Optical physics

https://doi.org/10.1038/s41566-024-01453-8

Strain-induced Landau levels in photonic crystals

Mahmoud Jalali Mehrabad & Mohammad Hafezi

Nanofabricated strained photonic crystals in silicon platforms enable the formation of photonic Landau levels at telecommunication wavelengths, with broad potential applications for enhanced light–matter interactions on-chip.

A fascinating feature of electrons is that they can be controlled with a magnetic field thanks to their intrinsic 'spin' and 'charge'. In the classical picture, an electron in the presence of an external magnetic field experiences a force, described by the Lorentz law. This force causes the electron's trajectory to curve into circular cyclotron orbits. In the quantum domain, the motion of electrons in a cyclotron is quantized, leading to the splitting of their energy spectrum into discrete states known as Landau levels. These Landau levels are highly degenerate, meaning that multiple electrons can occupy the same energy level.

In the 1980s[1], this quantized, magnetic-field-induced cyclotron motion of electrons gave birth to the field of topology in physics. Specifically, it was shown that when two-dimensional electron gas systems were subjected to strong perpendicular magnetic fields, the fascinating physics of quantum Hall arises. Robust quantization of the Hall conductance, the emergence of chiral electronic edge states at the system's boundaries, and many other quantum Hall and topological insulating states were demonstrated, and these discoveries were celebrated by three Nobel physics prizes in 1985, 1998 and 2016.

Later, in 2009 (ref. 2), it was shown that the honeycomb lattice of graphene could be strained to engineer similar electronic Landau levels, in which strain acts as a pseudo-magnetic field. This realization motivated research into using strain as a pseudo-magnetic field, even for uncharged particles, including neutral cold atoms[3] and continuum (free-space) photons[4]. In electronic crystals magnetic fields can be used to induce Landau levels, but the uncharged nature of photons necessitates alternative approaches to bring about similar control over photons. To address this challenge, a quest began to engineer Landau levels for photons and enable similar exotic quantum Hall physics in the realm of photonics. Photonic crystals were found to be exciting candidate materials because the physics of photons in a photonic crystal is nearly identical to the physics of electrons on a lattice, in the single-particle regime.

Therefore, motivated by earlier work on graphene, efforts were made to engineer a photonic crystal analogue of graphene, in which carbon atoms are replaced by holes, helical waveguides or pillars to form honeycomb photonic crystals. Examples of unstrained realizations include laser-defined waveguides in glass[5] and suspended honeycomb photonic crystal slabs[6]. To realize pseudo-magnetic fields and other gauge fields in photonic graphene, a strained version of the laser-defined waveguides in glass[7] as well as GaAs microcavity polaritonic pillars[8] have also been developed.

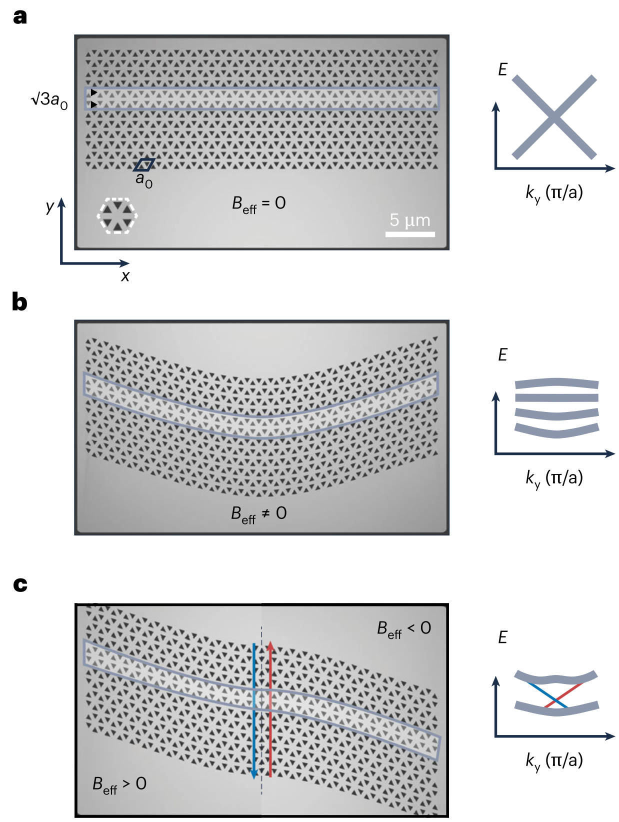

Fig. 1 | Strain-induced Landau levels in photonic crystals. a, A photonic crystal analogue of graphene with a hexagonal unit cell (with lattice constant a_0), comprising six equilateral triangular holes in a honeycomb lattice. In this unstrained case, the effective magnetic field is zero (B_{eff} = 0) and the band structure of the lattice (the energy E as a function of wavevector along the y direction k_y) includes linear bands crossing at the Dirac point. **b**, A strained photonic crystal, in which the lattice is deformed in the negative y-direction, leads to the formation of dispersive Landau levels. **c**, Interfacing two strained photonic crystals with opposite strains leads to the formation of unidirectional boundary states, marked by red and blue arrows (here shown for one circular polarization only).

