Tuning of the Berry curvature in 2D perovskite polaritons

Laura Polimeno1,2,3, Giovanni Lerario2, Milena De Giorgi2, Luisa De Marco2, Lorenzo Dominici2, Francesco Todisco2, Annalisa Coriolano1,2, Vincenzo Ardizzone2, Marco Pugliese1,2, Carmela T. Prontera2, Vincenzo Maiorano2, Anna Moliterni4, Cinzia Giannini5,6,7, Antonio Fieramosca8, Dmitry D. Solnyshkov9,10, Giuseppe Gigli1,2, Dario Ballarini2, Qihua Xiong6,7, Antonio Fieramosca8, Dmitry D. Solnyshkov9,10, Guillaume Malpuech9 and Daniele Sanvitto1,2,3

The engineering of the energy dispersion of polaritons in microcavities through nanofabrication or through the exploitation of intrinsic material and cavity anisotropies has demonstrated many intriguing effects related to topology and emergent gauge fields such as the anomalous quantum Hall and Rashba effects. Here we show how we can obtain different Berry curvature distributions of polariton bands in a strongly coupled organic–inorganic two-dimensional perovskite single-crystal microcavity. The spatial anisotropy of the perovskite crystal combined with photonic spin–orbit coupling produce two Hamilton diabatic points in the dispersion. An external magnetic field breaks time-reversal symmetry owing to the exciton Zeeman splitting and lifts the degeneracy of the diabolical points. As a result, the bands possess non-zero integral Berry curvatures, which we directly measure by state tomography. In addition to the determination of the different Berry curvatures of the multimode microcavity dispersions, we can also modify the Berry curvature distribution, the so-called band geometry, within each band by tuning external parameters, such as temperature, magnetic field and sample thickness.

The generation of artificial gauge fields is a central topic in modern physics and has recently been investigated in a great variety of physical platforms, such as ultra-cold atomic gases1–4, photonic crystals5–7, graphene and graphene-like materials8–11, mechanical systems12,13 and exciton–polaritons14–16. One of the main concepts behind the theory of artificial gauge fields in photonic systems lies in the topological and geometrical properties of bands associated with the buildup of a non-zero Berry curvature. The Berry curvature is an artificial gauge field14 which behaves as a pseudomagnetic field in the reciprocal space, and is determined by the change in wave function with particle momentum.

The Berry curvature, the integral of which is a topological invariant called the Chern number, plays a key role in topological physics. To achieve a non-zero integral value of the Berry curvature for a band in a photonic system, both optical spin–orbit coupling and breakdown of time-reversal symmetry (TRS) are necessary15. Indeed, the combination of such geometrically non-trivial bands and a band gap then allows the opening of a topological gap16,17.

Recently, the frontiers of this field have been extended to the exciton–polariton systems resulting from the strong coupling of excitons and photons. The importance of the exciton–polaritons17 lies in the possibility of having a high degree of freedom in the engineering of the particles’ Hamiltonian when combining the physical phenomena associated with the exciton component, such as the exciton Zeeman effect, with those due to the photon energy dispersion in optical confined systems, in particular, photonic spin–orbit coupling18. Several strategies to realize topological systems with polaritons have been suggested19–21, including the use of artificial lattices with honeycomb geometries that have been shown to support Dirac cone dispersions22,23 and edge modes24. Recently, artificial lattices have been realized both in organic25 and perovskite materials26, paving the way for the realization and control of quantum states stable at room temperature due to the intrinsic robustness of the exciton in these materials.

In this context, polariton systems based on two-dimensional (2D) hybrid organic–inorganic perovskites27–31 represent a unique platform for topological studies due to the possibility of easily tuning the optoelectronic properties of the polariton device31, without the need of complex fabrication techniques.

In this work we study the topological properties of an exciton–polariton planar resonator made of 2D perovskites. The bare photonic modes demonstrate linear birefringence, and, in some cases, emergent optical activity32,33. In particular, we demonstrate that a non-zero integral value of the Berry curvature (B_z) is obtained in the presence of an external magnetic field, necessary to break the TRS, making use of the exciton Zeeman splitting. Furthermore, we perform direct measurements of the Berry curvature distribution, the so-called band geometry, at different temperatures from cryogenic up to room temperature. We demonstrate that the band geometry can be controlled through the exciton/photon fractions of the polariton mode, the intensity of an external magnetic field (via Zeeman splitting) and temperature.

