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Topological orders in Silicon photonics

Mohammad Hafezi
MARYLAND UNIV COLLEGE PARK
3112 LEE BLDG
COLLEGE PARK, MD 20742 - 5100

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3112 LEE BUILDING MD-005
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Topological features - global properties which are not discernible locally - have attracted tremendous research attention in many fields of physics, ranging from condensed matter to ultra cold gases. Recently, photonic systems have been under investigation to explore various types of topological orders and to potentially develop robust optical devices. In this project, we investigated various aspects of topological states by analyzing the transport properties both in non-interacting and interacting regimes, and measuring topological invariants in the non-interacting regime. We theoretically investigated the strongly interacting limit and develop effective theories for topological orders in a non-equilibrium system. Furthermore, we have developed numerical methods to study many-body correlated states in the driven-dissipative regimes.

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Abstract

Topological features – global properties which are not discernible locally – have attracted tremendous research attention in many fields of physics, ranging from condensed matter to ultra cold gases. Recently, photonic systems have been under investigation to explore various types of topological orders and to potentially develop robust optical devices. In this project, we investigated various aspects of topological states by analyzing the transport properties both in non-interacting and interacting regimes, and measuring topological invariants in the non-interacting regime. We theoretically investigated the strongly interacting limit and develop effective theories for topological orders in a non-equilibrium system. Furthermore, we have developed numerical methods to study many-body correlated states in the driven-dissipative regimes.

Technical Section:

A hallmark feature of topological physics is the presence of one-way propagating chiral modes at the system boundary. The chirality of edge modes is a consequence of the topological character of the bulk. For example, in a non-interacting quantum Hall model, edge modes manifest as mid-gap states between two topologically distinct bulk bands. The bulk– boundary correspondence dictates that the number of chiral edge modes, a topological invariant called the winding number, is completely determined by the bulk topological invariant, the Chern number. We measured the winding number in a 2D photonic system, for the first time. By inserting a unit flux quantum at the edge, we showed that the edge spectrum resonances shift by the winding number. This experiment provided a new approach for unambiguous measurement of topological invariants, independent of the microscopic details, and could possibly be extended to probe strongly correlated topological orders [S. Mittal, S. Ganeshan, J. Fan, A. Vaezi, and M. Hafezi , Nature Photonics, 10, 180–183 (2016)].

We proposed a method of measuring topological invariants of a photonic crystal through phase spectroscopy. We showed how the Chern numbers can be deduced from the winding numbers of the reflection coefficient phase. An explicit proof of the existence of edge states in a system with a nonzero reflection phase winding number was given. The method was illustrated for one- and two-dimensional photonic crystals of nontrivial topology. [AV. Poshakinskiy, AN. Poddubny, and M. Hafezi Phys. Rev. A, 91, 043830 (2015)]

We proposed a scheme for realizing fractional quantum Hall states of light. In our scheme, photons of two polarizations were coupled to different atomic Rydberg states to form two flavors of Rydberg polaritons that behaved as an effective spin. An array of optical cavity modes overlapping with the atomic cloud enabled the realization of an effective spin-1/2 lattice. We showed that the dipolar interaction between such polaritons, inherited from the Rydberg states, can be exploited to create a flat, topological band for a single spin-flip excitation. At half filling, this gave rise to a photonic (or polaritonic) fractional Chern insulator—a lattice-based, fractional quantum Hall state of light. [M. F. Maghrebi, N. Y. Yao, M. Hafezi, T. Pohl, O. Firstenberg, and A. V. Gorshkov Phys. Rev. A, 91, 033838 (2015)]

We studied a coupled array of coherently driven photonic cavities, which maps onto a driven-dissipative XY spin- 1/2 model with ferromagnetic couplings in the limit of strong optical nonlinearities. Using a site-decoupled mean-field approximation, we identified steady-state phases with canted antiferromagnetic order, in addition to limit cycle phases, where oscillatory dynamics persist indefinitely. We also identified collective bistable phases, where the system supports two steady states among spatially uniform, antiferromagnetic, and limit cycle phases. We compared these mean-field results to exact quantum trajectory simulations for finite one-dimensional arrays. The exact results exhibited short-range antiferromagnetic order for parameters that have significant overlap with the mean-field phase diagram. In the mean-field bistable regime, the exact quantum dynamics exhibited real-time collective switching between macroscopically distinguishable states. We presented a clear physical picture for this dynamics and established a simple relationship between the switching times and properties of the quantum Liouvillian. [R. Wilson, K. Mahmud, A. Hu, A. Gorshkov, M. Hafezi, and M. Foss-Feig , Phys. Rev A, 94, 033801 (2016)].

