, however, transmission and reflection are simultaneously low in the frequency span displayed. The fact that both RCP and LCP waves have almost identical S_{11} indicates that the HTW operates as a leaky wave antenna for LCP wave. This antenna operation mode is easily modulated by the values of the slit width *s* and the helix turns *n*, while the transmission line operation mode remain unaffected by these parameters [51]: transmission decreases (i.e., leakage increases) with increasing slit width *s* or increasing number of turns *n*. This initial study shows that the HTW can transmit the CP light with the same handedness as its helix but partly transmit or even block the other handedness within the same bandwidth. Hence, the proposed HTW can be used to distinguish the circular handedness of an incident electromagnetic wave. Some engineering of the HTW parameters would allow for further improvement of the difference in transmittances of LCP and RCP waves.

In order to show the underlying physics of the circular-polarization-selective transmission of the HTW, Fig. 2(a) displays the simulated electric field distributions of the HTW at $z = 0$ plane (i.e., the middle plane of the HTW) for LCP and RCP incident waves at 9 GHz. It can be observed that little radiation occurs for RCP incident wave. In contrast to the weak radiation of the RCP incident case, significant leakage radiation occurs for LCP incident case. Interestingly, such leakage radiation forms a vortex. These results show unambiguously that the wavefront of the leaky waves is indeed helical and it carries an orbital angular momentum for LCP incident case. In other words, the coupling between spin angular momentum and orbital angular momentum produces spin-to-orbital angular momentum conversions—helicity-dependent vortex. To study clearly this helicity-dependent radiation, Fig. 2(b) presents the electric field distributions on the $x = 0$ middle plane at the frequency of 9 GHz. It can be seen that the power is well confined in the HTW for RCP incident wave and little radiation can be observed, resulting in a very high transmission, and therefore, a transmission line operation. In contrast, when LCP wave is incident onto the HTW, the power largely leaks through the slits and radiates to free space, leading to a low transmission for LCP incident wave. These results are consistent with the transmission spectra shown in Fig. 1(b).

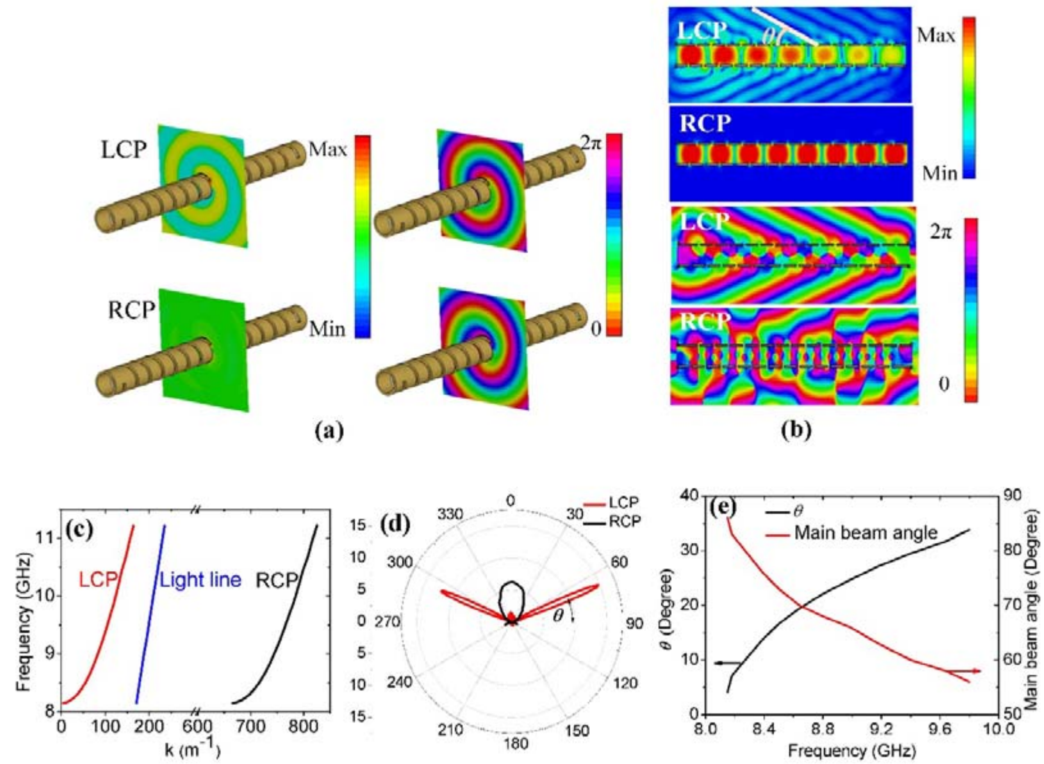

FIG. 2. (a) Electric field intensity (right) and phase (left) distributions at z = 0 plane for LCP and RCP incident waves at 9 GHz. (b) Electric field intensity (top) and phase (bottom) distributions at x = 0 plane for LCP and RCP incident waves at 9 GHz. (c) Wavevector on the surface of the HTW for LCP and RCP incident waves. (d) Simulated far-field radiation patterns (φ = 90°, linear scale) for LCP and RCP incident waves at 9 GHz. (e) Angle θ and main beam direction versus frequency for LCP incident case.

