Observation of Topologically Enabled Complete Polarization Conversion

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Exploiting topological ideas has been a major theme in modern photonics, which provides unprecedented opportunities to design photonic devices with robustness against defects. While most previous works in topological photonics have focused on band theory, recent theories extend the topological concepts to the analysis of scattering matrices and suggest a topological route to complete polarization conversion (CPC). Here, the experimental observation of the topological CPC is reported. Using angle-resolved reflection measurements, it is unveiled experimentally that the CPC between arbitrary two polarizations occurs at vortex singularities of reflection coefficients in momentum space, reflecting its topological nature. Besides, it is visualized directly that for a given input polarization, the output one can cover the entire Poincaré sphere over a wide frequency range by varying the incident angle, guaranteed by the topological nature of CPC, which is in sharp contrast to the conventional polarization–conversion approaches that usually suffer from the bulky volume, limited choice of eigen-polarization states, or narrow operation bandwidths. Remarkably, that BICs lie on the critical coupling curves that define the condition for CPC is experimentally demonstrated. This work paves the way to exploring the topological properties in scattering matrices for controlling light polarization and creating robust photonics devices.

1. Introduction

Topology is a mathematical concept concerned with geometric properties that are preserved under continuous deformation. Since the seminal work by Thouless et al.,[1] there has been a rapidly growing interest in exploiting the topological properties of physical systems characterized by quantized topological invariants.[2–23] In a topologically nontrivial system, the physical quantities associated with topological invariants are robust against small perturbations, as the quantized invariants cannot change continuously. In photonics, topological ideas are currently under active investigation to design and control the behavior of light. Previous works on topological photonics have largely focused on topological band theory and topological invariants (such as Chern number) defined by Bloch wavefunctions in photonic band structures.[22–46] As a physical consequence of the band topology, backscattering-immune edge states reside at interfaces between two topologically distinct media,[27] enabling a plethora of applications ranging from robust optical delay lines[47–49] to on-chip communications[50] and topological lasers.[51–55]

Recently, tremendous efforts have been devoted to achieving topological photonic phenomena beyond the framework of topological band theory and with no parallel in condensed matter physics. For instance, it has been revealed that the far-field polarization vector of guided resonance modes of...
photonic crystal (PhC) slabs can exhibit vortex configurations in momentum space, which carry quantized topological charges defined by the number of times of polarization vectors winding around the vortex singularity. Intriguingly, the guided resonance mode at the vortex singularity has an infinitely large quality factor, also known as a bound state in the continuum (BIC).\cite{56–59} Moreover, owing to their topological nature,\cite{60} BICs are robust against small perturbations and have found many applications, including high-quality-factor lasers,\cite{61} optical vertex generators,\cite{62} and ultrasensitive sensors.\cite{63}

More recently, topological concepts have been theoretically extended to the analysis of scattering matrices.\cite{64–67} This shows the possibility of realizing the complete polarization conversion (CPC) at isolated incident wavevectors on a compact metasurface, which is enabled by the topological properties of scattering matrices.\cite{64,65} The topological CPC between two linear polarizations has a deep connection with the BICs: the BICs lie on the critical coupling curves that define the condition for the CPC. Besides, the topological CPC and the symmetry of the metasurface can further enable the complete conversion of a given input polarization state to any possible one on the Poincaré sphere (we hereafter refer to it as full-Poincaré-sphere CPC) over a wide range of frequencies. Remarkably, owing to its topological nature, the full-Poincaré-sphere CPC is robust against the effect of material losses and can work over a wide frequency range.\cite{65} Despite the great interest in the topological CPC, there has been no systematic experimental observation to date due to the lack of an ideal photonic system.

