様　式　C－19、F－19－1、Z－19　(共通)

科学研究費助成事業　　研究成果報告書

令和　４ 年 １０ 月 ２１ 日現在

機関番号：８２４０１
研究種目：若手研究(A)
研究期間：2017～2019
課題番号：１７Ｈ０４８５１

研究課題名（和文）Creation of bosonic fractional quantum Hall states in exciton-polaritons

研究課題名（英文）Creation of bosonic fractional quantum Hall states in exciton-polaritons

研究代表者
Ｆｒａｓｅｒ　Ｍｉｃｈａｅｌ（Fraser, Michael）

国立研究開発法人理化学研究所・創発物性科学研究センター・研究員

研究者番号：１０６４７０５１

交付決定額（研究期間全体）：（直接経費）　　19,000,000円

研究成果の概要（和文）：光と物質のトポロジー状態の作成を、新しい方法論を使用して追求した。特に（a）マイクロキャビティー励起子ポラリトン凝縮体の急速な回転によって、および（b）構造化されたトポロジカルおよび非エルミートポラリトン格子の生成研究によってである。
本研究ではポラリトンの高速回転が可能な最初の実験的手法を作成した。自発的に形成されたポラリトン凝縮物の駆動回転を実験的に計測し、大量の角運動量を注入する能力と、密な渦格子の形成を理論的に検証した。構造化されたトポロジカルおよび非エルミートポラリトン格子を作成できる、半導体マイクロキャビティのプロトン注入を使用した新しい製造プラットフォームを確立した。

研究成果の学術的意義や社会的意義
The development of two original platforms for topological states of light in an integrated, non-linear environment moves us towards the realisation of fractional quantum Hall states of light and a robust, controllable source of anyons, enabling potential topological quantum computing applications.

研究成果の概要（英文）：The creation of topological states of light and matter was explored using new methodologies, specifically (a) by the rapid rotation of a condensate of microcavity exciton-polaritons, and (b) investigation of new methods to fabricate structured topological and non-Hermitian (control over gain and loss landscape) lattices of exciton-polaritons.
We have created the first experimental technique capable of rapid rotation of polaritons and determined the optimal conditions for realising a bosonic fractional quantum Hall effect. Driven rotation of a spontaneously formed polariton condensate has been experimentally measured, and we have verified theoretically the ability to inject large amounts of angular momentum, as well as the formation of dense vortex lattices. We have also established a new fabrication platform using proton-implantation of semiconductor microcavities, which is capable of creating structured topological and non-Hermitian lattices of polaritons.

研究分野：condensed matter physics

キーワード：exciton-polariton　quantum Hall　quantized vortex　topological　rapid rotation

１．研究開始当初の背景（Background of the beginning of research）

Synthetic topological states of light and matter are receiving intense research attention, driven partially by the promise of controlling the dynamics of light, electrons, atoms and other particles in a way which is protected from the presence of disorder, by topology. Topological matter was first realized in the electronic integer and fractional quantum Hall effects (FQHE) [J. K. Jain, 'Composite fermions' Cambridge University Press (2007)], but rapid progress is being made in engineering synthetic platforms of light and matter exhibiting robust topological transport, spawning a new field known as topological photonics [T. Ozawa, *et al.*, Rev. Mod. Phys. 91, 015006 (2019).]. These emerging photonic platforms which typically consist of optical resonator networks promise new ways of controlling the flow of light as well as lasing dynamics. A particularly exciting possibility for these systems is the emergence of robust fractional excitations when strong interactions or non-linearity is present. The fractional exciton known as a non-Abelian anyon is implicated in an error-resistant topological quantum computation architecture [C. Nayak, *et al.*, Rev. Mod Phys. 80, 1083 (2008).], and thus systems hosting them are highly sought-after. Engineered hybrid photon-matter platforms are promising candidates for the realization of robust, controllable non-Abelian anyons.