1Dipartimento di Matematica e Fisica, ‘Ennio de Giorgi’, Università del Salento, Lecce, Italy. 2CNR NANOTEC, Institute of Nanotechnology, Lecce, Italy. 3INFN Istituto Nazionale di Fisica Nucleare, Lecce, Italy. 4Istituto di Cristallografia, CNR, Bari, Italy. 5Paul Scherrer Institute, Villigen, Switzerland. 6State Key Laboratory of Low-Dimensional Quantum Physics and Department of Physics, Tsinghua University, Beijing, P. R. China. 7Beijing Academy of Quantum Information Sciences, Beijing, P. R. China. 8Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Nanyang, Singapore. 9Institut Pascal, PHOTON-NZ, Université Clermont Auvergne, CNRS, SIGMA Clermont, Clermont-Ferrand, France. 10Institut Universitaire de France (IUF), Paris, France. E-mail: milena.degiorghi@nanotec.cnr.it; luisa.demarco@nanotec.cnr.it; dmitry.solnyshkov@uca.fr
Our findings pave the way for the formation of topological states and manipulation of their topological properties in perovskite-based polariton systems, capable of working at room temperature.

**Polarized polariton dispersion**

4-Fluorophenethylammonium lead iodide \((F(C_6H_5(CH_2)_2NH_3)\_2PbI_4)\) perovskite crystals (PEAI-F) were synthesized by an antisolvent vapour-assisted crystallization method \(^1\) on top of a distributed Bragg reflector (DBR). Single-crystal X-ray diffraction measurements highlight the in-plane distortion of the inorganic layers with octahedra tilting (Supplementary Figs. 1 and 2 and Supplementary Tables 1–3), which could favor the optical birefringence of the material. After mechanical exfoliation to obtain crystals with thickness between 3 and 10 \(\mu\)m, the planar cavities are closed with a silver-top mirror (Fig. 1a).

The samples inserted in a cryostat equipped for high magnetic field measurements are non-resonantly excited. Polarization-resolved photoluminescence is measured at magnetic fields of 0–9 T and at temperatures from 4 K up to room temperature. Figure 1bc shows typical energy dispersions versus in-plane momentum, obtained from the photoluminescence spectra as \((I_\text{H} - I_\text{V})/(I_\text{H} + I_\text{V})\) along opposite \(k\) directions at 0 T and 4 K, where \(I_\text{H}\) and \(I_\text{V}\) are the photoluminescence intensities of the horizontal and vertical polarizations, respectively. A manifold of modes, which come in pairs due to linear polarization splitting, results from the free spectral range of the Fabry–Perot resonator at \(k\) in one in-plane \(k\) direction \((k_\text{H})\), while no crossing points are visible in the orthogonal direction \((k_\text{V})\) (Fig. 1c). The birefringence splitting for the lowest observed energy polariton mode is \(-2\) meV, which is about two orders of magnitude higher than the typical energy splitting observed in inorganic GaAs-based microcavities \((15–30\mu\text{eV})\) \(^{15,36}\). This value decreases when the photon fraction \(p\) decreases while approaching the exciton energy. In the same way, the polariton’s effective mass is \(~m^*_0/p\) where \(m^*_0\) is the bare photon mass of mode \(j\). We now concentrate on a given polarization doublet.

The different energy–momentum dispersions of the two modes in a given pair relate to the transverse electric (TE) and transverse magnetic (TM) polarization anisotropy, resulting in an energy splitting of the polariton modes of the order of few meV, which increases at higher wavevector \(k\). Such momentum-dependent splitting is due both to the intrinsic asymmetry of the cavity and to the difference between the in- and out-of-plane refractive indexes of the perovskite \(^{16}\). In the absence of any other refractive index asymmetry, the splitting should be zero at zero momentum \((k_\text{H},k_\text{V})=(0,0)\) \(\mu\text{m}^{-1}\). In the PEAI-F-based sample, the presence of the fluorine at the termination of the interlayer in between the perovskite wells introduces an in-plane optical anisotropy, leading to an additional energy splitting \((x–y)\) splitting between linearly polarized modes at the \((k_\text{H},k_\text{V})=(0,0)\) \(\mu\text{m}^{-1}\) point, shifting the degeneracy points (Hamilton’s diabolical points) towards higher wavevectors (Fig. 1b) in one in-plane \(k\) direction \((k_\text{H})\), while no crossing points are visible in the orthogonal direction \((k_\text{V})\) (Fig. 1c). The birefringence splitting for the lowest observed energy polariton mode is \(-2\) meV, which is about two orders of magnitude higher than the typical energy splitting observed in inorganic GaAs-based microcavities \((15–30\mu\text{eV})\). This value decreases when the photon fraction decreases (Supplementary Fig. 4C) due to the flattening of the dispersions at the exciton resonance. Another pure optical contribution is an emergent optical activity (OA), similar to that reported in refs. \(^{32,33}\), which arises when modes of different parities couple and anti-cross, giving rise to circularly polarized contributions even in the absence of an applied magnetic field. Contrary to the Zeeman splitting, the OA contribution depends on the sample thickness, that is, it increases when increasing the thickness of the material.