We theoretically studied the transport of time-bin entangled photon pairs in a two-dimensional topological photonic system of coupled ring resonators. This system implemented the integer quantum Hall model using a synthetic gauge field and exhibits topologically robust edge states. We showed that the transport through edge states preserved temporal correlations of entangled photons whereas bulk transport did not preserve these correlations and could lead to significant unwanted temporal bunching or anti-bunching of photons. We studied the effect of disorder on the quantum transport properties; while the edge transport remained robust, bulk transport was very susceptible, and in the limit of strong disorder, bulk states became localized. We showed that this localization was manifested as an enhanced bunching/anti-bunching of photons. This topologically robust transport of correlations through edge states could enable robust on-chip quantum communication channels and delay lines for information encoded in temporal correlations of photons [S. Mittal, V. Vikram Orre, and M. Hafezi , Optics Express, 24, 15631-15641 (2016)].

We presented an all-dielectric photonic crystal structure that supports two-dimensionally confined helical topological edge states. The topological properties of the system were controlled by the crystal parameters. An interface between two regions of differing band topologies gives rise to topological edge states confined in a dielectric slab that propagate around sharp corners without backscattering. Three-dimensional finite-difference time-domain calculations show these edges to be confined in the out-of-plane direction by total internal reflection. Such nanoscale photonic crystal architectures could enable strong interactions between photonic edge states and quantum emitters [S. Barik, H. Miyake, W. DeGottardi, E. Waks and M. Hafezi, New J. Phys., 18, 11301 (2016)].

Entanglement, and, in particular, the entanglement spectrum, plays a major role in characterizing many-body quantum systems. While there has been a surge of theoretical works on the subject, no experimental measurement has been performed to date because of the lack of an implementable measurement scheme. We proposed a measurement protocol to access the entanglement spectrum of many-body states in experiments with cold atoms in optical lattices. Our scheme effectively performs a Ramsey spectroscopy of the entanglement Hamiltonian and is based on the ability to produce several copies of the state under investigation, together with the possibility to perform a global swap gate between two copies conditioned on the state of an auxiliary qubit. We show how the required conditional swap gate can be implemented with cold atoms, either by using Rydberg interactions or coupling the atoms to a cavity mode. We illustrate these ideas on a simple (extended) Bose-Hubbard model where such a measurement protocol reveals topological features of the Haldane phase. [Hannes Pichler, Guanyu Zhu, Alireza Seif, Peter Zoller, and Mohammad Hafezi Phys. Rev. X **6**, 041033 (2016).]

Publications

A. Papers published in peer-reviewed journals

[1] AV. Poshakinskiy, AN. Poddubny, and M. Hafezi "Phase spectroscopy of topological invariants in photonic crystals" Phys. Rev. A, 91, 043830 (2015)

[2] M. F. Maghrebi, N. Y. Yao, M. Hafezi, T. Pohl, O. Firstenberg, and A. V. Gorshkov "Fractional Quantum Hall States of Rydberg Polaritons" Phys. Rev. A, 91, 033838 (2015).

[3] S. Mittal, S. Ganeshan, J. Fan, A. Vaezi, and M. Hafezi "Measurement of topological invariants in a 2D photonic system",Nature Photonics, 10, 180–183 (2016)

[4] R. Wilson, K. Mahmud, A. Hu, A. Gorshkov, M. Hafezi, and M. Foss-Feig "Collective Phases of Strongly Interacting Cavity Photons", Phys. Rev A, 94, 033801 (2016)

[5] S. Mittal, V. Vikram Orre, and M. Hafezi "Topologically robust transport of entangled photons in a 2D photonic system", Optics Express, 24, 15631-15641 (2016)

[6] Hannes Pichler, Guanyu Zhu, Alireza Seif, Peter Zoller, and Mohammad Hafezi Phys. Rev. X 6, 041033 (2016).