The microcavity exciton-polariton quasi-particles used in this work consist of coupled photon and exciton modes in a semiconductor structure (see Figure 1a). This is a highly controllable optical platform with flexibility over the fraction of matter and photon that make up the polariton. Bose-Einstein condensates of exciton-polaritons are now routinely observed in high quality samples [I. Carusotto and C. Ciuti, Rev. Mod. Phys. 85, 299 (2013)]. At the start of this research program, all studies of topology in the exciton-polariton platform employed structured lattices [C. Schneider, K. Winkler, M. D. Fraser, M. Kamp, Y. Yamamoto, E. A. Ostrovskaya and S. Höfling, Rep. Prog. Phys. 80, 016503 (2016)] made either by deep etching of micropillars, or by an etch and overgrowth method. Both techniques only modify the photon component of the exciton-polaritons. Furthermore, driven rotation of a spontaneously formed exciton-polariton condensate had not yet been achieved.

２．研究の目的　(Purpose of research)

The aim is to investigate new ways of creating robust topological states capable of supporting robust non-Abelian anyons, using the hybrid light-matter platform of microcavity exciton-polaritons.

３．研究の方法　(Method of study)

This project consists of distinct parts including theoretical study, creation of technologies for fabrication of new sample types, and optical experimental measurements. Two key methodologies for achieving topological states of exciton polaritons have been investigated.

The first technique explores a direct analogy to the traditional fractional quantum Hall effect for bosons [A. L. Fetter, Rev. Mod. Phys. 81, 647 (2009)]. The two-dimensional electron gas in a strong magnetic field, is replaced by a rapidly-rotating, harmonically trapped condensate of exciton-polaritons. As the high rotation limit is approached, the rotation cancels out the trapping potential, creating degenerate bands with the form of Landau levels. For sufficiently rapid rotation and other optimized conditions, a phase transition to a strongly correlated non-condensed phase is predicted in analogy to the fractional quantum hall state, but has yet proved difficult to observe in atomic condensates.

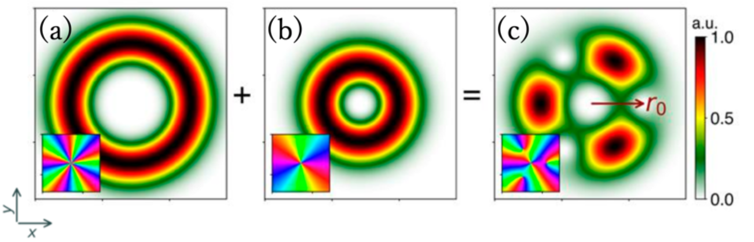

Figure 1: Superposition profile of two LG modes of index (a) $l = 5$ and (b) $l = 2$ giving the broken axial-symmetry mode (c) This laser mode is used to both pump and rotate a condensate.

Prior to this study, driven rotation had not yet been achieved in the exciton-polariton platform. We have designed a new technique with the potential to rapidly rotate a polariton condensate, employing the use of off-resonant superpositions of Laguerre-Gauss (LG) modes (Figure 1). The condensate pump, which both generates polaritons and rotates the condensate, consists of two distinct axially symmetric LG modes of differing l-index, a superposition of which breaks the axial symmetry yielding a mode containing a ring of (singly quantized) defects. The superposition is converted to a rotating amplitude mode by adding a small frequency difference Δf, and thus the satellite vortex defects will rotate at a pump frequency $\Omega_l = \Delta f$.

In this project, theoretical study of quantum Hall effects in the exciton-polariton system by rapid rotation and the efficiency of achieving these states using this new rotation technique are investigated. An experimental apparatus to realize rapidly rotating exciton-polaritons is constructed, and the first driven rotation of a spontaneously formed polariton condensate has been measured.

The second technique studied employs the use of structured Hermitian and non-Hermitian lattices of polaritons to realize topological models such as the Harper-Hofstadter or Haldane models. We establish a new technique for creating potential lattices for exciton-polaritons, by using structured proton implantation induced interdiffusion. This technique uses high energy protons to create defects in the semiconductor lattice at precise positions. A subsequent high temperature anneal recovers this damage and leads to a shift of the energy of either the exciton or photon mode depending on the vacancy position and density. This technique is expected to offer significant advantages over other techniques for the study of topological matter including narrow photoluminescence linewidth and a wide tuning range of effective mass. The fabrication process for these samples is established in this work.

