Experimental observation of a polarization vortex at an optical bound state in the continuum

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Optical bound states in the continuum (BICs) are states supported by a photonic structure that are compatible with free-space radiation, yet become perfectly bound for one specific in-plane momentum and wavelength.[1,2] Recently, it was predicted that light radiated by such modes around the BIC momentum-frequency condition should display a vortex in its far-field polarization profile, making the BIC topologically protected.[3] We study a 1-dimensional grating supporting a transverse-magnetic mode with a BIC near 700 nm wavelength, verifying the existence of the BIC using reflection measurements, which show a vanishing reflection feature. Using k-space polarimetry, we measure the full polarization state of reflection around the BIC, highlighting the presence of a topological vortex. We use an electromagnetic dipole model to explain the observed BIC through destructive interference between two radiation channels, characteristic of a Friedrich-Wintgen type BIC.[4] Our findings shed light on the origin of BICs and verify their topological nature.

Recent works have shown that simple photonic structures can support *embedded eigenstates*[1] – states of light that are bound despite the fact that they are not protected from coupling to the radiation continuum through either symmetry, or momentum mismatch[2,5]. These bound states in the continuum (BIC) have infinite lifetime, not because they are forbidden from leaking, but because different radiation channels interfere destructively with each other in the far field[6]. Such bound states of light have been demonstrated for dielectric systems with 1D and 2D periodicity[5,7,8], and have been proposed to occur also in lossless 3D finite plasmonic systems[9,10], even if for realistic optical materials they may be unattainable. Owing to their unbounded quality factor, they are deemed to hold great promise for enhancing light-matter interactions[2], including applications in solid-state lasers[11], sensing[12] and narrowband filters.[13] Zhen et al.[3] have predicted that 2D BICs are expected to be inherently robust, due to the fact that they are intimately related to a topological invariant in their polarization properties. This property elegantly connects photonic BICs to a wide range of topological phenomena. In this work, we prove experimentally this claim by tracing the polarization of far-field radiation associated with the leaky-wave dispersion of a grating that exhibits a BIC. Our measurements show two BICs associated with a polarization vortex, each of topological charge +1. Whereas earlier studies have demonstrated very high quality factors of BICs in similar dielectric 1D[14] and 2D[7,11] periodic systems, no experiments thus far have studied their topological nature. We argue that the polarization vortex is a much more robust evidence for the radiation cancellation mechanism from which BICs arise than simply monitoring the amplitude and Q-factor of the leaky-wave signature in reflectivity. Indeed, while theory predicts infinite Q and a vanishing amplitude reflection signature for ideal BICs, in real systems the embedded eigenstate and its far field signature are limited to finite Q by roughness, loss, imperfections and the unavoidable finite size of the sample. The vortex is robust to such sample imperfections. Interestingly, not only do we observe the vortex despite a background reflection present in our measurements, but this background also leads to an additional fingerprint of the vortex, observable in the helicity of the far-field reflection. Furthermore, we provide a simple theoretical model that sheds light on the polarization vortex at a BIC in terms of the radiation properties of magnetic and electric dipoles induced on the dielectric elements of the grating. This represents a "bare-bones" physical model that fully predicts the topological polarization properties of BICs, which fits well with the observed phenomena, and offers new insights into the origin of these anomalous states.

Figure 1a-d highlights the main concept behind this work: the polarization vortex signature of a BIC, illustrated by calculations for our workhorse sample. We deliberately choose the simplest possible structure that can support a BIC, inspired by the design proposed by Zhen et al.[3]: a 1D silicon nitride (Si_3N_4) grating (n=2.05, 200 nm thick, Figure 1a,b) fabricated on top of an 8 um SiO_2 membrane and embedded in an index-matching environment (n=1.517), with a periodicity *d* of 350 nm, fill fraction of 63% and overall dimensions of about 0.22 x 0.24 mm^2. This grating supports both a TM- and a TE-like leaky mode. These are waveguide modes that couple to free space through grating diffraction, as evident from their folded-back dispersion.[15] It was theoretically shown by Zhen et al. that systems that have up-down mirror symmetry and where permittivity ϵ obeys $\epsilon(x,y,z) = \epsilon^*(-x,-y,z)$ can support stable BICs.[3] Our system fulfils these criteria, and we chose its parameters such that a BIC is expected to appear in the TM mode, which can be inferred from the disappearance of the mode as its associated resonant feature vanishes in the reflection spectrum[3,7]. Figure 1c shows TE and TM reflectivity from Rigorous