**Theoretical model and magnetic field effect**

An effective two-band Hamiltonian describing a pair of polariton bands and accounting for the TE–TM splitting, birefringence, Zeeman splitting and OA \(^{32,33}\) reads:

\[
\begin{align*}
\hat{H} &= \begin{pmatrix} H_{\text{int}} & H_{\text{int,c}} \end{pmatrix} \begin{pmatrix} \hat{E}_{\text{in}} & \hat{E}_{\text{out}} \end{pmatrix} \begin{pmatrix} H_{\text{int}} & H_{\text{int,c}} \end{pmatrix}^\dagger \\
&= \begin{pmatrix} H_{\text{int}} & H_{\text{int,c}} \end{pmatrix} \begin{pmatrix} \hat{E}_{\text{in}} & \hat{E}_{\text{out}} \end{pmatrix} \begin{pmatrix} H_{\text{int}} & H_{\text{int,c}} \end{pmatrix}^\dagger \\
&= \begin{pmatrix} E_{\text{in}} & E_{\text{out}} \end{pmatrix} \begin{pmatrix} \hat{H}_{\text{int}} & \hat{H}_{\text{int,c}} \end{pmatrix} \begin{pmatrix} E_{\text{in}} & E_{\text{out}} \end{pmatrix}^\dagger,
\end{align*}
\]

where \(\hat{E}_{\text{in}}\) and \(\hat{E}_{\text{out}}\) are the in- and out-coupling matrices, respectively. The theoretical model, parameterized by the exciton resonance energy \(E_{\text{in}}\), is shown in Fig. 1d. A comparison with experiments is shown in Fig. 1e.

---

Fig. 1 | Sample structure and polarized photoluminescence dispersion of a 2D perovskite-based microcavity. a, Schematic representation of a sample. Perovskite crystals are embedded in a planar microcavity made by a bottom DBR with seven pairs of TiO\(_2\)/SiO\(_2\) layers and a top 80-nm-thick silver mirror. b,c, Degree of linear polarization of the photoluminescence signal of the lower polariton branches resolved in the energy versus \(k\) (b) and \(k\) (c) in-plane momentum space on a horizontal/vertical (H/V) basis. The perovskite in this sample is 7 \(\mu\)m thick. The dashed lines are the fitting of the system eigenstates derived from equation (2) with zero magnetic field \((\Delta\psi = 0)\) for \(j\) with the following parameters: \(E_{\text{c}} = 2.308\) eV, \(m_m = 4.4 \times 10^{-4} m_e\), \(\beta = 3.3 \times 10^{-4}\) eV \(\mu\text{m}^{-2}\) and \(\alpha = 1.1\) meV.
The dashed blue and red lines in Fig. 1b,c represent the energy eigenvalues of the system for a pair of orthogonally polarized polariton modes using equation (2). The OA contribution is negligible in the fitting of the energy dispersion because the resulting energy splitting (≈0.1 meV) is small compared to the full width at half maximum of the modes (≈1.5 meV). By comparing the dispersion spectra along the two directions, the presence at $k_y = \pm 3.7 \mu m^{-1}$ of two Hamilton diabolical points can also be observed (Fig. 1b).

For these states, which are degenerate in energy, the TE–TM energy splitting exactly compensates the $x$–$y$ splitting.

It is now possible to lift the dispersion degeneracy at the two diabolical points by applying an external magnetic field ($B$) perpendicular to the planar microcavity by using a peculiar property of polaritons, their excitonic component, through the Zeeman effect (Fig. 2a,b). This effect breaks the TRS and the polariton modes acquire a circular polarization component. By applying 9 T, the spectrum opens up at the two crossing points of the polariton dispersions, generating an anticrossing gap (Fig. 2c,d). Here we can extract the Zeeman strength for each couple of orthogonal modes from the photoluminescence profile of the unpolarized energy dispersion spectra (Fig. 2b). We found that the Zeeman splitting increases at higher energies due to the higher exciton fraction of the polaritonic modes (Supplementary Fig. 4B), in contrast to the TE–TM and $x$–$y$ splitting, which instead decrease, moving towards the exciton energy (Supplementary Fig. 4C).

