Photonic quadrupole topological insulator using orbital-induced synthetic flux

Julian Schulz1,*, Jiho Noh2,†, Wladimir A. Benalcazar3,4, Gaurav Bahl2, and Georg von Freymann1,5

1Physics Department and Research Center OPTIMAS, TU Kaiserslautern, 67663 Kaiserslautern, Germany
2Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
3Department of Physics, Princeton University, Princeton, New Jersey 08542, USA
4Department of Physics, Emory University, Atlanta, GA 30322, USA
5Fraunhofer Institute for Industrial Mathematics ITWM, 67663 Kaiserslautern, Germany

*schulz@rhrk.uni-kl.de  †jihonoh@illinois.edu

Abstract: We demonstrate that mixing different orbitals can induce synthetic π-flux threading the lattice. As an experimental demonstration of such a concept, we realize a quadrupole topological insulator in a photonic lattice. © 2023 The Author(s)

The richness of physical properties in molecules and crystalline structures is closely related to the underlying orientation and connectivity of atomic orbitals. The recent advance in the ability of synthetic systems to replicate the properties of the real materials allowed for the orbital degree of freedom to be incorporated into synthetic systems by using analogous wavefunctions with distinct nodal structures. In particular, mixing orbitals, such as s and p orbitals, has been shown to be useful for generating systems that require alternating phase patterns such as the sign of couplings within the system. Here, we show that by further breaking the symmetries of such mixed-orbital lattices, it is possible to generate a synthetic magnetic flux of π threading the lattice. As a demonstration of such capability, we experimentally demonstrate a quadrupole photonic topological insulator [1], which requires π-flux threading each plaquette of the lattice, in a two-dimensional lattice of circular and elliptical waveguides that consist of modes with both s and p orbital-like symmetry representations. The judicious control of different orbitals in a four-site unit cell, as shown in [Fig. 1(a)], creates a synthetic magnetic flux of π that opens a gap at “half-filling”, which, along with the modulation in the coupling strengths, results in the gapped system with a quadrupole topological insulator phase. We exploit the property that as a wavefunction crosses one of the p-orbitals [site 3 in Fig. 1(a)] in a unit cell, a π-phase is accumulated, thereby inducing a synthetic flux in the plaquette.

The Bloch Hamiltonian for this system, in the tight-binding approximation (only including nearest-neighbor couplings), can be written as

\[
H(k_x, k_y) = \begin{pmatrix}
0 & 0 & \gamma - \lambda e^{i k_x a} & \gamma - \lambda e^{i k_y a} \\
0 & 0 & -\gamma + \lambda e^{-i k_x a} & \gamma - \lambda e^{-i k_y a} \\
\gamma - \lambda e^{-i k_x a} & -\gamma + \lambda e^{i k_x a} & 0 & 0 \\
\gamma - \lambda e^{-i k_y a} & 0 & 0 & 0
\end{pmatrix},
\]  

(1)

where \(a\) is the lattice constant and \(\gamma\) and \(\lambda\) are the nearest-neighbor coupling terms within and across unit cells, respectively. The bulk Hamiltonian is gapped for \(|\gamma/\lambda| \neq 1\) but closes when \(|\gamma/\lambda| = 1\), where the topological transition occurs. This system closely resembles that of the quadrupole insulators presented in Ref. [1]. The Hamiltonian in Eq. (1) has two mirror symmetries \(M_x\) and \(M_y\), which do not commute with each other, and also has \(C_4\) symmetry. These symmetries protect the quantization of both components of the bulk dipole moments \(p_{x,y}\), and the quadrupole moment \(q_{xy}\). Using the nested Wilson loop method, we compute the polarizations and find that \(p_{x,y} = 0\) for both \(|\gamma/\lambda| > 1\) and \(|\gamma/\lambda| < 1\). On the other hand, we find that \(q_{xy} = 0\) for \(|\gamma/\lambda| > 1\) but \(q_{xy} = 1/2\) for \(|\gamma/\lambda| < 1\).