Coupled Wave Analysis (RCWA), clearly evidencing a BIC at 720 nm wavelength. Crosscuts showing linewidth narrowing, and a TM mode profile are shown in the supplement. The expected topological signature of the BIC is summarized in Figure 1d (schematized from dipole model and rigorous coupled wave analysis, see supplemental material). The diagram indicates the polarization state of far-field radiation associated with the leaky mode as a function of the 2D parallel momentum (k_x,k_y)= nk_0 (cosϕsinθ,sinϕsinθ,cosθ), with n the surrounding index and k_0 the vacuum wavenumber. Right at the BIC, the polarization state shows a vortex, defined as a point around which the polarization vector makes one or more full 2π rotations. A topological charge q can be assigned to such a point, defined as[3]

$$q = \frac{1}{2\pi}\oint_C \nabla_{\boldsymbol{k}}\alpha(\boldsymbol{k})\, d\boldsymbol{k}\,, \qquad q \in \mathbb{Z},$$

where C is a closed path around the point, traversed in the counter clockwise direction, and α is the angle that the polarization vector makes with the x-axis. The charge can be either positive or negative, and the magnitude indicates the number of times α winds around the vortex. The vortices sketched in Figure 1d are of charge +1.

Experimentally this prediction implies a significant challenge: to precisely track the polarization response not just at a single wavelength, but across the entire leaky wave dispersion surface, i.e., as a function of polar (θ) and azimuthal (ϕ) angle while matching, for each angular setting, the frequency to the leaky wave dispersion relation. Rather than using a traditional ellipsometry technique we employ a polarimetric k-space imaging scheme[16–20] as shown in Figure 1e. This offers the crucial advantage of measuring all angles of incidence that fit the NA of a microscope objective in parallel on a CCD, without needing any scanned rotation stage. The sample is illuminated through a NA=1.39 objective and reflected light is collected through the same objective. Rather than imaging the sample, we image the back focal plane (BFP) of the objective using an additional lens. This maps in-plane wave vectors k_x and k_y, encoding for θ and ϕ with an effective angular resolution of about 0.5°. We build a data cube in (k_x,k_y,ω)-space using a supercontinuum laser as tuneable light source between 500 and 900 nm, filtered to 1 nm bandwidth by an acousto-optical tuneable filter. A spinning diffuser in the illumination ensures that we simultaneously offer a very homogeneous illumination of the entire objective BFP (all wave vectors are probed) as well as a large area of illumination on the sample. These are requirements to observe the narrow features in k-space associated to the BIC. Measurements are calibrated to a gold mirror (reflectivity reference) and an absorptive colour filter (background signal).

Figure 1f shows a k_y=0 cut through the measured grating reflection diagram that can be directly compared to the calculated dispersion. The TM leaky wave dispersion is clearly visible and disappears around 690nm wavelength, indicating the signature of a BIC. These results are in good agreement with calculations, while the wavelength shift of the BIC is likely caused by a difference in grating fill factor and refractive index of the surrounding medium. Weak interference fringes are visible due to a slight index mismatch between the thermal oxide membrane and the surrounding index-matching oil. The bright feature at large wave vector (offset to larger $|k_x|$ by $|k_x/k_0|$=0.15 from the TM leaky wave) arises not from specular reflection, but contains an additional contribution from the first grating diffraction order.

As this does not overlap with the leaky-wave features this diffraction order does not affect our analysis. Figure 1g shows a different cut through our data cube, i.e., a single-frequency slice measured in a single camera shot. This evidences the high angular-resolution mapping of the leaky-wave TE and TM features, which appear as concentric bright circles centred at the reciprocal lattice vectors k_x=±2π/d and radius in units of $|\mathbf{k}|/k_0$ equal to the mode index.