４．研究成果 (Research results)

(a) Quantum Hall effects in a rapidly rotating polariton condensate (Theory)

Quantum Hall effects by rapid rotation have only been considered thus far in the dilute atomic gas platform. An analysis of the parameter space diagram and the expected appearance of integer (mean-field) and fractional quantum Hall effects in the rapidly rotating polariton gas is established in this work (Figure 2). Specifically, the mass tunability possible in the exciton-polariton platform enables the selection of the optimal parameter space location for maximising the robustness of the fractional quantum Hall effect, i.e. when $g_{2D}M/\pi\hbar^2 \sim 1$, where g_{2D} is the interaction coefficient and M is the mass, which requires a high exciton-fraction polariton condensate. In collaboration with the University of Würzburg, we have grown microcavity samples which can host polariton condensates in this optimal parameter space.

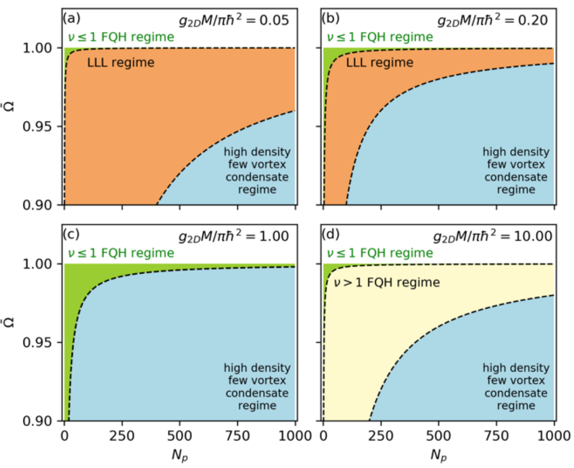

Figure 2: Parametric phase diagram of the mean-field LLL and fractional quantum Hall regimes in a rapidly rotating, harmonically trapped bosonic condensate. The parameter $g_{2D}M/\pi\hbar^2$ controls the transition from a mean-field lowest Landau level (LLL) dominated state to one where strong particle-particle interactions dominate and a FQH phase appears.

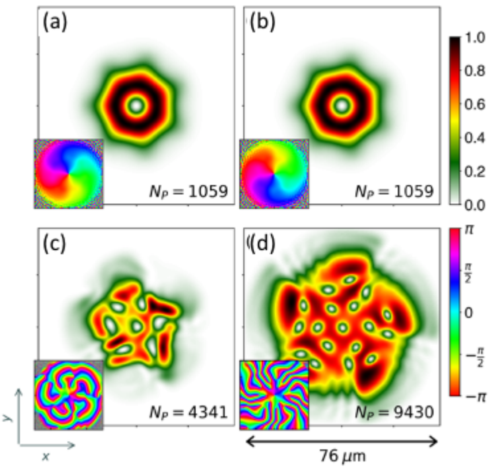

Figure 3: Steady state amplitude and phase (inset) showing control of angular momentum and vortex lattice formation in a rotating polariton condensate. (a) $\Omega_l = +0.5\,GHz$ and (b) $\Omega_l = -0.5\,GHz$, shows the deterministic control of a single vortex sign. At large rotation rates, Abrikosov lattices are formed with (c) 7 vortices and (d) 18 vortices. The number of particles N_p is indicated.

A second key result is the establishment of a robust technique for rapidly rotating an exciton-polariton condensate. The use of superpositions of LG modes is shown to be an efficient technique for injecting angular momentum into a polariton condensate, and the mechanism of operation and ideal pump parameters are established. In particular, in numerical calculations closely representative of the experiments (specifically, by solving the open-dissipative Gross-Pitaevskii equation), dense Abrikosov lattices of quantised vortices are observed to form using this pumping technique, even in the presence of open dissipation (Figure 3). A research article with these results is currently in preparation.

