 Observation of Topological Band Gap Solitons

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Abstract: We present the first experimental observation of solitons in the bulk of a photonic Floquet topological insulator. We probe a family of these nonlinear states residing on the topological band gap and performing cyclotron-like orbits. © 2020 The Author(s)

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The electronic states of certain materials are called topological when they cannot be smoothly deformed into a standard material without closing and reopening the bulk band gap. Such a system, known as a topological insulator, exhibits an insulating bulk and scatter-free robust edge or surface transport. Over the past few years, many of these topological materials have been predicted and realized in a wide variety of experimental platforms ranging from but not limited to electronic, photonic, phononic and ultra-cold atomic systems [1]. In particular, exploring topological properties in photonic systems [2] has emerged as an exciting field of research having great promise for practical applications. However, previous works in these systems mostly focused on the linear domain, where photons propagate independently, and inter-particle interactions are irrelevant. Here, we explore the interplay between topology and nonlinear dynamics and experimentally demonstrate spatial solitons [3] in a topological band gap. In our experiments, light propagation across the photonic topological insulator is governed by the discrete nonlinear Schrödinger equation where nonlinearity arises from the self-focusing optical Kerr effect. In this case, the propagating optical field induces a nonlinear dielectric polarization, producing an intensity-dependent refractive index. It should be mentioned that the Kerr effect is equivalent to the mean-field bosonic interactions in a Bose-Einstein condensate, described by the Gross-Pitaevskii equation.

Here we consider a periodically driven photonic square lattice with engineered nearest-neighbor couplings. The complete driving period \( z_0 \) is divided into four equal steps and each waveguide is successively coupled to one of its four nearest neighbors in a cyclic manner. A simplified schematic of the three-dimensional waveguide paths is shown in Fig. 1a. The linear Hamiltonian \( H(z + z_0) = H(z_0) \) is periodic along the propagation distance \( z \), and the coupling strengths are tuned such that the Floquet quasienergy spectrum supports a weakly dispersive bulk band and one-way propagating topological edge states connecting the top and bottom of the bulk band. The topology of this anomalous Floquet topological insulator [4, 5] is captured by the winding number [6].

In the nonlinear regime, the scalar-paraxial propagation of optical fields across this photonic lattice can be described by the following discrete nonlinear Schrödinger equation:

\[
i \frac{\partial}{\partial z} \psi_m(z) = \sum_{m'} H_{mm'} \psi_{m'} - g |\psi_m|^2 \psi_m ,
\]

where \( H_{mm} \) is the above-mentioned \( z \)-periodic tight-binding Hamiltonian, \( |\psi_m|^2 \) is the optical power at the \( m \)-th waveguide. The parameter \( g = 2\pi n_2/\lambda A_{\text{eff}} \), where \( n_2 \) is the nonlinear refractive index coefficient, \( A_{\text{eff}} \) is the effective area of the waveguide modes and \( \lambda \) is the wavelength of light. We note that the total energy and the renormalized power \( (\mathcal{P} = g \sum |\psi_m|^2) \) are conserved quantities in the absence of optical losses. To obtain self-localized nonlinear solutions (solitons), we iteratively solve Eq. (1) using a Floquet self-consistency method [7].

In these numerical calculations, a family of Floquet solitons was found in the topological band gap (see red circles in Fig. 1b). Unlike solitons in a static system, these Floquet solitons can alter their shapes and stroboscopically reproduce themselves with a periodicity \( z_0 \). More specifically, it was observed that the solitons exhibit a cyclotron-like motion which is the micromotion associated with the Floquet driving. Irrespective of the quasienergy, these solitons were found to be strongly localized on a single site, i.e. most of the optical power is contained at a single site surrounded by a small background. As detailed below, this intensity profile makes it possible to experimentally probe the soliton family by coupling light into a single optical waveguide.

Using femtosecond-laser-writing, this periodically modulated photonic lattice was fabricated inside a 76 mm long borosilicate glass sample (see Fig. 1c). For nonlinear characterizations, we used 5 kHz trains of linearly polarized 2 ps laser pulses at 1030 nm wavelength. We note that the spectral broadening due to the self-phase modulation, the chromatic dispersion and nonlinear loss due to multi-photon absorption were found to be negligible in our experiments [8]. To avoid edge effects, the light was coupled into a single waveguide in the central part of the lattice, and the output intensity patterns were captured as a function of average input power. The variation of the inverse participation ratio (a measure of localization) at \( z = 2z_0 \) is shown in Fig. 1d and the corresponding output intensity patterns for three different input powers are presented in Fig. 1e-g. At low optical power, i.e.,
Fig. 1. (a) Simplified schematic of the three-dimensional paths of four waveguides [see the dashed square in (c)] of the anomalous Floquet topological insulator. (b) Quasienergy spectrum as a function of renormalized power showing the family of bulk solitons (red circles) in the topological band gap. (c) Micrograph of the facet of the laser-fabricated topological insulator. (d) Nonlinear characterization of the topological insulator: IPR as a function of average input power measured at $z = 2z_0$. (e-g) Corresponding output intensity distributions for three different input powers. The red arrow in each image indicates the site where the light was launched at the input. (h) Most localized output intensity distribution measured at $z = 1.5z_0$. When the nonlinear effects are negligible, we observe linear discrete diffraction (Fig. 1e), since the input state overlaps only with the weakly dispersive bulk modes. As input power was increased, the output intensity patterns became more and more localized, and after exhibiting a peak at $P = 3.43$ mW (Fig. 1f), the IPR shows a dramatic delocalization as shown in Fig. 1g. The observed peak in Fig. 1d corresponds to the existence of the topological band gap solitons. It should be highlighted that the observed variation of IPR is different than what is usually observed in a trivial static lattice (e.g., square lattice), where IPR monotonically increases and then saturates at a very high nonlinearity. To confirm the cyclotron-like motion of the solitons, a similar experiment was performed using a lattice with maximal propagation distance $z = 1.5z_0$ instead of $z = 2z_0$ and a similar delocalization to localization to delocalization behavior was observed. In this case, the most localized output was observed near $P = 3.32$ mW as shown in Fig. 1h. Most of the optical power in Fig. 1h is located at a site which is across a diagonal from the injected site (indicated by the red arrow) confirming the cyclotron-like motion of the solitons.

In summary, we experimentally probed discrete spatial solitons spectrally residing in the band gap of a topological insulator. Unlike solitons in usual static lattices, these topological band gap solitons exhibit fundamentally different behavior. In other words, these nonlinear topological states perform cyclotron-like motion and show a distinct localization feature (i.e., delocalization to localization to delocalization) as a function of optical power. Our experiments open a new route towards the investigation of interacting bosonic topological insulators.

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