Below we provide an interpretation for this circular-polarization-selective behavior of our HTW and the helicity-dependent radiation. The electromagnetic field and its excitation surface current density in the HTW are both in periodical distribution, due to the azimuthal periodicity and helical symmetry of the tape helix, and consist in space harmonics according to the Floquet theorem [52]. When the propagation wave is circularly polarized, the propagation wavevector of the 1st space harmonic on the surface of the HTW is $k_1^{\sigma} = k_z + \sigma\frac{2\pi}{a} + \frac{2\pi}{a}$, where k_z is the propagation wavevector of the mode inside the unperturbed waveguide, σ = ±1 is the spin of the incident wave, + and – represent RCP and LCP, respectively. The second term 2πσ/*a* on the right side of the equation comes from the SOC; due to the angular momentum conservation, the spin angular momentum of the circularly polarized waveguide mode is converted to the orbital angular momentum of the outgoing beam [53]. The third term 2π/*a* is due to the periodical helical structure of the slits.

With the above in-line expression, we calculate the value of k_1^{σ} as shown in Fig. 2(c). It can be seen that k_1^{+1} is much larger than the free space wavevector k_0 for RCP incident wave case, resulting in no leakage radiation. This scenario corresponds to the well-known slow-wave structure widely used in travelling-wave tubes [52]. In contrast, k_1^{-1} is smaller than k_0 for LCP incident wave, which leads to the leakage radiation with conical pattern. These behaviors are corroborated in the far-field radiation patterns shown in Fig. 2(d). Notice that 0° corresponds to the waveguide axial direction. For LCP incident wave, the main lobe radiation directions are at 66.5° and 293.5°, respectively (i.e., conical mode) at 9 GHz. The far field radiation pattern for RCP shows, in contrast, the main lobe at 0° (i.e., axial mode). Notice that the conical mode has a more directive beam than the axial mode, as expected from its larger effective radiation length.

Since $k_1^{-1} < k_0$ for LCP incident wave, the propagation phase velocity is larger than that of free space, and thus, wakes are generated [35] at angle θ (see Fig. 2(b) for definition) that follows the

Cherenkov equation: $\theta = arcsin\left(\frac{\omega/k_0}{\omega/k_1^{-1}}\right) = arcsin\left(\frac{k_1^{-1}}{k_0}\right)$, see Fig. 2(e). Notice that θ increases with frequency. This response is characteristic of a forward leaky wave antenna [54] whose main beam direction is perpendicular to the wavefront direction. Moreover, as shown in Fig. 2(a), the leakage radiation forms a vortex, (i.e., the wavefront of the leaky wave is helical) akin to the helical Cherenkov radiation in charge particle experiments.

III. EXPERIMENTS

To verify the observations from the previous section, we fabricate HTW samples. The samples are fabricated by using a circular resin pipe with a diameter of d = 21.6 mm wrapped with copper foil with the width of w = 15 mm, the thickness of t = 0.5 mm, the slit width of s = 4 mm, and the lattice constant of $a = s + w$ = 19 mm. Two different HTW samples are fabricated with helix turns of n =14 and n = 30, corresponding to lengths of l = 290 mm and 600 mm, respectively. As shown in Fig. 3(a), the experimental setup for transmission measurement consists of two X-band coaxial-to-rectangular waveguide connectors, two rectangular-to-circular waveguide connectors, two circular polarizers, and an AV 3629 vector network analyzer (45 MHz − 40 GHz). Two circular polarizers are employed to generate a circularly polarized wave, and the opposite circularly polarized wave can be produced by rotated the two circular polarizers simultaneously by 90°. The network analyzer connecting the two coaxial connectors to its two ports is used to measure LCP and RCP transmissions.