Here, we report the direct experimental observation of the topological effect in scattering matrices and the full-Poincaré-sphere topological CPC over a wide frequency range, as the electromagnetic wave is reflected from a compact metasurface (see Figure 1c). Our metasurface features a “clean” band structure of guided resonances—only a single band in the frequency range of interest, enabling the topological CPC to span over the entire light cone, in contrast to a small portion of the light cone in the previous proposals.\cite{64–66} Therefore, our metasurface serves as an ideal platform to study the topological effect in reflection matrices and the full-Poincaré-sphere topological CPC. Using polarization-sensitive angle-resolved reflection measurements, we directly probe the vortex configuration and the topological charge of the complex reflection coefficients between two polarization states in momentum space. We experimentally confirm that the CPC occurs at vortex singularities at isolated incident momenta, implying the topological nature of CPC. Besides, we experimentally observe that topological BICs lie on the critical coupling curves that define the condition for topological CPC between two orthogonal linear polarization states as previous theoretical speculation,\cite{61} establishing an intriguing connection between two seemingly unrelated topological phenomena. Notably, we experimentally verify that for a given input polarization state, the output polarization states can cover the entire Poincaré sphere using a single metasurface over a broad frequency range. Therefore, a single topological metasurface can operate in parallel as many polarization converters, implementing all unitary polarization transformations that otherwise would require cascading several photonic components. This topological approach is in stark contrast to the conventional versatile polarization conversion by rotating the optical axis of several cascaded birefringent quarter-wave plates,\cite{68} or tuning materials’ parameters of a metasurface,\cite{60} which suffer from the intrinsically bulky volume, restricted operating bandwidth, or limited choice of eigen-polarization states.

2. Results and Discussion

2.1. Observation of the Topological CPC between |p> and |s> Polarization States and Its Relation with BIC

As illustrated in Figure 1a, the designed metasurface consists of an array of square copper patches separated from the copper sheet by a dielectric spacer. Each copper patch connects to the ground plane through a metallic via. All incident waves will be reflected by the copper sheet. Details of the metasurface design can be found in Supporting Information S1. Only zeroth-order diffraction can occur, as the frequency range of interest is below the diffraction limit. Consequently, the reflection matrix of our designed reflective metasurface can be defined as $R = [R_{pp}, R_{ps}, R_{sp}, R_{ss}]$, where $R_{ps}$ denotes the reflection coefficients of a $p$-polarized incident wave reflected into a $s$-polarized wave. For a lossless system, $R$ is a unitary matrix.

We start with the experimental demonstration of the topological CPC between two orthogonal linear polarizations, i.e., |p> and |s> polarizations. For |p> (|s>) waves, the electric field is parallel (perpendicular) to the incident plane determined by the incident wavevector $\mathbf{k}$ and the normal of the metasurface (see inset in Figure 1b). In experiments, we adopt a pair of highly collimated lens antennas respectively as transmitting and receiving antennas. The parallel wavevector of the incident wave is $k_y = (k_x, k_y)$. All elements in $R$ can be measured by tuning the polarization of antennas (see Note S1, Supporting Information). The normalized measured cross-polarization conversion efficiency $|R_{sp}|^2$ as a function of $k_y$ is shown in Figure 1b. We observe CPC with $|R_{sp}|^2 = 1$ at two isolated k-points related by the mirror symmetry in a quarter of k-space.

To experimentally demonstrate the topological properties of CPC, we plot the measured vector field $[\text{Re}(R_{sp}), \text{Im}(R_{sp})]$ in k-space. As shown in Figure 1c, one can see a saddle point in the upper triangular region with $k_y > k_x$ and a drain point in the lower triangular region with $k_y < k_x$. At these singularity points, $|R_{sp}|^2 = 0$, and thus, $|R_{sp}|^2 = 1$, owing to the unitarity of $R$ matrix. Moreover, these two topological singularities are related by the mirror operation with respect to the $k_y = k_x$ plane. The topological charges carried by the singularities are defined as

$$q = \frac{1}{2\pi} \int_C \nabla \cdot \Phi \left( \mathbf{k} \right) d\mathbf{k}, \mathbf{q} \in \zeta$$

(1)

