Multimode Floquet Photonic Topological Insulators

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Abstract: We show that it is possible to have a multimode Floquet photonic topological insulator. We show that the use of high order modes introduces new degrees of freedom that can help to realize novel topological phenomena.

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Photonic lattices provide a versatile platform to design novel structures that enable us to control and manipulate the propagation of light in nontrivial ways. These photonic structures have been used not only to bring condensed matter concepts to optics, as the Floquet photonic topological insulators [1], but also to demonstrate for the first time important phenomena. For example, photonic topological Floquet Anderson insulators [2], photonic anomalous Floquet topological insulators [3] and the idea of topological insulator quasicrystals [4]. Also, changing the phase and magnitude of the coupling between the waveguides in these lattices, leads to interesting results. For example, it was theoretically proposed in [5], that topological polaritonic states could be formed by coupling excitons and photons with the help of a complex angle dependent phase coupling. In [6], local "pseudomagnetic fields" were created by deforming the honeycomb lattice and therefore changing the magnitude of the couplings. However, in most of these examples, only the fundamental mode of these waveguides has been used. In this regard, photonic lattices with higher order modes have an advantage. This is because compared to the symmetric profile of the fundamental mode, the higher order modes with asymmetric phase profiles offer new degrees of freedom. For example, using higher order modes we could change the coupling strength without deforming the lattice and therefore we can "deform" the lattice in nontrivial ways. Hence, these enable us to achieve photonic lattices with very different characteristics. In this work, we explore this potential for the case of Floquet photonic topological insulators.

Here, we show that it is possible to have a multimode Floquet photonic topological insulators. This is, a photonic lattice that behaves as a topological insulator but for the second mode of each waveguide instead of the fundamental one. Using the second mode has nontrivial implications, since as we show, for the second mode the coupling constant and its phase are angle dependent due to natural asymmetry of such modes.

The first problem in finding such a photonic lattice is that usually the second order mode is already in the continuum, no bounded, due to the low refractive index contrast of these lattices. To solve this problem within experimentally reachable parameters we fine tune the refractive index contrast, the shape of the waveguides, and the

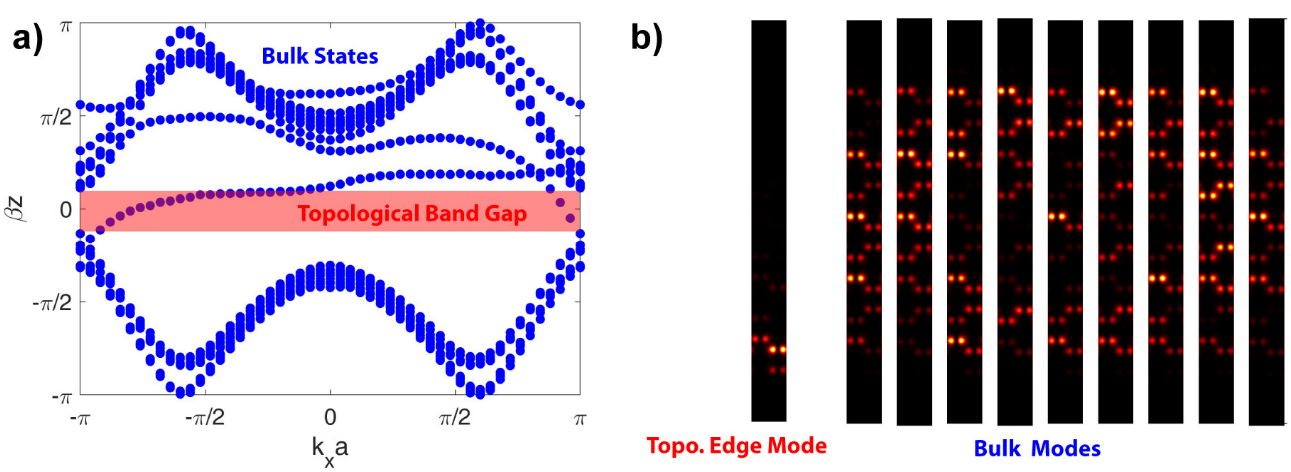

Fig. 1. (a) Dispersion diagram of the Floquet topological insulator photonic lattice for the second mode bands. The gapless states that go across the topological band gap are the edge states. **(b)** The field plot of the Floquet second band eigenmodes.