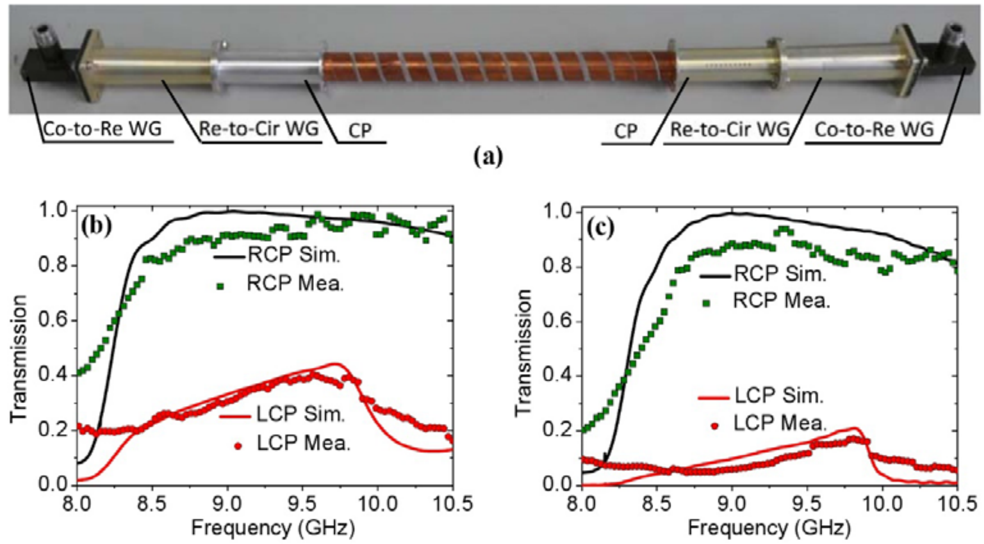

FIG. 3. (a) Experimental setup for transmission S_{21} measurement. The transmission spectra for the HTW with (b) n =14 and (c) n = 30. Solid curves indicate the simulations and color symbols represent the measured results.

Figures 3(b) and 3(c) show the transmission spectra of the two HTW samples. For both samples, a very high transmission is observed for RCP incident electromagnetic wave, whereas low transmission is detected for LCP incident wave (the longer the sample, the lower the transmission), as expected from our previous discussion. Namely, for the LCP case, the transmission coefficient is 0.32 and 0.061 at 9 GHz for the HTW samples with n = 14 and n = 30, respectively. Since conductive loss can be neglected, these values yield to a leakage constant α = 3.78 Np/m (α/k_0 = 0.02), and 3.59 Np/m (α/k_0 = 0.019) at 9 GHz for the HTW samples with n = 14 and n = 30, respectively. The slightly difference in leakage constant can arguably be assigned to truncation effects due to the finite-size of the waveguide. The leakage constant α versus frequency is shown in [51]. The experimental results (color symbols) show a good agreement with the simulations (solid curves). For both samples, a large transmittance ratio is observed at a broadband frequency range from 8.3 to 9.75 GHz, which corresponds to a fractional bandwidth of 16.1%. The measured reflections are low both for LCP and RCP waves [51], which agrees with the simulations. Our results thus manifest that the HTW can transmit almost completely the circular polarization wave with the same helicity as its helix slit, whereas partly transmits or even blocks the opposite one over a broadband frequency range.

The far-field radiation patterns of both samples are also investigated experimentally. These measurements are carried out in an anechoic chamber with an AV 3629 vector network analyzer, and a standard X-band linearly polarized horn antenna. As shown in Fig. 4(a), the fabricated HTW (Ant. 1) is placed on an azimuth positioner serving as an emitter and the standard X-band linearly polarized horn antenna (Ant. 2) is served as a receiver. An X-band coaxial-to-rectangular waveguide connector, a rectangular-to-circular waveguide connector and a circular polarizer feed the HTW to generate a CP wave.

Figures 4(b) and 4(c) display the far-field radiation patterns of the HTW with n = 14 and n = 30, respectively. For the HTW with n = 14, the far field radiation pattern for the LCP incident wave shows that the measured main lobe radiation directions are centered at 65.2° and 294.8° at 9 GHz, respectively. The maximum measured magnitude of the main lobes is 14.7 (11.7 dB) due to the leakage radiation. The measured radiation pattern is in a good agreement with the simulation, with a deviation of only ~1.3° in the main lobe directions. As compared with the LCP case, the far field radiation pattern for RCP incident wave shows a wider main lobe at 0° whose magnitude is ~6 (7.8 dB). This is due to the fact that little power of this mode is radiated. Similar results are observed with n = 30 in Fig. 4(c), except that the measured magnitude of the main lode is 26.5 (14.2 dB) for LCP incident case because of the longer leakage length. All these far-field radiation patterns are consistent with the preceding studies of the transmission spectra and the electric field distributions.