(b) Quantum Hall effects in a rapidly rotating polariton condensate (Experiments)

An experimental apparatus has been constructed to realise rapid rotation of exciton-polaritons. This experiment consists of an exciton-polariton condensate at a temperature of 4K, which may be imaged with a spatial resolution of ~700 nm and for which time resolved dynamics at a resolution of <1 ps are established. Measurements of phase (Michelson interferometer), momentum space dynamics and energy-momentum tomography are also possible.

Specifically enabling the rapid rotation of the polariton condensate is the new experimental establishment of a LG (or top-hat) superposition laser mode with a frequency offset Δf. This superposition is created using two-phase locked lasers (a Ti:Sapphire laser and an external cavity diode laser with tapered fiber amplifier). The phase locking is possible at frequency offsets between a few MHz and 10 GHz through a custom-built phase-locked loop. This frequency range is optimised for rotation polariton condensates, for which photonic condensates require high frequencies (GHz), while heavier excitonic condensates use lower frequencies (100s of MHz). An example of these phase-locked laser mode superpositions for a Gaussian and an LG mode with varying quantum number l is shown in Figure 4.

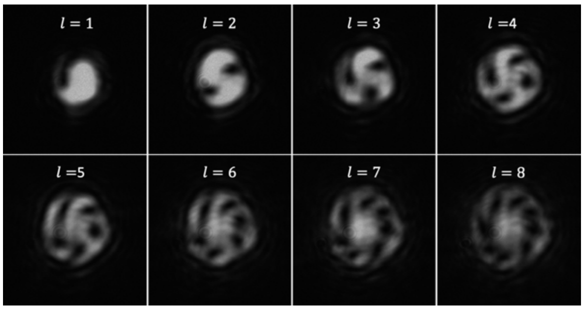

Figure 4: Experimental superpositions of Gaussian and LG modes for quantisation numbers $l = 1 \rightarrow 8$, for rapid, driven rotation of a polariton condensate.

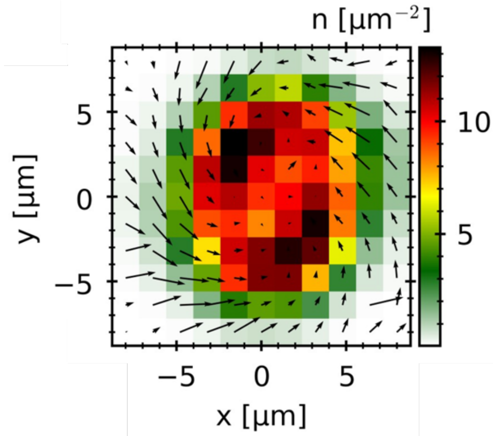

Figure 5: Experimental measurement of the rotational flow of an optical rotated exciton-polariton condensate. Vectoral flow map is overlayed on a measurement of the condensate density distribution.

Using this apparatus, the first experimental rotation of a spontaneously formed exciton-polariton condensate has been observed. To achieve this, we have directly measured the incorporation of angular momentum, which was controlled by the rotating optical beam. Figure 5 shows a measurement of the vectoral rotational flow overlayed onto the spatial condensate density profile for a pump rotation speed of 5 GHz, clearly showing a counter-clockwise rotational flow of the condensate. The mechanism for optically driving rotation of the polariton condensate is also elucidated by comparing experimental measurements with numerical solutions to the open-dissipative Gross-Pitaevskii equation, with the key finding that driven optical rotation is achieved by a combination of both mechanical and non-Hermitian stirring contributions.

These results are submitted for review:

- Y. dV. I. Redondo, C. Schneider, S. Klembt, S. Höfling, S. Tarucha, and M. D. Fraser "Optically driven rotation of an exciton-polariton condensate" arXiv:2209.01904

(c) Structured non-Hermitian and topological lattices by proton implantation (sample fabrication)

The use of on-chip fabricated structured potentials is a convenient tool for creating topological states of polaritons, and photons in general. However, the two existing technologies for polaritons typically suffer from processing difficulty, severely degraded photoluminescence linewidth, and are only sensitive to the photon fraction of the polariton. We have established the technique of proton-implantation induced interdiffusion which we have now demonstrated to have considerable advantages over other established methods including:

- Large energy shifts (10s of meV) to both excitons and photons representative of the tight-binding regime,
- heavy polaritons may also be deeply confined,
- mass can be controlled as a lattice variable,
- polariton lifetime can be spatially controlled enabling the creation of non-Hermitian potential lattices, and
- photoluminescence linewidth for small, but useful energy shifts, remains unchanged.

