研 究 終 了 報 告 書

「Realization of the strongly-correlated topological Haldane model in exciton-polaritons」

研究期間： 2017 年 10 月～2021 年 3 月
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1． 研究のねらい

The development of photonic platforms that exhibit topological non-triviality promises a new realm in the control of dynamics of light in photonic circuits and lasers. Further combining a topological photonic platform with a artificially enhanced photon-photon interaction strength offers a pathway to the realization in optics of robust non-Abelian anyons, particles with fractional exchange statistics essential for realising topological quantum information applications.

This project explores the use of semiconductor microcavity exciton-polaritons, hybrid quasiparticles formed in a semiconductor microcavity from a confined photon mode and an electronic excitation called an exciton, as a potential platform to realise such applications.

To advance the use of this platform for non-linear topological photonics, we establish new methodologies and experimental techniques including the fabrication of potential lattice landscapes independently for excitons and photons yielding for topological and non-Hermitian properties, in addition to optically-induced gauge fields for exciton-polaritons.

2． 研究成果

（1）概要

A new approach is established to fabricate strongly-confining, topological and non-Hermitian potential landscapes in exciton-polariton microcavities, using high-energy proton beams to independently control the exciton and photon energies with high spatial resolutions and large energy shifts. The functionality of this technique is firmly established, with the demonstration of small photon and exciton spectral linewidths and preservation of a robust polariton condensation. A fabrication recipe for arbitrary potential lattices with sub-1 μm spatial resolution with this technique is demonstrated and is successfully extended to a dual-layer implant mask with alignment of layers precise enough to fabricate almost arbitrary non-Hermitian potential landscapes.

Further, the creation of polariton Landau levels using of artificial gauge fields induced through time-dependent optical modes is theoretically and experimentally studied. This new technique is found to be suitable for off-resonantly driving rotational and longitudinal dynamics of a polariton condensate, and potentially also strongly-correlated topological polariton matter.

（2）詳細

1）研究テーマA

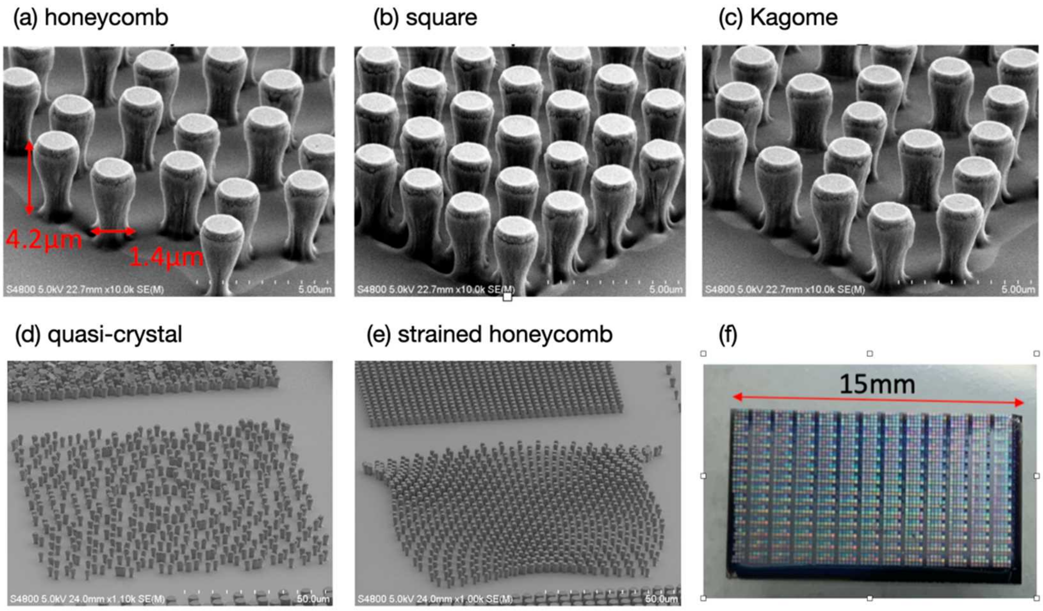
This theme specifically considered the establishment of an experimental apparatus for excitation and measurement of polariton spatial and temporal dynamics, as well as lattice bandstructure tomography, in additional to the development of a fabrication process for proton-implanted lattice potentials (for excitons and photons). The experimental apparatus construction and testing was rapidly completed. Preliminary testing of the effects of high energy proton beams on the photon and exciton energies, and the Bose-Einstein condensation properties of proton beam modified polariton microcavities was studied in depth. Under suitable conditions, the spectral properties of proton-implanted exciton-polaritons are similar to unmodified samples, and the condensation transition is qualitatively conserved. Further, a recipe for fabrication of structured potential landscapes using tall dielectric micropillar masks on the microcavity surface to permit selective implantation of certain spatial regions. As this is an original and newly established technique, testing of numerous material combinations and potential recipes was conducted. Several stages of the development of this recipe were complicated by the lack of suitable plasma processing equipment for the selective removal of SiO2 micropillars from a GaAs/AlGaAs microcavity. This problem was solved by adding an additional dielectric layer to protect the microcavity from the mask processing.