To verify if these non-trivial dispersions are consistent with conical diffraction theory\textsuperscript{a}, we have measured the polarization-resolved photoluminescence spectra of the modes along all six polarization axes of the Poincaré sphere, corresponding to horizontal–vertical (H–V), diagonal–antidiagonal (D–A), and circular right–left (R–L) polarization. In particular, at energy $E = 2.313$ eV, for which the two modes cross each other at the diabolical points, we observe that the linear polarization direction precesses when moving along the two crossings (dashed lines in Supplementary Fig. 5a,b), in agreement with conical diffraction theory. At the diabolical points, the polarization value is the linear superposition of the polarizations of the crossing modes. Along the $k_y$ direction, diametrically opposed points possess orthogonal polarization for each ring and the polarization map is centrosymmetric with respect to the origin of the momentum plane $|k_x,k_y| = 0.0 \mu m^{-1}$.

The full knowledge of the mode polarization is a fundamental parameter since it defines the particle pseudospin (Stokes vector). This can be thought as a two-degree-of-freedom phase associated with the particles, or in other words as a vector charge\textsuperscript{35} property, and it makes it possible to extract the quantum geometric tensor (QGT)\textsuperscript{36} (Supplementary Information, section VI). Such a tensor contains the information on how the orientation of the pseudospin changes when moving along the momentum plane. The orientation of the Stokes vector $S(k)$, which represents the polarization state as a point on the Poincaré sphere, allows the components of the QGT, and in particular the Berry curvature (Supplementary Information, section VI), to be reconstructed\textsuperscript{37}.

Note that by using the effective Hamiltonian from equation (1), the QGT components can be computed analytically\textsuperscript{36}; in particular, the Berry curvature reads:

$$ B_x = \pm \frac{\rho (\alpha_0 \cos \varphi_0 + \alpha_0 \cos \varphi_0 + \alpha_0 \cos \varphi_0 + \beta k^2 \cos \varphi_0)}{\left(\beta k^2 - \beta a k^2 \cos \varphi_0 + \alpha \cos \varphi_0 + \beta k^2 \cos \varphi_0 + \alpha \cos \varphi_0 + \beta k^2 \cos \varphi_0 + \alpha \cos \varphi_0 + \beta k^2 \right)^2} $$

where $\alpha$ and $\beta$ are unitary vectors in the corresponding directions. This formula shows that the variation of the parameters $\alpha$, $\beta$, $\zeta$ and $\Delta$, given by the different exciton/photon fraction at each mode, allows a remarkable change of the Berry curvature distribution in reciprocal space, that is, of the so-called band geometry, as we demonstrate experimentally below.
Tuning of the Berry curvature

Figure 3a–d shows the experimental Berry curvature distribution related to the lower energy band of the two LPBs for the modes \( j, j+1, j+2 \) split by the magnetic field (the dispersion is shown in Supplementary Fig. 6a). The Berry curvature is evaluated for each state of the 2D dispersion. Figure 3a,b shows the Berry curvature distribution for mode \( j \) at 0 and 9 T, respectively. The Berry curvature peaks around the two anticrossing points, forming two broadened Berry monopoles. At \( B=0 \) T this distribution is affected by the OA; in this case, instead of being zero, the circular polarization degree of the Berry curvature at the two anticrossing points are of opposite sign. The integrated Berry curvature over the whole band (Chern number) is still zero, as was the case in refs. \(^{32,33} \). At \( B=9 \) T (Fig. 3b), TRS is broken by the exciton Zeeman splitting, which is here much larger than the OA (\( \zeta = 0.01 \text{ meV} \cdot \mu \text{m} \)). The two anticrossing points of each split band now have the same sign of the circular polarization. The bands are therefore characterized by a non-zero Chern number. The exciton–photon fraction varies across different LPB pairs (values for each band doublet are reported in Supplementary Table 4) and this results in different parameters which enter the effective Hamiltonian. This completely modifies the shape of the Berry curvature distribution, as shown in the Fig. 3c,d.