The initial study of the effect of proton-implantation on planar GaAs microcavity samples was extended to create structured lattice potentials. The samples are patterned with a fabricated implant mask of high-aspect ratio SiO_2 micro-pillars (1.4 μm wide, 4.2 μm high), which block the high energy protons from specific regions with $\sim 1\,\mu m$ spatial resolution. This is a new fabrication process, and its development required considerable optimization to achieve well-formed micro-pillars without damaging the underlying microcavity material. In particular, the incorporation of a Si_3N_4 layer was found to be necessary. This process is outlined in Figure 4a, with an example photo of a functional device (Fig 4b) and scanning electron micrographs (SEM) (Fig 4c,d) of polariton lattices with varying parameters, including honeycomb, kagome, square, strained honeycomb, higher-order topological kagome and quasi-crystal structures.

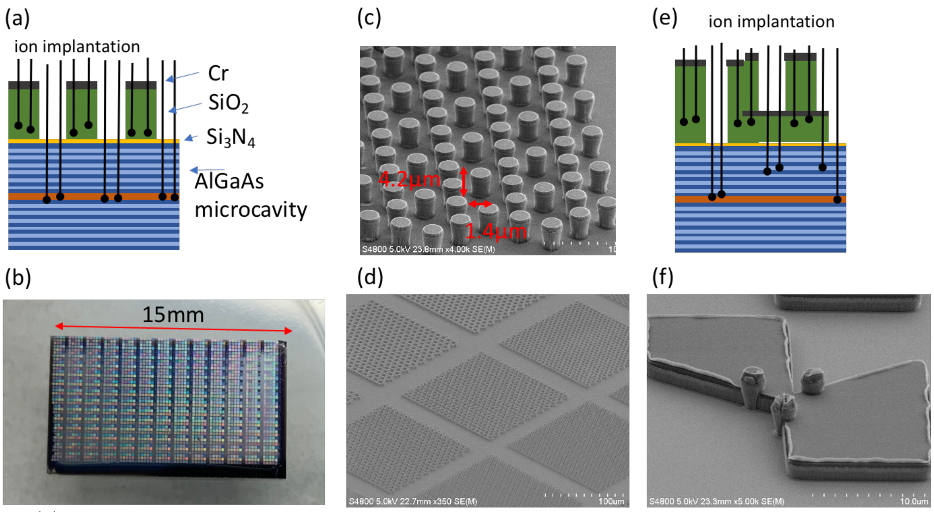

Figure 5: (a) Proton implantation fabrication process for Hermitian polariton landscapes, with (b) a functional fabricated chip consisting of 100s of variations of polariton lattices. (c) and (d) show some example SEM images. (e) the dual-layer implant mask for fabrication of non-Hermitian samples and (f) an SEM image of a fabricated dual-layer sample forming part of a topological lattice.

This work is extended to create non-Hermitian potentials by optimising the fabrication process for a dual-layer micro-pillar mask (Fig 4e,f). The dual-layer mask enables the option of having a thick mask which completely blocks protons from the semiconductor microcavity, while a thin layer attenuates the proton energy so the vacancies occur at a shallower depth. By this single implantation process, spatially structured energy shifts to both photons and excitons are simultaneously possible. The appropriate combination of these energy shifts leads to a controllable landscape of not only polariton energy, but also polariton lifetime and mass. This is the first integrated technique capable of fabricating non-Hermitian landscapes with polaritons.