We experimentally verify the quadrupole topology of the system by considering a two-dimensional lattice of waveguides [Fig. 1(a)]. A square unit cell is composed of four waveguides: two circular waveguides and two elliptical waveguides that have the major axes tilted from the y-axis by ±45°, respectively. We control the radii of waveguides such that the lowest-energy mode (s-orbital) of the circular waveguides and the second-lowest-energy mode (p-orbital) of the elliptical waveguides have the same energy, which enables the coupling between the different modes. We inject light with a wavelength of 760 nm to a selected waveguide at the input facet of the waveguide array fabricated using a Nanoscribe Photonic Professional GT [2] and measure the diffracted light at the output facet. The radii of the major and minor axes of the elliptical waveguides are 0.6 μm and 1.3 μm, and the radius of the circular waveguides is 0.5 μm. The distances between the waveguides determine the coupling.
Fig. 1. (a) Schematic of the quadrupole topological insulator with orbital-induced synthetic flux. For the tight-binding model, $\gamma$ and $\lambda$ are the nearest-neighbor coupling terms within (black) and across (red) unit cells, respectively. Dashed lines represent coupling terms with negative signs due to the overlap with the negative part of the $p$-orbital. Numbers indicate the basis of the Hamiltonian operator. (b-e) Measured intensity profiles at the output facet of the waveguide structures. (b) Light is injected into the waveguide at the left corner of the waveguide array in the trivial phase and (c) non-trivial phase, respectively, and (d) when light is injected into the auxiliary waveguide directly at the left corner of the waveguide array in the non-trivial phase and (e) trivial phase, respectively. Waveguides, where light is injected at the input facet, are indicated with yellow arrows. The intensity profiles are normalized to their respective maximum value to increase visibility.

strength, which in our structure are dimerized to be $1.6 \, \mu m$ and $2.1 \, \mu m$ for strong and weak couplings, respectively. The core of the waveguide is made out of SU8 with a refractive index of $n_{\text{core}} = 1.59$ and is surrounded by IP-Dip, which has a refractive index of $n_{\text{clad}} = 1.54$.

To experimentally observe the corner-localized modes [3], the light was injected into a waveguide at one of the corners of the waveguide array, and in Fig. 1(b-c), we show the diffracted light observed from the output facet after propagating 1 mm through the structure for two different topological phases. In the topologically trivial phase, the light diffracts across the bulk [Fig. 1(c)] while it stays localized at the corner in the non-trivial phase [Fig. 1(b)], which is the manifestation of the corner localized modes being in the bandgap. However, this alone does not prove the quadrupole properties, as this behavior was also observed in a similar system system without a $\pi$-flux. There, the corner state lies not in a bandgap but is a bound state in the continuum [4]. To demonstrate that the corner localized modes in our system are indeed topologically non-trivial modes due to the quadrupole topology, we introduce auxiliary waveguides. These auxiliary waveguides are weakly coupled to the lattice such that they can be used as an external drive injecting light into the lattice at the energy of their bound modes, which is chosen to be at midgap, without significantly changing the intrinsic modes of the lattice [5]. In our system, the light initially injected at the auxiliary waveguide couples only to the corner state in the non-trivial phase [Fig. 1(d)] but does not couple into the system in the trivial phase [Fig. 1(e)]. This proves experimentally that the $\pi$-flux in the unit cell, induced by having both $s$ and $p$ orbitals in the system, creates a bandgap, and that the corner localized modes in the non-trivial phase are pinned at midgap due to the quadrupole topology of the system.

References

1. W. A. Benalcazar, B. A. Bernevig, and T. L. Hughes, “Quantized electric multipole insulators,” Science 357, 61–66 (2017).
2. J. Schulz, S. Vaidya, and C. Jürg, “Topological photonics in 3d micro-printed systems,” APL Photonics 6, 080901 (2021).
3. J. Schulz, J. Noh, W. A. Benalcazar, G. Bahl, and G. von Freymann, “Photonic quadrupole topological insulator using orbital-induced synthetic flux,” Nat. Commun. 13, 6597 (2022).
4. A. Cerjan, M. Jürgensen, W. A. Benalcazar, S. Mukherjee, and M. C. Rechtsman, “Observation of a higher-order topological bound state in the continuum,” Phys. Rev. Lett. 125, 213901 (2020).
5. J. Noh, W. A. Benalcazar, S. Huang, M. J. Collins, K. P. Chen, T. L. Hughes, and M. C. Rechtsman, “Topological protection of photonic mid-gap defect modes,” Nat. Photonics 12, 408–415 (2018).