The Berry curvature evolves towards a ring-like shape at higher excitonic fractions in good agreement with the simulated Berry curvatures (Fig. 3e–h), considering the experimental values of \( \alpha, \beta, \Delta_\alpha, \zeta \) and \( \varphi_\alpha \) extracted for each polariton mode. The evolution of the Berry curvature can therefore be understood by taking into account that at higher energies the exciton fraction of the polariton modes increases, resulting in a more pronounced Zeeman splitting\(^{38} \) and a decrease in the TE–TM and \( x-y \) splitting, due to the dispersion flattening at the exciton transition. It is the opposite trend of the contributions to the effective magnetic field with respect to the photon–exciton fraction of the polariton modes, which ultimately makes it possible to observe Berry curvatures with different shapes inside the same device. Interestingly, the orientation of the linear birefringence (polarization of mode at \( k_x=0 \) for zero applied field) clearly depends on the exciton–photon fraction, with \( \varphi_\alpha \approx 0 \) for \( j \) and \( j+1 \) and \( \varphi_\alpha \approx 30^\circ \) for \( j+2 \). This is visible in Fig. 3d,h, where the Berry curvature maxima are not along the \( k_x=0 \) axis. Small discrepancies between experimental and simulated Berry curvatures can be attributed to dissipative effects and inhomogeneity of the sample that are neglected in the theoretical model.

In this sample, the contribution of the OA to the Berry curvature map is crucial at \( 0 \) T, but it becomes only a small correction at \( 9 \) T. However, we observed that the OA magnitude changes from one crystal to another, proportional to the crystal thickness (Supplementary Information, section VII). It decreases in thinner samples because of a larger mode splitting, while the OA is prominent in thicker crystals, strongly affecting the Berry curvature even at \( 9 \) T (Supplementary Fig. 7).

So far we have shown how to control the parameters of the effective Hamiltonian and qualitatively modify the Berry curvature distribution by passing from one branch to another. In the next part we demonstrate fine control of the Berry curvature distributions and values in a given band by continuous tuning of either the magnetic field intensity or the temperature.

To observe the evolution of the Berry curvature with respect to the applied magnetic field, in the following we use samples with thinner crystals (~2 μm), which results in a negligibly small OA (Supplementary Fig. 8). Figure 4a shows the trend of the maximum of the Berry curvature \( B_0 \) (with the integral curvature normalized to 1) as a function of the magnetic field for two different polariton bands: \( B_0 \) decreases for each band by increasing the magnetic field. This parameter is fully relevant for band characterization and determines the maximal value of the anomalous Hall deviation which can be observed for a given band: \( \Delta X_{\text{AH}} \approx \sqrt{B_0} \). The experimental data (black and red points) are fitted with equation (S3) (black and red lines), considering 0.372 and 0.229 as photonic fractions for band 2 and band 1, respectively.

Figure 4b shows the maximum of the Berry curvature of a polariton band versus the sample temperature. When the temperature increases from 4 to 100 K, the exciton resonance moves towards higher energy (Extended Data Fig. 1a–c), resulting in a blue shift of the polariton modes. This leads to a continuous increase of the photonic fractions for each mode and a corresponding perturbation of the Berry curvature distribution (Extended Data Fig. 1d–f).
characterized by another quantitative parameter, the asymmetry ratio (Extended Data Fig. 1g). For band 1, reported in Extended Data Fig. 1a–c, \( B_0 \) increases while increasing the photonic fraction from 0.344 at 4 K to 0.366 at 100 K.

To summarize, in Fig. 4c we show all the maximum values of the Berry curvature that we have been able to measure in our samples. The points in blue correspond to the cases shown for different bands (Fig. 3 and Supplementary Fig. 8); the points in red correspond to data changing the photonic fraction on the same microcavity sample (Fig. 4). They are much closer to each other and demonstrate the possibility of finely tuning the value of the Berry curvature while a coarse tuning is obtained by changing polariton bands.

Finally, we have also extracted the Berry curvature at room temperature for a \( \approx 3\)–\( \mu \)m-thick crystal, despite the broadening of the polariton modes at higher temperatures (Supplementary Fig. 9). The Berry curvature at 9 T for the mode at 2,280 meV is reported in Supplementary Information, section X and clearly shows two localized maxima in the reciprocal space.

Conclusions

We have demonstrated the topological features of a 2D perovskite-based polariton system, from cryogenic to room temperature and for different band geometries. By combining the material’s optical birefringence and emergent optical activity with the Zeeman effect, we have shown that perovskite-based polariton systems give a unique opportunity to engineer the shape of the Berry curvature distribution and its maximal values by actively tuning different parameters, such as the crystal thickness, the applied magnetic field and the temperature.