The BIC was predicted[3] to coincide with a vortex in the polarization direction of far-field radiation of the leaky TM mode. As sketched in Figure 1d, the input/output channel is expected to be linearly polarized, with the polarization angle making a full 2π rotation around the BIC. To observe this vortex, we measure the full polarization state for each wavelength λ and each wave vector k_x and k_y. This would be extremely tedious with a traditional ellipsometer that scans angle by angle, but is straightforward in our k-space imaging technique by using a linear polarizer and a quarter waveplate that are introduced in the detection arm as Stokes polarimeter[17,20]. We summarize the polarization ellipse of reflected light by the orientation α of its major axis relative to the x-axis and the ellipticity angle χ (definitions in Figure 2a). The magnitude of χ determines how elliptical the polarization is, while its sign indicates handedness. Figure 2b shows intensity and α of the sample reflection, for several fixed-frequency data slices at wavelengths above, at, and below the BIC. Each slice crosses both the TE and the TM leaky dispersion. Only at the TM branch does the ellipse orientation α *change sign* around the wavelength of the BIC. Going from low to high wavelength (from left to right in Figure 2b), the value of α near the TM-mode feature switches from negative to positive for positive k_y (red → blue), and the opposite for negative k_y (blue → red). This is consistent with the type of behaviour sketched in Figure 1d, and represents the signature of a vortex in the polarization state of the TM-mode radiation.

To better visualize the vortex, we track the polarization response over the TM leaky mode dispersion surface, instead of examining fixed-frequency slices. To determine the dispersion surface, we assume that the TE and TM mode dispersion can be described at each wavelength as a circle (slight elliptical correction, <2% x-y radius difference) centred at $k_x/k_0 = \lambda/d$, with radius set by the effective index. Using this reasonable assumption and fitting the effective index we find the dispersion surface (k_x,k_y,$\omega(k_x,k_y)$), indicated by the red lines in figure 2c. Next, to visualize the polarization response of the TM leaky mode, we collapse (i.e., project) this dispersion surface onto the (k_x, k_y) plane (see Methods). Figure 3 shows such 'collapsed resonance' maps of α and χ, for TM and TE modes. Two vortices are visible in the α map of the TM mode, both on the x-axis at opposing $k_x/k_0 = \pm 0.4$. Around these points, we see α flip quadrants 4 times, indicating a full 2π rotation. This observation directly proves that the BIC is associated to a polarization vortex in its far field.

Somewhat surprisingly, we see that not only α shows the presence of a vortex, also the ellipticity parameter χ changes dramatically around the BIC. Theory predicts the BIC and TM leaky wave to have a linear polarization response[3], so one might expect χ to be identically zero throughout k-space. However, in our experiment the signal mixes with a weak background reflection due to the imperfect matching between the immersion oil and the thermal oxide membrane . This background is not exactly in phase or co-polarized with the TM reflection, leading to an elliptically polarized reflection. The vortex in alpha for the TM contribution is then imprinted onto the ellipticity profile as a four-fold change of handedness around the BIC, which thus acts as another strong indication of the presence of the polarization vortex at the BIC. In the supplement, we further show how this vortex in χ can be explained using the dipole model introduced in the next paragraph. Importantly, the nodal lines in α and χ, namely, lines where α and/or χ equal 0 or 90 degrees, are seen to cross at non-high-symmetry points only in the maps of the TM mode (branch with BIC), while nodal-line crossings are clearly absent in the maps of the TE mode (branch with no BIC) except at the origin. In the supporting information, the same plots are shown for y-polarized input light, further confirming the existence of a BIC through presence of a vortex in the polarization response.