which describes the times of the vector field winding around the singularity. Here, $C$ is a closed path around the singularity, traversed in the anticlockwise direction, and $\Phi$ is the phase of $R_{pp}$. In Figure 1d, we plot the measured phase distribution of $R_{pp}$ in k-space, namely, $\Phi(k_x, k_y)$. One can see that the phase decreases anticlockwise by $2\pi$ around the saddle point, indicating a topological charge $q = -1$. Conversely, the phase increases anticlockwise by $2\pi$ around the drain point, indicating a topological charge $q = +1$. The reflection dip in the co-polarization reflection...
Figure 1. Observation of the topological CPC between $|p\rangle$ and $|s\rangle$ polarization states and its relation with BIC. a) The schematic diagram of the experimental setup. The right inset shows the details of the unit cell. Here, $a = 10$ mm; $h = 4$ mm; $b = 8$ mm; $r = 2$ mm. b) Measured normalised $|R_{sp}|^2$ in momentum space. Inset: the electric field component of $|p\rangle$ ($|s\rangle$) polarization state. c) Measured vector field [Re($R_{pp}$), Im($R_{pp}$)] in $k$-space with zoom-in plots near isolated singularities. d) Measured phase distribution of $R_{pp}$ in $k$-space. e) Measured co-polarization reflection spectra $|R_{pp}|^2$ at the drain point of (c). Both the vector field and phase distribution of $R_{pp}$ exhibit a nonzero topological charge, implying the topologically nontrivial property of CPC. f–i) are simulation results, corresponding to (b)–(e), respectively. j) Simulated band structure of the guided resonance modes. The colour represents the quality factors of the guided resonance modes on a logarithmic scale, approaching infinity at the $\Gamma$ point. Insets: the first Brillouin zone. The dashed box denotes the symmetry-protected BIC. k) Simulated $|d_s|$, $|d_p|$ is zero along $\Gamma M$. l) Simulated $|d_s|$, $|d_p|$ is zero along $\Gamma X$. m) Measured critical coupling curves. The red dots indicate the CPC positions, which are extracted from the measured reflection spectrum $|R_{pp}|^2$. The black dashed lines represent the numerically calculated critical coupling curves on which $|d_s| = |d_p|$. 

The simulated results in Figure 1e–h also show the same topological effect. Moreover, the topological CPC is robust against material losses and can work over a broad bandwidth$^{[64]}$ (see Notes S5 and S10, Supporting Information). According to the temporal coupled-mode theory$^{[64,70]}$ (also see Note S3, Supporting Information), we have
Figure 2. Observation of the topological CPC between $|p\rangle$ polarization state and an arbitrary one. From left to right: schematic diagrams, polarization conversion efficiencies, vector fields, and reflection phase distributions for the polarization conversion between $|p\rangle$ and a) $|45\rangle$, b) $|135\rangle$, c) $|RCP\rangle$, or d) $|LCP\rangle$ polarization states, respectively. The inset in (a): Illustration of the polarization ellipse. The horizontal axis represents $|s\rangle$ state, the vertical axis represents $|p\rangle$ state, $\chi$ is the ellipticity angle, and $\beta$ is the orientation angle.

Here, $d = (d_s, d_p)^T$ with $d_p$ ($d_s$) being the coupling rate of guided resonances to $|p\rangle$ ($|s\rangle$) wave; $\sigma_z$ is an identity matrix with $\sigma_z = [1, 0; 0, 1]$; $\sigma_y$ is a Pauli matrix with $\sigma_y = [0, 1; -1, 0]$; $\gamma$ is the radiation loss of guided resonances, and $|d_p|^2 + |d_s|^2 = 2\gamma$; $C_B = [C_s, 0; 0, C_p]$ represents background scattering. When the critical coupling condition is satisfied, i.e., $|d_p| = |\omega_0 - \omega|$, the CPC between $|p\rangle$ and $|s\rangle$ waves will occur. Because $|d_p| = 0$ along $\Gamma M$ (see simulated $|d_p|$ in Figure 1k) and $|d_s| = 0$ along $\Gamma X$ (see simulated $|d_s|$ in Figure 1l), there must be at least one critical coupling curve with $|d_p| = |d_s|$ residing between $\Gamma X$ and $\Gamma M$. Therefore, CPC can be achieved along the critical coupling curve unless $|d_p| = |d_s| = 0$. The numerically calculated critical coupling curves are plotted as the black dashed lines in Figure 1m. The experimentally extracted topological CPC positions (red dots in Figure 1m) in $k$-space indeed distribute around the critical coupling curves. We have thus experimentally proved that the critical coupling defines the condition for topological CPC.

In addition, owing to the nonradiative nature of BIC, both $|d_p|$ and $|d_s|$ should be zero at BICs. For the TE mode (with an electric field along the $z$-axis) studied here, the copper layer under the bottom of the metasurface acts as a mirror and can restore the effective up-down mirror symmetry of the mode. Our metasurface, therefore, hosts symmetry-protected BIC, corresponding to an infinitely large quality factor of guided resonances at $\Gamma$ (see Figure 1j). From Figure 1k–m, one can see that the BIC indeed shows $|d_p| = |d_s| = 0$ and lies at the crossing point of critical coupling curves. Thus, BICs are closely related to the topological CPC (see Note S6, Supporting Information).