By varying the temperature and the intensity of the external magnetic field, we actively influence the distribution of the Berry curvature, providing easy access to various theoretically predicted shapes. These kinds of structures can be used for multiplexing future optical valleytronic devices, such as transistors based on the anomalous Hall effect, operating at different wavelengths at the same time and at different temperatures.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-021-00977-2.

Received: 23 August 2020; Accepted: 9 August 2021; Published online: 21 October 2021

References

1. Aidedsburger, M., Nascimbene, S. & Goldman, N. Artificial gauge fields in materials and engineered systems. C. R. Phys. 19, 394–432 (2018).
2. J. Dalibard, Introduction to the physics of artificial gauge fields. Preprint at https://arxiv.org/abs/1504.05520 (2015).
3. Goldman, N., Budich, J. C. & Zoller, P. Topological quantum matter with ultracold gases in optical lattices. Nat. Phys. 12, 639–645 (2016).
4. Goldman, N., Juzeliunas, G., Öhberg, P. & Spielman, I. B. Light-induced gauge fields for ultracold atoms. Rep. Prog. Phys. 77, 126401 (2014).
5. Lu, L., Ioannopoulos, J. D. & Soljacic, M. Topological photonics. Nat. Photon. 8, 821–829 (2014).
6. Hafezi, M. Synthetic gauge fields with photons. Int. J. Mod. Phys. B 28, 1441002 (2014).
7. Ozawa, T. et al. Topological photonics. Rev. Mod. Phys. 91, 015006 (2019).
8. Pozdeev, G. A., M. Katsnelson, M. & Guinea, F. Gauge fields in graphene. Phys. Rep. 496, 109–148 (2010).
9. Ren, Y., Qiao, Z. & Niu, Q. Topological phases in two-dimensional materials: a review. Rep. Prog. Phys. 79, 066501 (2016).
10. Huber, S. D. Topological mechanics. Nat. Phys. 12, 621–623 (2016).
11. Gao, T. et al. Observation of non-Hermitian degeneracies in a chaotic exciton–polariton billiard. Nature 526, 554–558 (2015).
12. Estrecho, E. et al. Visualising Berry phase and diabolical points in a quantum exciton–polariton billiard. Sci. Rep. 6, 37653 (2016).
13. Lim, H.-T., Togan, E., Kroner, M., Miguel-Sanchez, J. & Imamoglu, A. Electrically tunable artificial gauge potential for polaritons. Nat. Commun. 8, 14540 (2017).
14. Berry, M. V. Quantal phase factors accompanying adiabatic changes. Proc. R. Soc. Lond. A 392, 45–57 (1984).
15. Gianfrate, A. et al. Measurement of the quantum geometric tensor and of the anomalous Hall drift. Nature 578, 381–385 (2020).
16. Raghu, S. & Haldane, F. D. Analogs of quantum-Hall-effect edge states in photonic crystals. Phys. Rev. A 78, 033834 (2008).
17. Karzig, T., Bardyn, C. E., Lindner, N. H. & Refael, G. Topological polaritons. Phys. Rev. 5, 031001 (2015).
18. Kavokin, A., Malpuech, G. & Glazov, M. Optical spin Hall effect. Phys. Rev. Lett. 95, 135501 (2005).
19. Bardyn, C. E., Karzig, T., Refael, G. & Liew, T. C. Topological polaritons and excitons in garden-variety systems. Phys. Rev. B Condens. Matter Mater. Phys. 91, 161413 (2015).
20. Nalitov, A. V., Solnyshkov, D. D. & Malpuech, G. Polariton Z topological insulator. *Phys. Rev. Lett.* **114**, 116401 (2015).

21. Klmbt, S. et al. Exciton–polariton topological insulator. *Nature* **112**, 552–556 (2018).

22. Jacqmin, T. et al. Direct observation of Dirac cones and a flatband in a honeycomb lattice for polaritons. *Phys. Rev. Lett.* **114**, 116402 (2014).

23. Real, B. et al. Semi-Dirac transport and anisotropic localization in polariton honeycomb lattices. *Phys. Rev. Lett.* **125**(18), 186601 (2020).

24. Milicévic, M. et al. Orbital edge states in a photonic honeycomb lattice. *Phys. Rev. Lett.* **118**, 107403 (2017).

25. Scafirimuto, F., Urbonas, D., Scherf, U., Mahrt, R. F. & Stöferle, T. Room-temperature exciton–polariton condensation in a tunable zero-dimensional microcavity. *ACS Photonics* **5**, 85–89 (2018).