2）研究テーマB

This stage considers the design and experimental fabrication of complex potentials by two-stage implantation and study of their interplay with structured laser (gain) profiles. To facilitate this process in an experimentally simplified recipe, instead of a two-stage implant process which would require very sophisticated mask alignment, a two-layer mask and single-stage implant process recipe was established. This modification removes the issue of difficulty of aligning excitonic and photonic implant profiles, and enables, with a single implant process, almost arbitrary non-Hermitian potential lattice structures. Specific structures considered experimentally and currently being tested include non-Hermitian dimers, 1D non-Hermitian chains and three-node non-Hermitian potentials with (real-valued) triangular symmetry.

3）研究テーマC

This theme specifically considered scaling of fabricated lattice devices and the experimental establishment of topological potentials for polaritons via an on-chip topological Haldane model. The structures have been fabricated and scaled successfully, and geometries including honeycomb, square, Kagome, quasi-crystal and strained honeycomb have all been fabricated (see figure 1a-e respectively). Measurements of lattice spectra and polariton band-structures were delayed due initially to fabrication equipment difficulties (see theme A), and thereafter, pandemic-related logistical issues, but these measurements are shortly anticipated. The fabrication of such devices and the rapid iteration of lattice design together with new microcavities structures is now routine in our laboratory. A typical fabricated device image (consisting of lattices of varying properties arrayed across a semiconductor microcavity chip) is shown in figure 1(f).



4) 研究テーマ D

This theme considers specifically the theoretical study of numerical dynamics of polariton condensates under the proposed topological and non-Hermitian potentials. Numerical and analytical solutions to the open-dissipative Gross-Pitaevskii equation are studied in topological and non-Hermitian lattice geometries. For structured potentials we have in particular focused on the formation and robustness of chiral edge states in (non-Hermitian) Kagome lattices. Numerical study of polariton condensate dynamics under a rapidly varying optical pump were also extensively studied, leading us to develop a new technique for off-resonantly controlling longitudinal and rotational dynamics of a polariton condensate, the first such technique for this system. We have demonstrated the formation of dense lattices of quantized vortices under such time-dependent off-resonant rotational excitation, which is a promising route towards the creation of quantum Hall states of polaritons by rapid rotation.

5) 新しい研究テーマ

In the term of this project, the methods of investigation have evolved considerably beyond the above themes, to include new approaches and techniques with which to achieve the same mid- and long-term goals. Specifically, these have included (a) the theoretical and experimental study of rapid, driven rotation of an exciton-polariton condensate, and the formation of strongly-correlated topological states using this process and (b) the fabrication of nano-scale trapping potentials using the proton implantation technique for realizing polariton blockade. Significant progress has also been achieved in both of these areas.

3. 今後の展開

With the development of this integrated platform for (non-Hermitian) potential landscapes for exciton-polaritons now established, the next stages in the short term include specifically the experimental demonstrations of the following:

(a) non-reciprocal hopping between lattice sites, a necessary feature for demonstrating a topological Haldane model (in a square or Kagome configuration).

(b) Demonstration of flatbands in polariton lattices without degradation of the polariton spectral linewidth

(c) Demonstration of tightly-confined polaritons in a trap diameter of sub-1 μm, to approach the quantum-correlated blockade regime for polaritons

(d) Measurement of 1D topological bandstructures using non-Hermitian potential lattices

The parallel development of these elements, fabricated as distinct chips, may then be combined to realise the longer-term goal of strongly-correlated, topological states of exciton-polaritons.