Recent work has brought these efforts to the nanometre scale and compact on-chip platforms, following a recent theoretical proposal[9]. Two independent groups — Barsukova et al.[10] and Barczyk et al.[11] — recently reported in *Nature Photonics* the formation of Landau levels in a strained honeycomb photonic crystal of triangular holes fabricated in silicon slabs at telecommunication wavelengths.

Starting with an unstrained honeycomb photonic crystal made of equilateral triangular holes in a hexagonal unit cell with sub-micrometre lattice periodicity and a silicon slab thickness of 220 nanometres, they demonstrate the formation of the Dirac-like dispersion of the lattice, with near-linear bands crossing at the Dirac point. The use of triangular holes instead of conventional circular counterparts avoids parasitic bulk bands near the Dirac point and was motivated by a design that was previously used for engineering a spin–Hall topological photonic waveguide[6]. Then, by designing a photonic crystal in which the lattice is designed to be strained in one dimension, they synthesize an effective magnetic field, which leads to the formation of dispersive Landau levels (see Fig. 1).

From a practical point of view, on-chip engineering of photonic Landau levels can have broader applications if it is combined with accessible excitation and detection mechanisms. To address this challenge, each group used a different technique. Barczyk and colleagues took advantage of the shrinking of unit-cell deformation, which is a well-known technique for bringing the bands above the light cone in these photonic crystals, to facilitate experimental free-space detection of the Landau levels. This technique has a small but noticeable effect on the band structure because it lifts the Dirac point degeneracy and leads to the opening of a mini-gap. Barsukova and colleagues instead used the period-doubling procedure, an alternative method that preserves the degeneracy of the Landau levels.

Notably, the Landau levels engineered with this approach are not flat but instead quite dispersive, as predicted by the theory[9]. Importantly, Barsukova and colleagues show that the implementation of a pseudo-electric field can help to flatten the Landau levels. However, when using this method, each individual Landau level needs a different pseudo-electric field to be flattened.

The small footprint, on-chip integrability, sub-wavelength controllability and compatibility with current nanofabrication technology render these demonstrations of Landau levels in silicon photonic crystals intriguing. For example, it would be exciting to explore the engineering of enhanced light–matter interactions (see a recent example of photonic flat-bands for free electron radiation[12]) and lasing with solid-state, colloidal or quantum well excitons integrated into such photonic crystals. Moreover, on-chip engineering of Landau levels is only one of the manifestations of strained photonic crystals. Looking ahead, it would be intriguing to explore other applications, such as engineering other synthetic gauge fields. Furthermore, since this synthetically engineered strain can be locally designed on a photonic crystal, one can design a variety of periodically strained superlattice structures. This may enable such synthetic gauge fields to be harnessed in moiré lattices and quasi-crystals, and their interplay with integrated two-dimensional materials to be explored. Finally, the low-loss and large-area characteristics of these silicon photonic crystal systems (which can involve thousands of unit cells on a single device) could provide an excellent platform for investigating the role of disorder in Landau levels, topological edge states and metasurface modes.

Mahmoud Jalali Mehrabad & **Mohammad Hafezi**
Joint Quantum Institute, University of Maryland, College Park, MD, USA.
e-mail: mjalalim@umd.edu; hafezi@umd.edu

Published online: 6 June 2024

References

1. Klitzing, K. V., Dorda, G. & Pepper, M. *Phys. Rev. Lett.* **45**, 494–497 (1980).
2. Guinea, F., Katsnelson, M. I. & Geim, A. K. *Nat. Phys.* **6**, 30–33 (2009).
3. Aidelsburger, M., Nascimbene, S. & Goldman, N. *C. R. Phys.* **19**, 394–432 (2018).
4. Schine, N., Ryou, A., Gromov, A., Sommer, A. & Simon, J. *Nature* **534**, 671–675 (2016).
5. Rechtsman, M. C. et al. *Phys. Rev. Lett.* **111**, 103901 (2013).
6. Barik, S. et al. *Science* **359**, 666–668 (2018).
7. Rechtsman, M. C. et al. *Nat. Photon.* **7**, 153–158 (2012).
8. Jamadi, O. et al. *Light Sci. Appl.* **9**, 144 (2020).
9. Guglielmon, J., Rechtsman, M. C. & Weinstein, M. I. *Phys. Rev. A* **103**, 013505 (2021).
10. Barsukova, M. et al. *Nat. Photon.* https://doi.org/10.1038/s41566-024-01425-y (2024).
11. Barczyk, R., Kuipers, L. & Verhagen, E. *Nat. Photon.* https://doi.org/10.1038/s41566-024-01412-3 (2024).
12. Yang, Y. et al. *Nature* **613**, 42–47 (2023).

Competing interests

The authors declare no competing interests.