[7] S. Barik, H. Miyake, W. DeGottardi, E. Waks, and M. Hafezi "Two-Dimensionally Confined Topological Edge States in Photonic Crystals", New J. Phys., 18, 11301 (2016)

B. Papers published in non-peer-reviewed journals or in conference proceedings

[1] S. Mittal, and M. Hafezi "Round the bend with microwaves" Nature 522, 292 (2015). New & Views

C. Papers presented at meetings

[1] META, New York (August 2015), Invited

[2] Physics of Quantum Electronics, Snowbird, Utah, (Jan 2015), Invited

[3] SPIE Photonics West, San Francisco, "Photons in synthetic gauge fields" (Feb 2015) , Invited

[4] SPIE Photonics West, San Francisco, "Controlling Photonic Transport Using Synthetic Gauge Field", (Feb. 2015), Invited

[5] APS March meeting, invited session, San Antonio, "Preparation and measurement of strongly interacting states of photons" (Mar 2015) , Invited

[6] APS March meeting, invited talk, San Antonio, "Photons in synthetic gauge fields" (Mar 2015) , Invited

[7] Winter school, Fai della Paganella, "Topological features in photonics" (Mar 2015)

[8] Winter workshop, Aspen Center for Physics, "Measuring topological invariants in photonic systems" (Mar 2015) , Invited

[9] Advanced Photonics Congress, OSA meeting, "Measuring Topological Invariants in Photonic Systems" (Jun 2015) , Invited

[10] Ecole de Physique, Quebec, Canada "Propriétés topologiques des systèmes photoniques" (Jun 2015) , Invited

[11] Light-matter interactions in low dimensions, ITAMP-Harvard workshop, "Topological states in driven photonic systems" (Jun 2015) , Invited

[12] Amsterdam Summer Workshop on Low-D Quantum Condensed Matter, University of Amsterdam, "Topological states in driven photonic systems" (Jul 2015) , Invited

[13] PIERS, Prague, "Measuring Topological Invariants in Photonic Systems" (Jul 2015), Invited

[14] Gordon Research Conference on Quantum Control of Light & Matter, "Measuring Topological Invariants in Photonic Systems" Mt. Holyoke College (Aug 2015) , Invited

[15] Workshop Physics of bulk-edge correspondence, Tokyo, "Quantum Hall physics in photonics systems and observation of chiral anomaly" (Sep 2015) , Invited

[16] KITP-UCSB, program on Synthetic Quantum Matter, "Driven quantum Hall models in photonic systems" (Sep 2016). Invited

[17] PIERS, Shanghai, “Towards Non-classical Topological Physics in Photonic Structures” (Aug 2016). Invited

[18] KITPC-PKU conference, Synthetic Topological Quantum Matter, Beijing, “Topological physics in nanophotonics” (Aug 2016), invited

[19] META conference, Malaga, Spain, “Topological photonics: ring resonators and photonic crystals” (Jul 2016), invited

[20] Quantum simulation and many-body physics with light, Crete, Greece “Quantum transport in topological photonic structures” (Jun 2016), invited

[21] Solvay Workshop on 'Quantum simulation with cold matter and photons', Brussels, Belgium “New prospects in topological photonics” (Feb 2016) invited

[22] Physics of Quantum Electronics, Snowbird, Utah, “Topological Physics in Photonic Systems” (Jan 2016) invited

[23] Seminar Applied Physics, Stanford University, “Topological robustness in photonic systems”, (Dec 2015), invited

[24] Colloquium, ESE Department, University of Pennsylvania “Exploring Topological Physics in Photonic Systems,” (Oct 2015) invited

[25] Frontiers in Optics and Laser Science, Rochester (October 2016), Invited

D. Papers submitted

[1] G. Zhu, M. Hafezi, and T. Grover “Measurement of many-body chaos using a quantum clock”, arXiv:1607.00079 (2016)

E. Honors

5.1 Young Investigator Program award, Office of Naval Research, 2015
5.2 Alfred P. Sloan Foundation Research Fellowship, 2015

F. List of participating personnel

1. **Postdoctoral fellow**
   Khan Mahmud
   Sunil Mittal
2. **Graduate student**
   Vikram Orre

3. **Undergraduate student**
   Alisa Babcock
   Treacy Hanley

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Mohammad Hafezi

Program Officer
The AFOSR Program Officer currently assigned to the award

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Abstract

Topological features - global properties which are not discernible locally - have attracted tremendous research attention in many fields of physics, ranging from condensed matter to ultra cold gases. Recently, photonic systems have been under investigation to explore various types of topological orders and to potentially develop robust optical devices. In this project, we investigated various aspects of topological states by analyzing the transport properties both in non-interacting and interacting regimes, and measuring topological invariants in the non-interacting regime. We theoretically investigated the strongly interacting limit and develop effective theories for topological orders in a non-equilibrium system. Furthermore, we have developed numerical methods to study many-body correlated states in the driven-dissipative regimes.

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Research Objectives

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