26. Su, R. et al. Observation of exciton polarization condensation in a perovskite lattice at room temperature. *Nat. Phys.* **16**, 301–306 (2020).

27. Pedesseau, L. et al. Advances and promises of layered halide hybrid perovskite semiconductors. *ACS Nano* **10**, 9776–9786 (2016).

28. Saparov, B. & Mitzi, D. B. Organic–inorganic perovskites: structural versatility for functional materials design. *Chem. Rev.* **10**, 4558–4596 (2016).

29. Thouin, F. et al. Stable bieexcitons in two-dimensional metal–halide perovskites with strong dynamic lattice disorder. *Phys. Rev. Mater.* **2**, 034001 (2018).

30. Fieramosca, A. et al. Observation of two thresholds leading to polariton condensation in 2D hybrid perovskites. *Adv. Opt. Mater.* **8**, 2000176 (2020).

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2021, corrected publication 2021
Methods

Synthesis of 2D perovskite flakes. A 0.5 M PEAI-F solution was prepared in a nitrogen-filled glovebox by dissolving PbI2 and 4-fluorophenethylammonium iodide (1:2 molar ratio) in γ-butyrolactone and stirring at 70°C for 1 h. 2D perovskite single crystals were synthesized using an antisolvent vapour-assisted crystallization method as follows: 3 μl of perovskite solution was deposited on top of a sputtered DBR and covered with a glass coverslip. Substrates and a small vial containing 2 ml of dichloromethane were placed inside a bigger Teflon vial which was closed with a screw cap and left undisturbed for 12 h at room temperature. During this time, crystals slowly grew in a saturated environment of dichloromethane (antisolvent) and millimetre-sized perovskite flakes finally appeared on top of the DBR. Their thickness varied from a few to tens of micrometres. Using SPV 224PR-M Nitto Tape or polydimethylsiloxane, mechanical exfoliation was carried out on the perovskite flakes to obtain single crystals of the desired thickness.

Microcavity sample fabrication. The DBR was made by depositing seven pairs of TiO2/SiO2 (63 nm/94 nm) layers by a radiofrequency sputtering process in an argon atmosphere under a total pressure of 6 × 10⁻¹ mbar and at a radiofrequency power of 250 W on top of a 1 mm glass substrate. The perovskite single crystals were grown on top of the DBR (see above) and an 80-nm-thick layer of silver was thermally evaporated on top of the structure (deposition parameters: current, 280 A; deposition rate, 3 Å s⁻¹).

X-ray diffraction. Single-crystal X-ray diffraction data measurements for PEAI-F were carried out at the beamline PXII (X06DA-PXII, http://www.psu.ch/ida/pxii/) at the Swiss Light Source (SLS), Villigen, Switzerland, using a Parallel Robotics Inspired (PRIGo) multiaxis goniometer and a Pilatus 2M-F detector. Data collection was performed at low temperature (T = 100 K) on a selected crystal mounted on litholoops (Molecular Dimensions). Complete data were obtained by merging two 360° scans at γ = 0° and γ = 90° of PRIGo. In shutterless mode, a 360° data set was collected in 5 min (beam energy, 17 keV, λ = 0.7293 Å, focus size, 90 × 50 μm², 0.25 s of exposure time per frame, 0.5° scan angle). The principal experimental details are given in Supplementary Table 1. Diffraction data were processed by XDS, a software organized in eight subroutines able to perform the main data reduction steps; the integrated intensities were scaled and corrected for absorption effects by the SCALE subroutine.

Structure solution was carried out by direct methods using SIR2019 (ref. 21), a package that exploits information on unit-cell parameters, diffraction intensities and expected chemical formula to identify the space group and determine the crystal structure by direct methods. The partial structure model located by SIR2019 was completed and refined using full-matrix least-squares techniques by SHELXL2014 (ref. 41). Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were positioned by difference Fourier map; their atomic coordinates were freely refined and the following constraints on their isotropic U value of hydrogen atoms were applied: \( U_{	ext{eq}}(\text{H}) = 1.2 U_{	ext{eq}}(\text{C}) \) and \( U_{	ext{eq}}(\text{H}) = 1.5 U_{	ext{eq}}(\text{N}) \) in the case of hydrogen atoms bonded to carbon and nitrogen atoms, respectively.