4. 自己評価

The long-term strategy of this research is to realise a robust non-linear topological photonics platform. We have advanced the use of semiconductor microcavity exciton-polaritons as a suitable candidate for realizing new applications to control the flow of light, extending to the potential for new physics via the creation of many-body quantum-correlated states of light. Having now successfully developed and demonstrated several new techniques to implement topological states of exciton-polaritons, these new experimental platforms are now solidly in the stage of measurement and demonstration of new functionality.

In particular, the creation of a robust fractional quantum state of matter is presently a highly sought after goal, and is as yet unachieved in photonics. The achievement of this long-term target may result in the realisation of a robust and controllable source of non-Abelian anyons, thereby driving a significant impact on our fundamental understanding of topological and quantum-correlated states of matter, in addition to becoming a viable platform to implement applications in topological quantum information. These applications, while currently very challenging to achieve, are distinctly new approaches to quantum simulation and quantum computation, and which offer potential new functionality or robustness compared with traditional quantum computing schemes.

There are many potential platforms, and approaches within those platforms to achieve this goal, and the exciton-polariton microcavity platform has emerged has a strong contender. We believe that further advancing these technologies, alongside our understanding of the system, will lead in the short-term to significant new fundamental discoveries and realization of new topological, non-Hermitian and quantum-correlated photonic matter. In the long-term, the potential for the emergence of new, disruptive quantum photonic technologies is significant, and is anticipated to follow advances in the control over this platform, together with new materials to upgrade the robustness of its key features.

5. 主な研究成果リスト

（1）代表的な論文（原著論文）発表

研究期間累積件数：2件

1. E. Estrecho, T. Gao, N. Bobrovska, M. D. Fraser, M. Steger, L. Pfeiffer, K. West, T. C. H. Liew, M. Matuszewski, D. W. Snoke, A. G. Truscott, and E. A. Ostrovskaya ‘Single-shot condensation of exciton polaritons and the hole burning effect’ Nature Communications **9**, 2944 (2018)
Insight is gained into the spontaneous condensation of exciton-polaritons by imaging long lifetime exciton polaritons in a high-quality inorganic microcavity in a single-shot optical excitation regime, without averaging over multiple condensate realisations. We demonstrate that condensation is strongly influenced by an incoherent reservoir and that the reservoir depletion, the so-called spatial hole burning, is critical for the transition to the ground state. Condensates of photon-like polaritons exhibit strong shot-to-shot fluctuations and density filamentation due to the effective self-focusing associated with the reservoir depletion. In contrast, condensates of exciton-like polaritons display smoother spatial density distributions and are second-order coherent.
2. E. Estrecho, T. Gao, N. Bobrovska, D. Comber-Todd, M. D. Fraser, M. Steger, K.West, L. N. Pfeiffer, J. Levinsen, M. M. Parish, T. C. H. Liew, M. Matuszewski, D. W. Snoke, A. G. Truscott, E. A. Ostrovskaya ‘Direct measurement of polariton-polariton interaction strength in the Thomas-Fermi regime of exciton-polariton condensation’ Physical Review B **100**, 035306 (2019)
A high-density exciton-polariton condensate is created in an optically induced box trap in the Thomas-Fermi regime. The full separation from the thermal reservoir allows the condensate dynamics to be dominated by interparticle interactions. This regime is used to directly measure the polariton-polariton interaction strength, and reduce the existing uncertainty in its value from four orders of magnitude to within three times the theoretical prediction.

（2）特許出願

研究期間累積件数：0 件（特許公開前のものも含む）

（3）その他の成果（主要な学会発表、受賞、著作物、プレスリリース等）

Invited international conference presentations:

[1]　Progress in the Mathematics of Topological States of Matter
AIMR, Tohoku University, Katahira Campus, Sendai (30 July, 2019)
"Engineering Non-Hermitian potential landscapes in exciton-polariton microcavities"

[2]　International Workshop Recent Advances in Topological Photonics
Korea Center for Theoretical Physics of Complex Systems (PCS) of the Institute for Basic Science in Daejeon, Korea　(June 20, 2019)
"Engineering topological states of exciton-polaritons with non-Hermitian potentials"

[3]　RIKEN Berkeley Workshop on Quantum Information Science (RB19)
Lawrence Berkeley National Laboratory, Berkeley, California (January 27, 2019)
"Engineering topologically non-trivial polariton states by non-Hermitian potential lattices"

[4]　International Conference on Terahertz Emission, Metamaterials and Nanophotonics (TERAMETANANO-3) Uxmal, Mexico (March 29, 2018)
"Structured complex potentials for exciton-polariton condensates"