While the presence of a vortex with quantized topological charge explains the robustness of the BIC, it does not tell us what microscopic mechanism underlies it. It was shown by Friedrich and Wintgen that a particular subclass of BICs arises from destructive far-field interference between two resonators.[2,4,21] To identify these resonators in our grating, we calculate the contributions of electric and magnetic dipole elements to the polarization currents induced in the grating unit cell using full-wave numerical simulations (Figure 4a). At the TM resonance, the z-oriented electric dipole p_z and y-oriented magnetic dipole m_y exhibit a resonant peak, dominating over all other multipolar contributions. This fact suggests that the BIC might be understood by considering the radiation properties of these two dipolar contributions alone. We thus set up a 'bare bones' dipole model, calculating the reflection from a non-diffractive sheet of non-interacting polarizable particles, each responding to an impinging plane wave with a superposition of an induced z-oriented electric and y-oriented magnetic dipole p_z and m_y, respectively (Figure 4b). Importantly, we chose particle polarizability to match the relative strengths and phase of p_z and m_y found in the grating unit cell. Figure 4c-d show the magnitude and polarization of the reflected field. Destructive interference occurs at opposite k-vectors on the k_x-axis, with each intensity node associated with a polarization vortex, as clearly seen in Figure 4d. The location of the nodes at $k_x = \pm 0.5$, which is set by the ratio of p_z to m_y , is in good agreement with the value found in the grating full-wave calculations (0.45). This simple model demonstrates that our BIC can be understood as a Friedrich-Wintgen bound state arising from the interference between two resonant dipolar contributions. In the supplementary material, we furthermore use this dipole model to show that the superposition of the BIC reflection with a background reflection from the grating and substrate explains why also the polarization ellipticity angle χ shows a vortex at the BIC, as observed for the TM mode in Figure 3. Finally, we note that our dipole model is also applicable to other structures supporting BICs. For example, in the supplement we show that a different combination of dipoles can give vortices that 'bounce' upon variation of the relative dipole strength, as predicted by Zhen et al. for BICs in 1D and 2D gratings.[3] We expect that combinations of dipoles may be able to match the behaviour of any BICs on the lowest-frequency TM- and TE-like branches in 1D or 2D gratings, whose induced polarization currents contain negligible multipolar terms. An extension of the model including multipoles could be applicable to BICs in higher-order branches, as recent results on BIC-like modes in single nanorods suggest.[22]

In conclusion, we experimentally demonstrated the existence of a polarization vortex at an optical bound state in the continuum. Using angle- and wavelength-resolved polarimetric reflectivity measurements on a silicon nitride grating, we traced the TM-like leaky-mode dispersion surface and directly observed a polarization singularity associated with each BIC. We classify the BIC as a Friedrich-Wintgen bound state using a simple dipole model that explains its origin as the result of complete destructive interference between electric and magnetic dipolar radiation contributions. This result confirms that BICs are tied to a topological property, namely, a vortex of the polarization state in wavenumber space. This vortex hence is robust in its existence under continuous perturbations and imperfections that do not destroy the underlying symmetries of the structure. In addition, we assert that measuring the existence of this topological property is more robust evidence for a BIC then standard reflection spectroscopy. Standard reflection measurements evidence a BIC by the *disappearance* of a reflection signal, which furthermore should present an arbitrarily high Q-factor while approaching the BIC frequency. Observation is challenging because it places nominally infinitely stringent demands on wave vector and frequency resolution. Moreover, finite sample size, absorption and sample disorder will smear out the BIC signature and lead to finite-Q resonances. Instead, the vortex is a robust signature of the radiation cancellation mechanism that defines the BIC, which can be robustly and easily measured from polarization properties *around* instead of *at* the BIC condition. This method is applicable to BICs in any 2D structure with parallel momentum conservation, can be extended to 1D and 0D structures, and allows to study vortices of higher topological charge, in which case one would observe more alternating regions of positive and negative angle α, when traversing a loop around the vortex. We believe that, by offering the first experimental evidence of the connection of bound states in the continuum and topological photonic effects, our findings may open new exciting directions in the study and application of robust BICs in different practical scenarios.

