Direct observation of “pseudospin”-mediated vortex generation in photonic graphene

Daohong Song[1], Liqin Tang[1], Yi Zhu[2,3], Mark Ablowitz[3], Vassilis Paltoglou[4] , Nikolaos K. Efremidis[4], Jingjun Xu[1], and Zhigang Chen[1,5]

1. *The MOE Key Laboratory of Weak-Light Nonlinear Photonics, and TEDA Applied Physical Institute and School of Physics, Nankai University, Tianjin 300457, China*
2. *Zhou Pei-Yuan Center for Applied Mathematics, Tsinghua University, Beijing, 100084, China*
3. *Department of Applied Mathematics, University of Colorado, 526 UCB, Boulder, Colorado 80309-0526, USA*
4. *Department of Applied Mathematics, University of Crete, 71409 Heraklion, Crete, Greece*
5. *Department of Physics and Astronomy, San Francisco State University, San Francisco, CA 94132*

Abstract: We observe vortex generation by selective excitation of two honeycomb sublattices at the vicinity of Dirac points. Such vortices arise from graphene “pseudospin”, suggesting that “pseudospin” could be observable and possess real angular momentum.

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“Pseudospin”, as an additional degree of freedom inherent in graphene [1], has intrigued scientists due to its importance in understanding fundamental phenomena such as Klein tunneling, absence of backscattering, and unusual half-integer quantum Hall effect [2]. Yet, thus far the pseudospin has been considered as uncontrollable, unmeasurable, and rather merely a mathematic formality. Recently, however, it was proposed that graphene pseudospin is a real angular momentum, just as the spin of electrons with a half-integer angular momentum [3]. Although the pseudospin is not linked with any magnetic moment of an electron and thus cannot be detected by Stern-Gerlach-type experiments, it could manifest itself in observable quantities and be detected in transport as well as optical measurements on graphene, as so predicted [4]. So far, to our knowledge, no experimental test has verified these predications. Here, we study linear propagation of light in the vicinity of the Dirac points in a honeycomb lattice – optical equivalent of graphene [5-8]. By selectively exciting the two sublattices of the photonic graphene, we experimentally observe the generation of a singly-charged vortex and its charge flipping in otherwise vortex-free probe beams linearly passing through the lattice. By comparing with numerical simulations of the linear massless Dirac equation, we argue that such a vortex might arise from the graphene pseudospin, advocating the belief that the pseudospin is not just for theoretical elegance but rather has a real angular momentum.

Photonic graphene can be established by the method of optical induction or with the fs laser-written technique that can create honeycomb lattices. Such photonic graphene has provided an ideal platform to explore graphene phenomena, some of which are difficult or even impossible to observe in carbon-based graphene, including for example conical diffraction and gap solitons, strain induced pseudospin magnetic field, Floquet topological insulator, and unconventional edge states [6-7]. The physical insight behind the optical analogous of these phenomena arises from the similarity between the paraxial equation that describes light propagation in honeycomb photonic lattices and the Schrödinger equation for the electrons evolution in graphene.

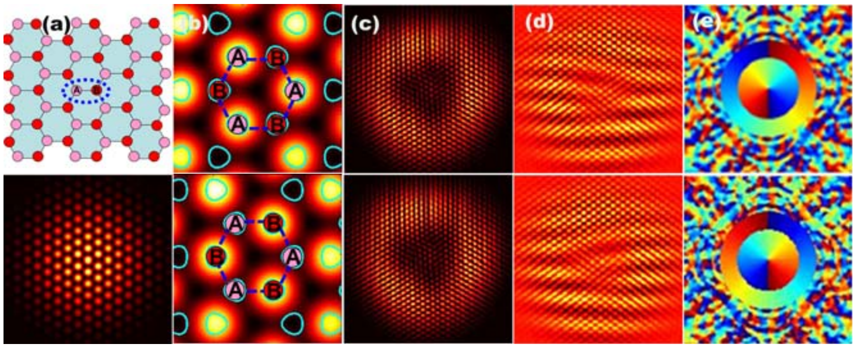

Fig.1: Numerical results showing pseudospin-mediated vortex generation in photonic graphene when sublattice A (top row) and B (bottom row) were excited separately. (a) Schematic of the honeycomb lattice (top) and the input beam pattern (bottom), where the dashed ellipse marks the unit cell of the lattice containing two unequal “atoms” A and B; (b) The input beam superimposed with sublattice A (top) and B (bottom), corresponding to different pseudospin states; (c) Linear output pattern of the probe beam; (d) Interference pattern of (c) with an inclined plane wave, showing the phase singularity in the center; (e) The phase pattern from solving the Dirac equation directly for two different pseudospin states.