Part of these research results have been accepted for publication, and other research results are currently being prepared for publication:

- M. D. Fraser, H. H. Tan, Y. del Valle Inclan Redondo, H. Kavuri, E. A. Ostrovskaya, C. Schneider, S. Höfling, Y. Yamamoto, S. Tarucha
  "Independent tuning of exciton and photon energies in an exciton-polariton condensate by proton implantation-induced interdiffusion" Advanced Optical Materials (to appear)

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　1件）

１．著者名 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	４．巻 9
２．論文標題 Single-shot condensation of exciton polaritons and the hole burning effect	５．発行年 2018年
３．雑誌名 Nature Communications	６．最初と最後の頁 2944
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-018-05349-4	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 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	４．巻 100
２．論文標題 Measurement of polariton-polariton interaction strength in the Thomas-Fermi regime of polariton condensation	５．発行年 2019年
３．雑誌名 Physical Review B	６．最初と最後の頁 35306
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.100.035306	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 M. D. Fraser, H. H. Tan, Y. del Valle Inclan Redondo, H. Kavuri, E. A. Ostrovskaya, C. Schneider, S. Hofling, Y. Yamamoto, S. Tarucha	４．巻 -
２．論文標題 Independent tuning of exciton and photon energies in an exciton-polariton condensate by proton implantation-induced interdiffusion	５．発行年 2022年
３．雑誌名 Advanced Optical Materials	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計10件（うち招待講演　5件／うち国際学会　0件）

１．発表者名 Michael D. Fraser
２．発表標題 "Engineering topologically non-trivial polariton states by non-Hermitian potential lattices"
３．学会等名 "RIKEN Berkeley Workshop on Quantum Information Science (RB19) Lawrence Berkeley National Laboratory, Berkeley, California"（招待講演）
４．発表年 2019年

1．発表者名
Michael D. Fraser

2．発表標題
"Engineering topologically non-trivial polariton states by non-Hermitian potential lattices"

3．学会等名
The Australian National University Polariton Workshop

4．発表年
2018年

1．発表者名
Michael D. Fraser

2．発表標題
"Dynamics of exciton-polaritons and engineering of topological non-triviality in non-Hermitian potential lattices lattices"

3．学会等名
7th CEMS Research Camp, Ikoinomura Heritage Minoyama, Chichibu（招待講演）

4．発表年
2018年

1．発表者名
Michael D. Fraser

2．発表標題
"Realization of a strongly-correlated Haldane model in polaritons lattices"

3．学会等名
"8th CEMS Topical Research Camp on 'Symmetry and Topology' Hotel Maholova Minds Miura"

4．発表年
2018年

1．発表者名
Michael D. Fraser

2．発表標題
"Engineering topologically non-trivial polariton states by non-Hermitian potential lattices"

3．学会等名
Center for Theoretical Physics of Complex Systems, Daejong, South Korea

4．発表年
2019年

１．発表者名
Michael D. Fraser

２．発表標題
Engineering topological states by non-Hermitian potentials

３．学会等名
Coherent Network Computing (CNC2019)　NTT Atsugi R&D Center/NTT Basic Research Laboratories

４．発表年
2019年

１．発表者名
Michael D. Fraser

２．発表標題
"Engineering topologically non-trivial polariton states by non-Hermitian potential lattices"

３．学会等名
University of Wurzburg, Wurzburg, Germany

４．発表年
2019年

１．発表者名
Michael D. Fraser

２．発表標題
Structured complex potentials for exciton-polariton condensates

３．学会等名
International Conference on Terahertz Emission, Metamaterials and Nanophotonics (TERAMETANANO-3), Uxmal, Mexico（招待講演）

４．発表年
2018年

１．発表者名
Michael D. Fraser

２．発表標題
Engineering Non-Hermitian potential landscapes in exciton-polariton microcavities

３．学会等名
Progress in the Mathematics of Topological States of Matter AIMR, Tohoku University, Katahira Campus, Sendai（招待講演）

４．発表年
2019年

1．発表者名 Michael D. Fraser
2．発表標題 Engineering topological states of exciton-polaritons with non-Hermitian potentials
3．学会等名 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（招待講演）
4．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

Quantum-states of exciton-polaritons polariton.riken.jp

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関