2.2. Observation of the Topological CPC between $|p\rangle$ Polarization State and an Arbitrary One

We further experimentally demonstrate that the topological CPC can occur between $|p\rangle$ state and an arbitrary one. We measure
Figure 3. Demonstration of the full-Poincaré-sphere topological CPC. a) Measured polarization ellipses in \( k \)-space. The black line segments denote reflected \(|p>\) states. The red (blue) lines correspond to right (left) handedness. \( W (\bar{W}) \) marks the CPC between \(|p>\) and \(|s>\) waves. b) Poincaré sphere and measured Stokes parameters of transformed polarization states. Each dot denotes a measured polarization state. The red dots are mapped from the red dashed curve in (a). c) Measured output polarization ellipses correspond to the dots labeled with numbers in (b). Each subfigure is tagged with the angle of incidence (polar angle, azimuthal angle). d) Measured Stokes parameter \( S_1 \), \( S_1 = -1 \) on \( \Gamma_X \) and \( \Gamma_M \), and \( S_1 = 1 \) at \( W \) and \( \bar{W} \). e) Measured phase difference \( \varphi_d \). Two phase singularities exist at \( W \) and \( \bar{W} \), respectively. The blue dashed line is the linear-in-linear-out curve, where the phase difference is \( 0 \) or \( \pi \). f) \( \varphi_d \) distributions in \( k \)-space (left) and its mapping onto the Poincaré sphere (right). \( WP-QWP \) is the measured linear-in-linear-out curve. \( W / \bar{W} \), \( K \), and \( R \) label the measured positions of transformed \(|s>, |45^\circ>\), \(|135^\circ>\), and \(|RCP>\) states, respectively. The red and blue regions correspond to \( \varphi_d > 0 \) and \( \varphi_d < 0 \), respectively.

The reflection coefficients \( R_{pp} \) and \( R_{sp} \), with which the reflection coefficients of the reflected wave with an arbitrary polarization state can be obtained (see Note S7, Supporting Information). In general, any polarization state can be defined by the polarization ellipse characterized by an orientation angle \( \beta \) and an ellipticity angle \( \chi \) as shown in the inset of Figure 2a. For linear polarization, the ellipse degenerates into a line segment, i.e., \( \chi = 0^\circ \). Especially, the \(|p>\) \((|s>)\) state corresponds to a vertical (horizontal) line segment with \( \beta = 90^\circ (0^\circ) \). Without loss of generality, we choose \( 45^\circ \)-linear \((|45^\circ>\), \( \chi = 0^\circ; \beta = 45^\circ\)), \( 135^\circ \)-linear \((|135^\circ>\), \( \chi = 0^\circ; \beta = 135^\circ\)), right-handed circular \((|RCP>\), \( \chi = +45^\circ\)), or left-handed circular \((|LCP>\), \( \chi = -45^\circ\)) polarization as the transformed state, respectively. The measured results, including polarization conversion efficiency, vector fields, and phase distributions in \( k \)-space are shown in Figure 2. One can see a saddle (source or drain) point with topological charge \( q = -1 (+1) \) in the upper (lower) triangular region with \( k_y > k_x (k_y < k_x) \) for both cases (We also plot the measured and simulated reflection spectra at the source point of \([\text{Re}(R|45^\circ>), \text{Im}(R|45^\circ>)\]) and the drain point of \([\text{Re}(R|135^\circ>), \text{Im}(R|135^\circ>)\]) respectively, in Figure S5, Supporting Information). In sharp contrast to the case in Figure 1, there exist simultaneously zero polarization conversion...
and topological CPC in k-space. Besides, the polarization conversion efficiency satisfies $|R_{xy}(k_x, k_y)|^2 + |R_{xx}(k_x, k_y)|^2 = 1$ ($\mu \in \{|RCP>, |LCP>, |45^\circ>, |135^\circ>\}$). Such phenomena are attributed to the nonorthogonality between $|p>$ polarization state and an arbitrary one, the energy conservation, and the symmetry of our metasurface (see Notes S3, S4, and S7, Supporting Information).