As shown in Fig. 1(a), the honeycomb lattice does not belong to the Bravais lattice, since its unit cell contains two unequal sites labeled as A and B, and it is in fact composed of two interpenetrating triangular sublattices. The unique symmetry of the lattice leads to that the first two bands touching together at six points called the Dirac points, where the dispersion spectrum at the vicinity is linear and the wave dynamics is governed by the Dirac equation

. The wavefunctions near the Dirac points are described by two-component spinor functions, with the basis of the two sublattices, mimicking the spin up and spin down of the spin 1/2 electron, thus referred to the "pseudospin". In the following, we will show by numerical simulation and experimental observation that the pseudospin associated with the two sublattices can lead to excitation-dependent vortex generation.

Numerically, the pseudospin states can be excited by sending three interfering plane waves with their wave vectors pointing at three alternative Dirac points in the *k*-space. In one setting (three waves are of equal phase), only sublattice A is excited, with vanishing intensity on subattice B (Fig.1(b) top), while in another setting (three waves are of a $2\pi/3$ phase difference at the Dirac points), only sublattice B is excited but not sublattice A (Fig.1(b), bottom). The output of the three waves is then monitored by another inclined plane wave for phase measurement at the exit from the honeycomb lattice. Typical results from simulation are summarized in Fig.1. Apparently, the output intensity exhibits a ring-like pattern with a lower central intensity (Fig.1(c)) – characteristic of the conical diffraction [5]. Although the output intensity patterns look quite similar, the phase structures for the two excited "pseudospin" states are different. In both cases, a singly-charged vortex is created, as identified by a fork bifurcation in the central fringes. Moreover, the generated vortex has opposite charges, as seen from opposite directions of fringe bifurcation. Specifically, the pseudsopin associated with sublattice A leads to a fork pointing to the left (Fig.1(d), top), but the pseudospin of sublattice B results in a fork pointing to the right (Fig1.(d), bottom). It should be noted that, the input beams contain no initial angular momentum. When both sublattices are excited, the vortex singularity disappears. Furthermore, when the honey-comb lattice is replaced by a single triangular lattice, again no vortex is generated. These results indicate that the vortex arises from graphene pseudsopin, as described by the Dirac equation [3]. This is further confirmed by directly solving the Dirac equation of honeycomb lattices, as shown in Fig1.(e) [8].

Experimentally, we have also observed similar vortex generation due to pseudospin in an optically induced honeycomb lattice [7]. The input beam consists of three broad Gaussian beams aiming at one group of three Dirac points in *k*-space. Sublattices A and B can be excited separately by slightly moving the focusing lens laterally. Experimental results (output after 2 cm) corresponding to simulation are shown in Fig. 2, where we can see clearly the vortex generation with opposite topological charge under two different excitations (Fig.2(b) and Fig.2(d)). When the lattice is absent, no vortex is observed whatsoever. These experimental results agree well with our numerical results.

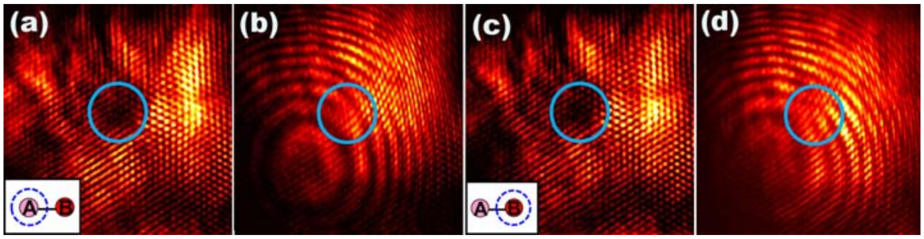

Fig.2: Experimental observation of vortex generation in optically induced photonic graphene corresponding to two different pseudospin states shown in Fig. 1. Shown are (a, c) output intensity patterns and (b, d) corresponding interferograms when only (a, b) sublattice A or (c, d) sublattice B is excited.

In summary, we have demonstrated the vortex generation mediated by the pseudospin in honeycomb photonic lattices. Our results not only suggest that the graphene pseudospin should have real angular momentum, but also represent a novel mechanism of generating optical beams with angular momentum by employing specially designed periodical structures.

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