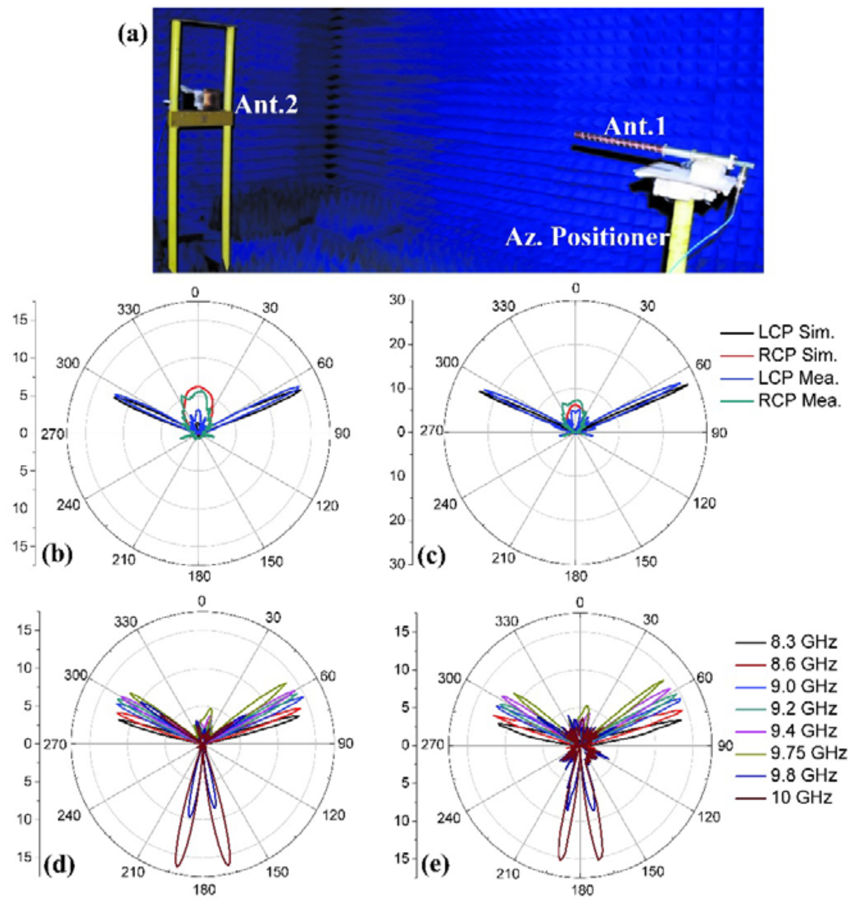

FIG. 4. (a) Experimental setup in an anechoic chamber, and the simulated and measured far field radiation patterns (φ = 90°, linear scale) for the HTW samples with (b) n = 14 and (c) n = 30 at 9 GHz. (d) Simulated and (e) measured far-field radiation patterns (φ = 90°, linear scale) of the HTW sample with n = 14 at various frequencies for LCP incident wave.

Finally, Figs. 4(d) and 4(e) present the frequency response of the simulated and measured far-field radiation patterns of the HTWs with n = 14 for the LCP incidence wave, respectively. It is shown that the main lobe direction moves from near broadside toward forward end-fire as the frequency increases. The measured directions of the main lobes are consistent with the simulations. It is worth noting that at the top end of the frequency scan (9.8 GHz and 10 GHz), the higher order space harmonic emerged with beam direction pointing very close to backward end-fire. The similar results are obtained for the HTW sample with n = 30, except that the main lobe magnitude is larger than that of the HTW sample with n = 14.

IV. CONCLUSIONS

To conclude, we have designed and fabricated a HTW structure to achieve a strong asymmetry between the circular polarizations of transmitted electromagnetic wave. We demonstrate numerically and experimentally that the circular-polarization-selective property of the HTW is due to the SOC. Transmission spectra, electric field distributions, and far-field radiation patterns show that a RCP electromagnetic wave propagates through the HTW with negligible radiation over a broadband frequency range. The HTW operates as a slow-wave structure for RCP incident wave. In contrast, low transmission is obtained and a significant leakage radiation is observed for the LCP case. The HTW operates in this case as a leaky wave antenna. Moreover, the leakage radiation forms a vortex, an analogue of a helical Cherenkov radiation for LCP case. This unique physical phenomenon originates from the fact that the coupling between the spin angular momentum and orbital angular momentum produces spin-to-orbital angular momentum conversions.

ACKNOWLEDGMENTS

Y. L. is supported by the National Natural Science Foundation of China (Grant No. 11204241); the

National Aerospace Science Foundation of China (Grant No. 2016ZF53061); the Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2017JM1009); the Fundamental Research Funds for the Central Universities (Grant No. 3102017jghk02004); the China Scholarship Council; and the Top International University Visiting Program for Outstanding Young Scholars of Northwestern Polytechnical University. Q. G. acknowledges support from the National Natural Science Foundation of China (Grant No.11604216). K. S. acknowledges support from the National Natural Science Foundation of China (Grant No. 61601375). S. Z. acknowledges support from European Research Council Consolidator Grant (TOPOLOGICAL); the Royal Society and the Wolfson Foundation; and Horizon 2020 Action, Project Nos. 734578 (D-SPA) and 648783. M. N.-C. acknowledges support from University of Birmingham (Birmingham Fellowship).

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