Methods

Sample Fabrication

Silicon wafers covered by 8 um thermal oxide and 200 nm Si_3N_4 (stoichiometric, grown by low pressure chemical vapour deposition) are first etched with KOH (30 wt%) from the back to open up 200 um wide freestanding membranes supported by a silicon frame. At 200 micron, the membranes are as large as our microscope field of view, yet small enough to avoid bending or rupture. Next, we perform e-beam lithography (20 keV eLine, 250 nm ZEP520a resist, writing in Fixed Beam Moving Stage configuration) to create a 1x1 mm grating on top of, and next to, the membrane. After development (MIBK:IPA 9:1, 20 seconds) we etch the grating into the nitride using an Oxford Instruments Plasmalab 100 Cobra ICP (80 sccm CHF3, 16 sccm SF6 at 2500 W ICP power and 50W RF power) for 22 seconds. This procedure optimizes side-wall angle definition.

Experimental setup

Light from an 8W NKT Supercontinuum source is spectrally filtered by a digitally controlled acousto-optic-tunable filter (Crystal Technologies, 1nm bandwidth) and relayed by a single mode fiber to illuminate a spinning diffuser (sandblasted glass). The diffuse light is imaged onto the BFP plane of the objective, ensuring that we overfill the BFP. We use an Olympus UPLanSApo 100x objective of nominal NA=1.4, with Fluka 10976 (n=1.517) immersion oil both on top of, and below, the sample membrane. The collection optics is exactly as reported in Osorio et al.[20], with the sole distinction that we inserted a beamsplitter (45:55 R:T pellicle) to combine/split the input and output light. During measurements, a Fourier lens ensures that we image the objective back focal plane. If we remove this lens, we have a real-space field of view on the camera of 90x67 μm (corresponding to 257 grating periods), which is evenly illuminated when we use the diffuser. The laser wavelength is scanned in steps of 5 or 10 nm for the measurements with x- and y-polarized input polarizations, respectively. At each wavelength, 15 camera images are averaged for better signal-to-noise ratio. We correct for laser intensity fluctuations between consecutive scans using the signal of a photodiode. We calibrated the wave vector axis by the grating orders of a large-pitch grating, while we calibrated the intensity axis by verifying the Fresnel coefficients of a bare silicon and a bare ZnSe substrate. Note that measuring reflectivity requires a reference. This is provided by taking a gold substrate as high-reflectivity standard, and using an absorptive color filter as "dark" reference for background subtraction. We have verified that the method is robust to our tolerances in setting focus and sample/objective tilt.

Fitting the TM mode dispersion

Since the vortices do not manifest themselves in a single-wavelength k-space pattern, but instead lie on the dispersion surface of the TM mode, we track the TM and TE mode dispersion surfaces to produce the collapsed resonance plots in Figure 3. At each iso-frequency image, the modes form circles centered at $k_x/k_0 = \lambda_0/d$, with a radius equal to the effective index. Due to the sample asymmetry between the x- and y-direction, we allow for a slight elliptical correction, i.e. different effective indices n_x and n_y along the x- and the y-directions, respectively. This correction lead to a maximum relative index difference of 2%. We find that effective indices of $n_x = 1.796 - 2.6 \cdot 10^{-4}\lambda_0 - \Theta(\lambda_0 - 610nm) \cdot 2.5 \cdot 10^{-4}\lambda_0$ and $n_y = 1.80 - 3.0 \cdot 10^{-4}\lambda_0$, with λ_0 the free-space wavelength in nm, describe the TM mode dispersion well. Here, the last term in n_x, containing the Heaviside function $\Theta(x)$, helps to track the mode at low wavelengths, where the circles approach the Γ-point and experience band bending, leading to a deviation from the elliptical shape. Similarly, the TE mode is well described by $n_x = 1.785 - 1.8 \cdot 10^{-4}\lambda_0 - \Theta(\lambda_0 - 650nm) \cdot 2.2 \cdot 10^{-4}\lambda_0$ and $n_y = 1.82 - 2.8 \cdot 10^{-4}\lambda_0$. Once the mode dispersion is found, we build up the collapsed resonance images by sampling our data on the dispersion surface and projecting this onto the k_x, k_y-plane.