Optical setup. The samples were inserted in a cryostat equipped with a resistor to control the operating temperature and cooled down to liquid helium temperature for high-magnetic-field measurements. Extended Data Fig. 2 shows a sketch of the optical setup. The measurements are performed in reflection configuration, using a closed-cycleattoDRY1000 cryostat, a continuous-wave laser at 488 nm and a start-up grant from Tsinghua University. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

The authors declare no competing interests.

Data availability

The datasets generated and analysed during the current study are available in the Open Science Framework (OSF) repository via the following link: https://osf.io/x5h7v/.

Author contributions

L.P. realized the experiments with the help of M.D.G. and G.L. D.S., G.L. and M.D.G. supervised the experimental part with the help of V.A., F.T. and D.B. L.P, L.D.M., A.C., M.P., C.T.P., Q.X., A.F. and V.M. fabricated the samples. A.M. and C.G. carried out the structure characterization by single-crystal X-ray diffraction and V.O. performed X-ray measurements. D.D.S., G.M., L.D. and L.P. performed the treatment of the experimental data. D.D.S. and G.M. performed analytical calculations. L.P., M.D.G., L.D. with the help of G.L. and D.S. wrote the manuscript with input from all the authors. All authors have contributed to the discussion of the work.

Competing interests

The authors declare no competing interests.

Additional information

Extended data are available for this paper at https://doi.org/10.1038/s41565-021-00977-2.

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1038/s41565-021-00977-2.

Correspondence and requests for materials should be addressed to Milena De Giorgi, Luisa De Marco or Dmitry D. Solnyshkov.

Acknowledgements

We acknowledge P. Cazzato for technical support, I. Tarantini for metal evaporation, and D. Gerace and A. Gianfrate for useful discussions. We acknowledge the project PRIN Interacting Photons in Polariton Circuits (INPhoPOL) (Ministry of University and Scientific Research (MIUR), 2017P9FBS_001, the project TECNOMED—Tecnopolo di Nanotecnologia e Fotonica per la Medicina di Precisione (Ministry of University and Scientific Research (MIUR) Decreto Direttoriale number 3449 of 4 December 2017, CUP B83B17000100001) and the Accordo bilaterale CNR/INFN (Russoni)—triennio 2021–2023. G.G. gratefully acknowledges the project PERSO-PERovskite-based Solar cells: Towards High Efficiency and Long-term Stability (Bando PRIN 2015, Italian Ministry of University and Scientific Research (MIUR) Decreto Direttoriale number 2488 of 4 November 2015, project number 20155LECJ). D.D.S. and G.M. acknowledge the support of the projects EU QUANTOPOI (846355), Quantum Fluids of Light (ANR-16-CE38-0021), ANR Labex GaNEXT (ANR-11-LABX-0014) and ANR programme Investissements d’Avenir through the IDEX-ISITE initiative 16-IDEX-0001 (CAP 20-25). Q.X. gratefully acknowledges the National Natural Science Foundation of China (number 12020101003), strong support from the State Key Laboratory of Low-Dimensional Quantum Physics and a start-up grant from Tsinghua University. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

For theoretical information, contact D.D.S. (dmitry.solnyshkov@uca.fr); for materials information, contact L.D.M. (luisa.demarco@nanotec.cnit.it).

The authors declare no competing interests.

Additional information

Extended data are available for this paper at https://doi.org/10.1038/s41565-021-00977-2.

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1038/s41565-021-00977-2.

Correspondence and requests for materials should be addressed to Milena De Giorgi, Luisa De Marco or Dmitry D. Solnyshkov.

Peer review information Nature Nanotechnology thanks the anonymous reviewers for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.
Extended Data Fig. 1 | See next page for caption.
Extended Data Fig. 1 | Temperature dependence. Comparison of the energy vs the \( k_y \) in-plane momentum dispersion maps of the photoluminescence intensity at 9 T as function of the temperature of a 3 μm-thick single crystal. As the temperature increases, the exciton moves towards higher energy, inducing the increase of the photonic fractions for all polariton bands. d), e), f) Experimental Berry curvature extracted from the polarization-resolved measurements, for the band 2 at D) 4 K, e) 50 K and D) 100 K. The photonic fraction of the band 1 increases from 0.344 at 4 K to 0.366 at 100 K. g) Asymmetry ratio (ratio between \( B_0 \) and the maximal \( B_z \) value on the axis \( k_y = 0 \mu \text{m}^{-1} \)) versus temperature. The error bars indicate the measurement uncertainty.
Extended Data Fig. 2 | Optical Setup. Sketch of the optical setup.