wavelength. To find the suitable range of parameters we start by making bound the second mode of a single waveguide, this is, the propagation constant of such mode must be negative. Interestingly, the fact that a single wave guide supports a second bound mode does not warranty that an array of the same waveguides will also support such a bound mode. For this reason, we start with a single waveguide, then move to a one dimensional waveguide. By studying the coupling between the elliptical waveguides on a one dimensional lattice we found that the magnitude of the second mode could be positive or negative depending on the angle due to the “dipole” shape of the second order mode. More importantly, there is an angle were the coupling is zero, this represent an interesting mechanism to cancel the interaction, if needed, between waveguides that are close to each other.

After we achieve a bounded second energy band for a 1D lattice of waveguides, we tailor a honeycomb lattice such that it has a large coupling, no radiating modes and Dirac points in the bandstructure. This is important because at each stage, from single waveguide to 1D lattice of waveguides and finally to a honeycomb lattice, the condition to have radiating modes is different. This is because the interaction between the waveguides repel the bands and can make bands become radiating, even as the array is made with waveguides that have the second mode bounded. In order to tailor the appropriate lattice, we keep two important things in mind. As we increase the wavelength, the mode overlap increases, and the coupling strength increases but the mode becomes less bounded and might become radiating. And if we decrease the wavelength, the mode overlap decreases, and the coupling strength decreases but the mode becomes bounded. The opposite is true with the index contrast. We also tune the parameters so that we have bands with "Dirac points". This is important because Dirac points are "minimal crossing" – any small perturbation can open a band gap.

In order to make the lattice topological we introduce helicity, as done for the first Floquet topological insulator using the single mode waveguides [1]. The idea is that by introducing helicity to the honeycomb lattice of straight waveguides, we want to open a topological bandgap. In contrast to photonic lattices that only use the fundamental mode and that can be described by a tight-binding system, using the second mode requires a full continuum analysis to find the eigenmodes of the lattice. The problem is that now we have a Floquet system that is continuous and calculating the eigenstates of a continuous z-dependent system is computationally very demanding. In principle one needs to propagate each pixel of the discretized 2D space. To cover the unit cell of a one-dimensional strip of the array one will need at least 1000x50 pixels, that is one needs to propagate 50,000 times different fields during a whole Floquet period. To solve this, we use the following method proposed in [7]. There, the N-modes of the static system, this is the system with straight waveguides, are identified as a basis for the bound modes of the Floquet system. The Floquet operator is represented in this basis by propagating just the N-basis vectors. Thus, this method allows us to solve for the Floquet bandstructure without going through the continuous problem of highly intensive numerical calculations. In this way, we calculate the Floquet band structure and eigenmodes for different values of the helical radius of the waveguides and find a value of the radius which opens the biggest bandgap possible. As the band gap increases, the group velocity which is given by the slope of the dispersion curve of the edge state also increases. This ensures that the edge states are more localized to the edges and its group velocity around the edge is faster. The Floquet second energy band structure and the eigenmodes for the desired radius are shown in Fig. 1. As we can clearly see there, there is a gapless family of states between the two bulk bands, and once we plot this eigenmode we can see that these are indeed edge states.

Lastly, we verify the topological protection of the edge states by propagating a beam at the edge of the honeycomb lattice. We observe that the beam goes around the corner of the lattice without backscattering due to the absence of counter-propagating states and without scattering into the bulk. Thus, this confirms the topological protection of the edge states of the second mode Floquet topological insulator photonic lattice.

In conclusion, we show the existence of topological edge states in multimode Floquet photonic topological insulators. We believe that the additional degrees of freedom of the higher order topological edge states will enable the realization of novel topological phenomena.

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