2.3. Demonstration of the Full-Poincaré-Sphere Topological CPC

Next, we experimentally verify that for a given input polarization state, the output one can cover the entire Poincaré sphere by varying the angle of incidence, enforced by the topological nature of CPC and the symmetry of the metasurface. In Figure 3a, we plot the measured polarization ellipses of the reflected wave in k-space, for the $p$-polarized incident wave. At $\tilde{W}$ and $\tilde{W}$ points, the polarization ellipses are horizontal lines, corresponding to the topological CPC between $|p>$ and $|s>$ waves. Besides, on the mirror symmetry lines, i.e., $k_x = 0$, $k_y = 0$, and $k_x = k_y$ lines, the transformed states are also $p$-polarized; these mirror symmetry lines are polarization-conserved lines.[65] We map each polarization state in k-space to Poincaré sphere defined by a set of Stokes parameters \(S_0, S_1, S_2, S_3\),

\[
\begin{align*}
S_0 &= |E_x|^2 + |E_y|^2, \quad S_1 = |E_x|^2 - |E_y|^2 \\
S_2 &= 2 |E_x E_y| \cos (\varphi_2), \quad S_3 = 2 |E_x E_y| \sin (\varphi_2)
\end{align*}
\]

where $E_x$ ($E_y$) represents $|p>$ ($|s>$) component in output waves, and $\varphi_2 = \arg(E_x) - \arg(E_y)$ is the phase difference between the output $|p>$ and $|s>$ components. In the experiments and simulations, each component can be obtained with a reflection coefficient. As shown in Figure 3b, the transformed polarization states cover the entire Poincaré sphere. As any polarization state can be represented by $S_1$ and $\varphi_2$, we also plot the measured $S_1$ and $\varphi_2$ in Figure 3d,e. It shows two phase singularities at $W/\tilde{W}$ and a linear-in-linear-out curve $P/W/\tilde{W}$ with $\varphi_2 = 0$ or $\pi$. We can strictly prove that, for $p$-polarized incident wave, the linear-in-linear-out curve is mapped to the equator ($S_1 = 0$) of the Poincaré sphere, and the $\varphi_2 > 0$ ($\varphi_2 < 0$) regions are mapped to the lower (upper) half of the Poincaré sphere, as shown in Figure 3f (see Note S8, Supporting Information). Besides, the full-Poincaré-sphere topological CPC can also occur for an arbitrary input polarization state in the case of lossless (see Note S9, Supporting Information). Therefore, our topological nonlocal metasurface can perform all unitary polarization conversions by varying the angle of incidence.

2.4. Broadband Full-Poincaré-Sphere Topological CPC

The full-Poincaré-sphere topological CPC is also a broadband effect.[65] From the measured results in Figure 4, one can see that the output polarization states can cover the entire Poincaré sphere over a wide frequency range extending from 12.4 to 13.3 GHz, with a relative bandwidth of 7%. This is because the topological CPC between arbitrary two polarization states on the Poincaré sphere is topological in nature. Moreover, the working bandwidth of the topological CPC can be further increased by optimizing the geometrical parameters of the metasurface (see Note S11, Supporting Information).

3. Conclusion

We have thus experimentally studied the angular-dependent response of the metasurface[71] and demonstrated the topological effects in scattering matrices of the metasurface, which gives rise to the topologically protected, spectrally broadband, full-Poincaré-sphere CPC. Different from the previous metasurface...
polarizers that lack $C_4v$ symmetry and can convert the polarizations at the vertical incidence angle,\cite{2,3} our metasurface has $C_4v$ symmetry and can only convert the polarizations at oblique incidence angles. In this way, a compact metasurface can function as many polarization converters in parallel, implementing all unitary polarization transformations. Our topological approach to polarization control is also applicable to higher frequencies, including infrared and visible frequencies, enabling various scientific and industrial applications, such as vector beam generation, polarization cameras, and quantum optics (see Note S12, Supporting Information). Moreover, we can achieve active control of the topological CPC by employing available dynamical control techniques\cite{25,26} enabling intelligent polarization manipulation. Our work also sheds light on exploring topological concepts beyond the conventional framework of band topology. We anticipate a richer set of intriguing topological phenomena when considering a higher dimensional space or the other aspects of scattering matrices. As the scattering matrices characterize the general responses of any linear wave system, it would be interesting to investigate physical phenomena and device applications based on the topological effects in scattering matrices of other wave systems, such as acoustic and elastic wave systems.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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