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Figure captions

Figure 1: Reflection and predicted polarization of a 1D grating supporting a BIC. a) Design of the 1D Si_3N_4 grating. **b)** sample cross-section (Pt only used for electron microscopy). **c)** Reflectivity from RCWA for x- (y-) polarized input beams (Horizontal (vertical) arrows). The red circle indicates the BIC. **d)** Sketch of the expected polarization of the TM mode radiation. Around each BIC, the polarization makes a 2π rotation, corresponding to vortices of topological charge +1. Note that this is not an iso-frequency contour, but a projection of the TM-dispersion surface on the $\mathbf{k_x}, \mathbf{k_y}$ plane. **e)** Experimental setup. The input light passes a rotating diffuser and linear polarizer (LP). We image the objective back focal plane using the Fourier lens (FL) and tube lens (TL). Laser power is monitored using a photodiode (PD). Another LP and a quarter waveplate (QWP) allow polarimetry. **f)** Measured reflectivity. **g)** Fourier image of reflection at 690 nm. TM and TE modes appear as closely spaced, bright rings.

Figure 2: Polarization properties of the leaky modes and visualizing the mode dispersion surface. a) Sketch of the polarization ellipse and polarization angles α and χ. **b)** Single-wavelength shots of intensity (top) and angle α (bottom) of the sample reflection. We zoom in on the TM mode crossing with the positive x-axis. Input light was x-polarized. Dashed (dotted) circles follow TM (TE) mode dispersion. The TM mode disappears on the x-axis around 690nm. Around this point, also α changes sign for the TM mode above and below the x-axis, in agreement with the presence of a vortex. Intensity ranges are given in the supplementary material. **c)** Visualization of our data cube, plotting measured reflectivity in 2D momentum vs. wavelength space. The wavelength range is 550 nm to 850 nm. Red dotted lines indicate the TM mode dispersion surface. Note that TE and TM modes lie very close to each other.

Figure 3: Collapsed resonance plots tracing polarization properties over the leaky-wave dispersion surface. We show polarization angles α (Panel a and c) and χ (Panel b and d) for the TM (Panels a,b) and the TE mode. A polarization vortex is visible in the map of α for the TM mode as indicated by the green circles, which is not present in the TE mode. Also the map of polarization ellipticity χ shows a clear transition around the BIC. All images were taken with input polarization along the x-axis.

Figure 4: Electromagnetic dipole model. a) Full-wave numerical calculations of the dominant induced dipole moments (per unit length) in the grating unit cell, as $\boldsymbol{k_x}/\boldsymbol{k_0}$ scans over the TM resonance at 710 nm wavelength (near the BIC). Especially $\boldsymbol{p_z}$ and $\boldsymbol{m_y}$ peak strongly at resonance, demonstrating the magneto-electric character of the mode. Units are explained in the supplement. **b)** Sketch of the individual radiation patterns of dipoles $\boldsymbol{p_z}$ and $\boldsymbol{m_y}$, which are induced in the grating and used in our dipole model. **c)** k-space map of the normalized reflection of a sheet of non-interacting electromagnetic dipoles with a $\boldsymbol{p_z}$ and $\boldsymbol{m_y}$ component. Two nodes occur symmetrically around the origin. The relative strength of the dipoles was chosen as $\boldsymbol{m_y} = \mathbf{0.5}\,\boldsymbol{p_z}$, matching the ratio found at the BIC in the grating unit cell ($\boldsymbol{m_y} = \mathbf{0.48}\,\boldsymbol{p_z}$). **d)** k-space map of polarization angle $\boldsymbol{\alpha}$, demonstrating that the nodes in reflection are polarization vortices.

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Contributions

F.M., A.A. and A.F.K. initiated the research project, and A.A. and A.F.K. supervised throughout the project. All reflection and polarimetry experiments, as well as their analysis, were done by H.M.D., under supervision of A.F.K. RCWA and full-wave simulations were done by F.M. Dipole model calculations were done by H.M.D. and F.M. Sample fabrication and calibration of the experimental setup was done by W.d.H. All authors discussed the results and were involved in the writing of the manuscript.

Competing interests

The authors declare no competing financial interests.